CERTIFICATION OF APPROVAL

Fuzzy Logic for pH Neutralization Process

by

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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.

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ABSTRACT

pH neutralization process is a process that is widely studied due to its highly nonlinear process reaction. Its nonlinearity behavior is caused by static nonlinearity between pH and concentration. This nonlinearity depends on the substances in the solution and on their concentrations. In this project, the nonlinearity of the process was investigated. Later, the mathematical model of the process was developed based on McAvoy et al [1]. In addition to the mathematical model, an empirical model was also obtained from Analytical & Chemical Pilot Plant located in the Process Control & Instrumentation Laboratory (23-00-06). Both models were then used to develop the Fuzzy Logic Controller (FLC) by using Advanced-Neuro Fuzzy Inference System (ANFIS) and also gain-scheduling method. In ANFIS implementation for empirical model, the FLC output was identical to the output from PID. Therefore it is concluded that FLC could be used to replace PID for empirical model. In ANFIS implementation for mathematical model, the FLC also could be implemented for mathematical model since the controlled variable successfully follows all the set point changes. For gain-scheduling method, the FLC was tested on servo and regulator problems. The servo test was performed by using a random number generator to generate random pH set points between 3 and 11 and the simulation is performed for 100 seconds. The result for the servo test was similar with the result from the ANFIS implementation for mathematical model. For regulator test, the disturbance was the ±20% variation in acid flow. The result for the regulator shows, the controller manages to eliminate the disturbance effect in the process variable. In overall, the project successfully shows that FLC could be a good alternative to PID controller.

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SYMBOLS, NOTATIONS AND ABBREVATIONS

&&	AND
δ	Manipulated variable step change
τ	Time constant
θ	Time delay
Δ	Controlled variable step change
$\in$	Set of
F_a	Acid flow rate, litre/sec
F_b	Basic/ Alkaline flow rate, litre/sec
C_a	Acid concentration, mol/litre
C_b	Basic/ Alkaline concentration, mol/litre
V	Volume, litre
x_a	Concentration of non-reacting acid, mol/litre
x_b	Concentration of non-reacting base, mol/litre
K_p	Proportional gain
K_c	Closed loop gain
T_i	Integral time
T_d	Derivative time
ANFIS	Advanced Neuro-Fuzzy Inference System
E	Error
ΔE	Change of error
ΔE/dt	Rate of change of error
FLC	Fuzzy Logic Controller
CSTR	Continuously Stirred Tank Reactor
DCS	Distributed Control System
FIS	Fuzzy Inference System
ODE	Ordinary Differential Equation
PID	Proportional Integral Derivative
SASB	Strong Acid Strong Base

CHAPTER 1

INTRODUCTION

1.1 Background

pH neutralization process is a process that is widely under research due to its highly nonlinear process reaction. Its nonlinearity behavior is caused by the static nonlinearity between pH and concentration.

PID controller which is a linear controller is not sufficient to control wide range of pH since it relies on the principle of linearity that guarantees a Y% change in the process variable following an X% change in the control effort. The ratio or gain between X and Y will be fixed, whether the process is running at maximum capacity, minimum capacity or somewhere in between. Hence, PID only works beautifully in linear process which makes it very bad for pH neutralization process which is very highly nonlinear.

A resort to the conventional PID controller was to apply gain-scheduling method as offered by commercial controller for example Commander 355 from ABB [2].

Gain-scheduling could be further upgraded by taking the advantages offered by fuzzy logic since fuzzy logic allows a continuous transition among the gain values in the table.

In this project, the nonlinear behavior of pH neutralization process will be studied to implement Fuzzy Logic Controller (FLC) on the process.

1.2 Problem statement

For wide range of pH value in the pH neutralization process, linear PID controller is not sufficient to control the process; therefore a new controller will be developed for the process. The controller will consolidate the gain-scheduling method and fuzzy logic design.

1.3 Objectives and Scope of Study

- To understand the nonlinearity behavior of the pH neutralization process.
- To develop the mathematical model of pH neutralization process.
- To obtain the empirical model of the pH neutralization process based on the Analytical & Chemical Pilot Plant located in the Process Control & Instrumentation Laboratory (23-00-06).
- To obtain the K_c and T_i for different pH set point in the mathematical model as part of the gain-scheduling method.
- To design fuzzy logic controller for the mathematical model and empirical model based on the Advanced-Neuro Fuzzy Inference System (ANFIS) and also gain-scheduling method.
- To test the FLC based on servo and regulator problems on the mathematical and empirical model of pH neutralization process.
- Make the comparison test between the Linear PID, Fuzzy Logic Controller (gain-scheduling method) and Fuzzy Logic Controller (ANFIS).

CHAPTER 2

LITERATURE REVIEW

2.1 pH neutralization

pH is the measurement of the acidity or alkalinity of a solution containing a proportion of water. Neutralization is the process to neutralize acidic and alkaline solution to produce salt and water. The process is highly nonlinear as shown in the Figure 1.

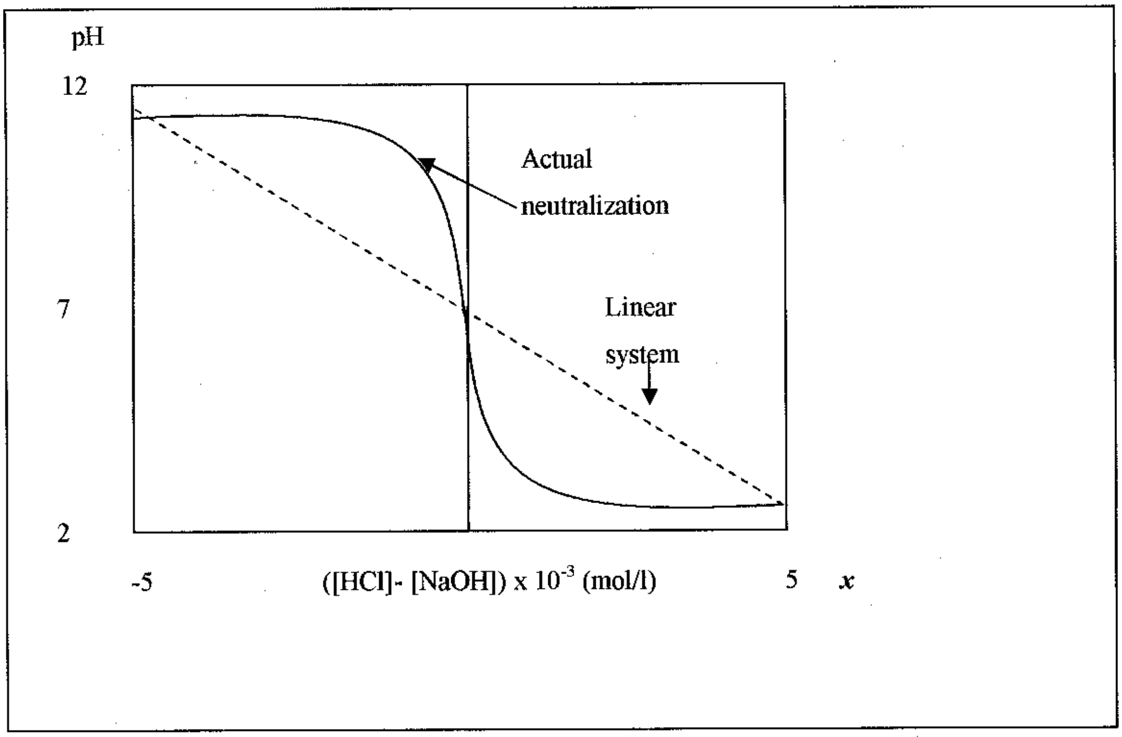

Figure 1: Titration curve for pH neutralization process.

Here is presented the chemistry point of views that explain the non linearity behavior of pH neutralization process as per explained by Astrom [3], pH is a measure of the concentration or more precisely the activity of hydrogen ions ($[H^+]$) in a solution. It is defined as:

$$pH = -\log[H^+] \tag{1}$$

However, the formula is not totally correct since $[H^+]$ has the dimension of concentration which is measured in the unit M= mol/l. The modified formula is:

$pH = -\log[H^+]f_H$ $\quad f_H$= constant with dimension l/mol (2)

However, the first formula is universally accepted in most of chemistry textbooks. Water molecules are dissociated (split up into hydrogen and hydroxyl ions) according to the formula:

$$H_2O \Leftrightarrow H^+ + OH^- \qquad (3)$$

In chemical equilibrium, the concentration of hydrogen H^+ (or rather H_3O^+) and hydroxyl ions are given by the formula:

$$\frac{[H^+][OH^-]}{[H_2O]} = \text{Constant} \qquad (4)$$

Only a small fraction of the water molecules are split up into ions. The water activity is practically unity, and we get:

$$[H^+][OH^-] = K_w \qquad (5)$$

The equilibrium constant K_w has the value 10^{-14} [(mol/l)^2] at 25°C.

So, where the nonlinearity come from?

It is good to depict the process with an example. Let's take a look on the neutralization process of m_A mol hydrochloric acid, HCl by m_B mol of sodium hydroxide NaOH in a water solution. The reaction takes place as follows:

$$HCl + NaOH \Leftrightarrow H^+ + OH^- + Na^+ + Cl^- \qquad (6)$$

Let's the total volume be V. The concentration of chloride ions is then:

$$[Cl^-] = x_A = m_A / V \qquad (7)$$

and the concentration of sodium ions is given by:

$$[Na^+] = x_B = m_B / V \tag{8}$$

because the acid and base are completely ionized. Since the number of positive ions equals the number of negative ions, it follows that:

$$x_A + [OH^-] = x_B + [H^+] \tag{9}$$

The concentration of hydroxyl ions can be related to the hydrogen ion concentration by Equation 5:

$$x = x_B - x_A = [OH^-] - [H^+] = \frac{K_w}{[H^+]} = 10^{pH-14} - 10^{-pH} \tag{10}$$

Solving for $[H^+]$ gives:

$$[H^+] = \sqrt{x^2/4 + K_w} - x/2 \tag{11}$$

$$[OH^-] = \sqrt{x^2/4 + K_w} - x/2 \tag{12}$$

This gives:

$$pH = f(x) = [H^+] = \sqrt{x^2/4 + K_w} - x/2 \tag{13}$$

Equation 13 proves the nonlinearity of the pH neutralization process with the curve as shown in Figure 1.

Let's us check the slope of the curve by taking its derivative of function ***f(x)***:

$$f'(x) = \frac{10 \log e}{10^{pH-14} + 10^{-pH}} \tag{14}$$

From the f'(x), the largest value is at pH=7. It decreases rapidly for larger and smaller values of pH. Therefore, the gain can vary by several orders of magnitude.

The curve shown is for the strong acid-strong base (SASB) reaction since strong acids and bases are completely dissociated when diluted in water. A weak acid is not completely dissociated, so it can absorb hydrogen ions by converting them to undissociated acid. A weak acid or weak base has an ability to resist changes in pH. This is the property called *buffering*. For weak acid/ base reaction, the curve would be less steep.

Figure 2 shows the MATLAB block diagram of Equation 13.

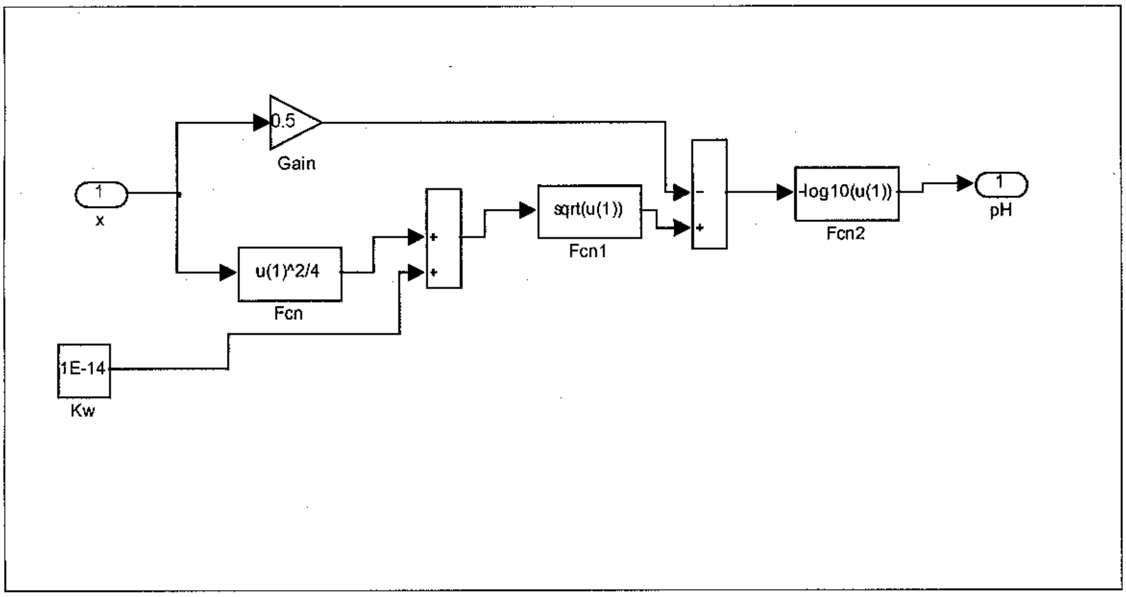

Figure 2: MATLAB SIMULINK block for Equation 13.

2.2 Mathematical model of pH neutralization process

Mathematical model of the process is developed based on McAvoy et al [1] model which are:

$$V\frac{dx_a}{dt} = F_a C_a - (F_a + F_b)x_a \tag{14}$$

$$V\frac{dx_b}{dt} = F_b C_b - (F_a + F_b)x_b \tag{15}$$

Units:

x_a, x_b, mol/ litre = concentration of non-reacting acid and base solution in the mixing tank

C_a, C_b, mol/litre = concentration of influent and neutralizing agent.

F_a, F_b ,litre/sec = flow rate of influent and reagent

The equations are presented physically as shown in Figure 3.

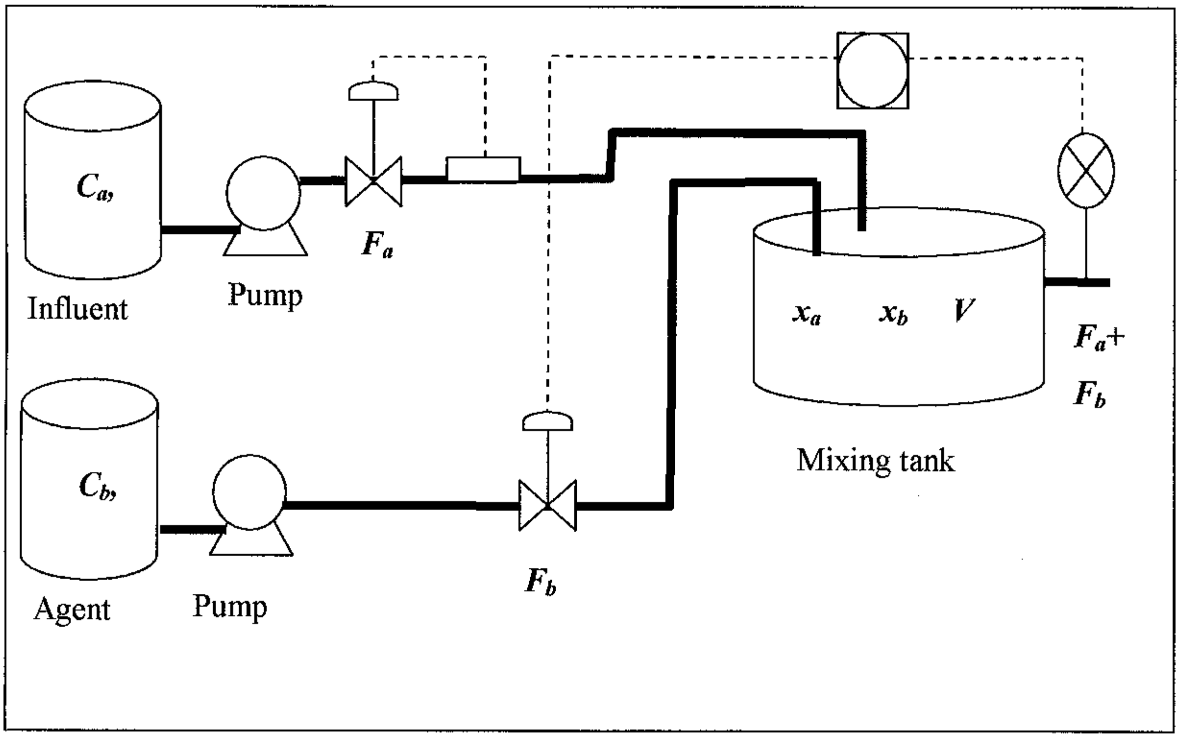

Figure 3: Physical representation of the pH neutralization process.

The given equations are based on Continuously Stirred Tank Reactor (CSTR). By assuming a prefect mixing in the tank isothermally, McAvoy derived the dynamic model which was verified experimentally.

To develop the equivalent MATLAB SIMULINK block, the Ordinary Differential equation (ODE) has to be represented in state space/ matrix form. The matrix form of the equations was:

$$\begin{bmatrix} \hat{x}_a \\ \hat{x}_b \end{bmatrix} = \begin{bmatrix} -(F_a + F_b)/V & 0 \\ 0 & -(F_a + F_b)/V \end{bmatrix} \begin{bmatrix} \hat{x}_a \\ \hat{x}_b \end{bmatrix} + \begin{bmatrix} F_a C_a / V \\ F_b C_b / V \end{bmatrix} u(t) \qquad (16)$$

$$y = \begin{bmatrix} 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{x}_a \\ \hat{x}_b \end{bmatrix} \tag{17}$$

**u(t)* represent the input to the system which could be the F_a, F_b, C_a, C_b

From the matrix equations, the block diagram of the equation is developed as shown in Figure 4 and 5.

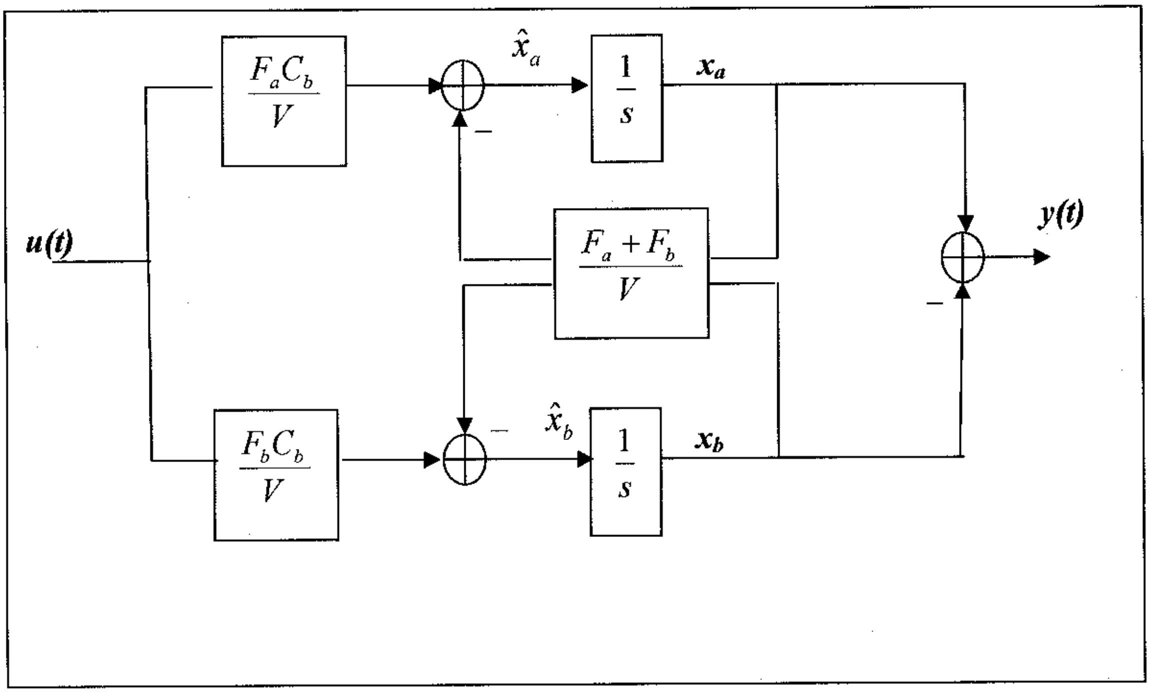

Figure 4: ODE block diagram

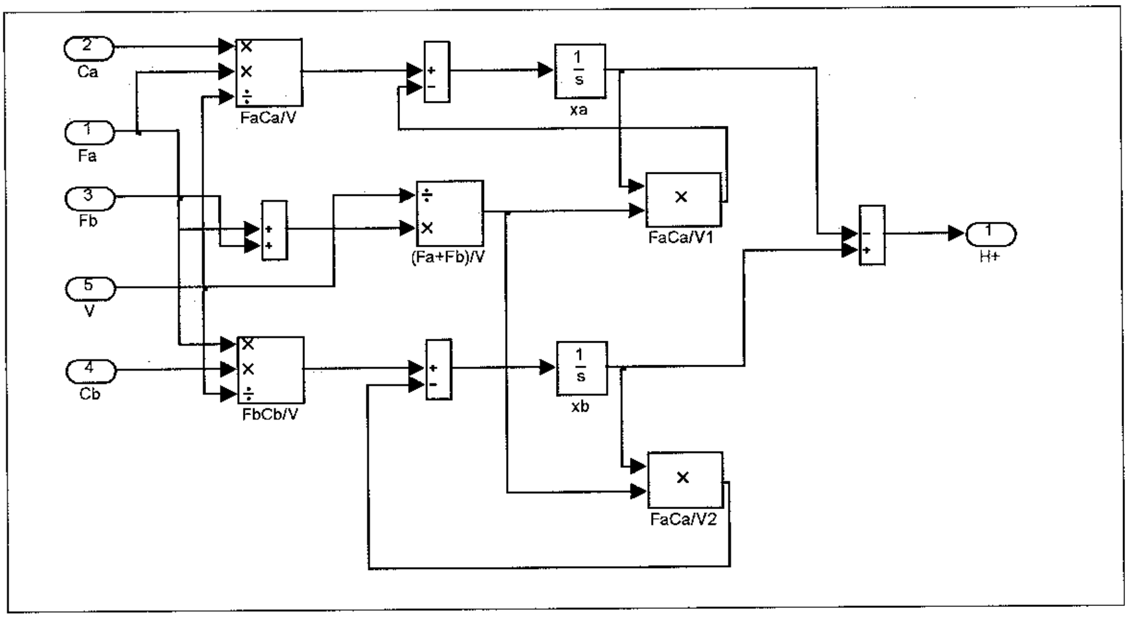

Figure 5: MATLAB SIMULINK mathematical model of pH neutralization plant.

2.3 Empirical model

Besides the mathematical modeling, the process can be identified through another easier method called empirical modeling. This method is specially designed for process control. The model is developed based on the dynamic relationship between selected input and output variables.

Empirical model is tailored for specific need of a particular process control and is not meant to satisfy all process design and analysis requirements and can not replace the mathematical models for all same processes.

In empirical modeling, model is determined by making small changes in the input variable about a nominal operating condition. The resulting dynamic response is used to determine the model. The general procedure is essentially an experimental linearization of the process that is valid for some region about the nominal conditions. The procedure for empirical transfer function model identification is shown in Figure 6 [4].

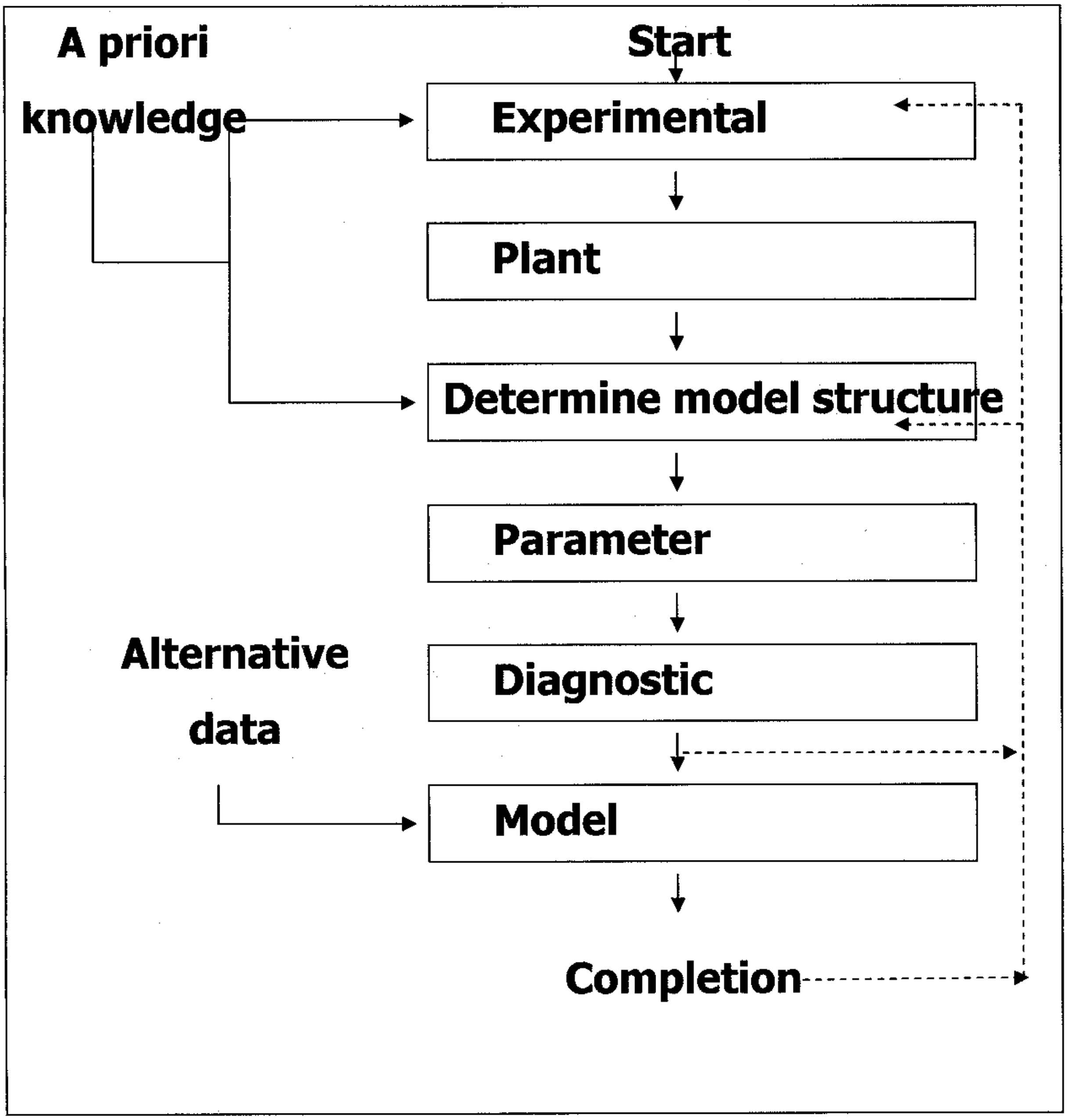

Figure 6: Procedure for empirical transfer function model identification.

Empirical modeling involves designed experiment, during which the process is perturbed to generate dynamic data. The success of the methods requires close adherence to principles of experimental design and model fitting. There are two identification methods namely the statistical method and also process reaction curve method.

Process reaction curve is the easiest one as compared to the statistical method and the most widely used for identifying dynamic models.

The process reaction curve method involves the following four actions:

1. Allow the process to reach steady state.
2. Introduce a single step change in the input variable.
3. Collect the input and output response data until the process again reaches steady state.
4. Perform the graphical process reaction curve calculations.

The model is based on a first-order-with dead-time model. The model is shown in Equation 18.

$$\frac{Y(s)}{X(s)} = \frac{K_c e^{-\theta s}}{\tau s + 1} \tag{18}$$

There are slightly two different graphical approaches to determine the process parameters. The first technique is adapted from Ziegler Nichols [5]. This method derives the process parameters by using graphical calculations as shown in Figure 7.

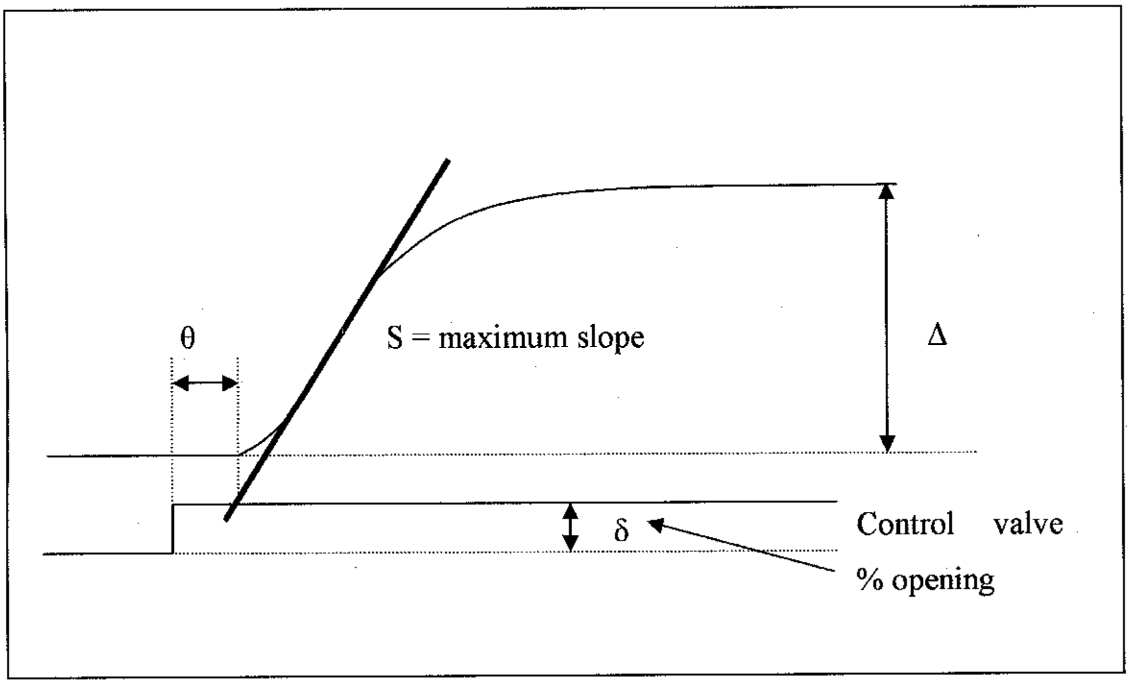

Figure 7: Process reaction curve for Method I.

The process parameters are determined from the equations:

$$K_c = \frac{\Delta}{\delta} \quad (19)$$

$$\tau = \frac{\Delta}{S} \quad (20)$$

θ = interception of maximum slope with initial value (as shown in Figure 7)

Method II uses the graphical calculations as shown in Figure 8.

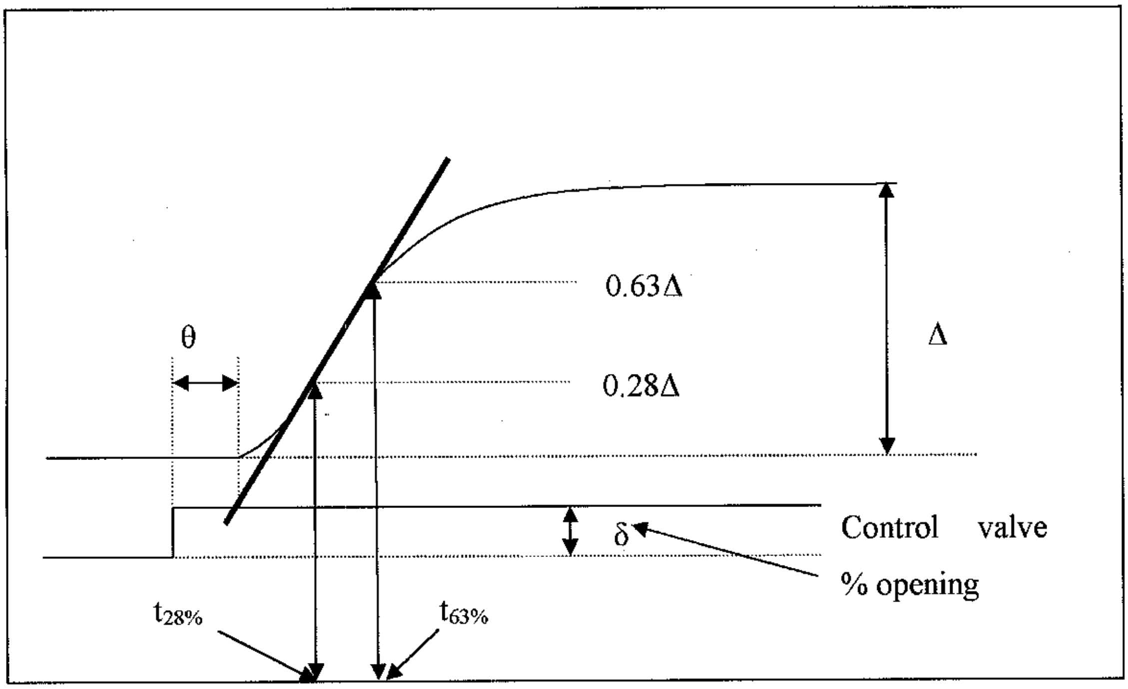

Figure 8: Process reaction curve for Method II.

The process parameters are determined from the equations:

K_c is similar as in Equation 19

$$\tau = 1.5(t_{63\%} - t_{28\%}) \quad (21)$$

$$\theta = t_{t63\%} - \tau \quad (22)$$

Because of the difficulty to evaluate the slop, especially when the signal has high frequency noise, Method I [6] typically has larger errors in parameter estimates; thus, Method II is preferred.

2.4 PID controller

There are three basic controller modes in PID controller:

2.4.1 Proportional (P)

The proportional controller receives voltage at a certain reading as its input, which comes from the comparator and represents the control difference. The controller reacts to the input by trying to make this control difference equal to zero as quickly as possible. This in turn results in the output of the controller to respond proportionally to the input variable. However, a settling signal can only appear at its output if an input voltage is also applied; it therefore requires a control difference at the input in order to be able to generate the manipulated variable at all output. Thus, the P controller cannot be used anywhere because the system that intends to implement it needs a settling signal at their input in order to maintain the controlled variable. However, it still can be used in a control circuit system with high amplification.

2.4.2 Integral (Reset)

The integral controller mode acts on the magnitude and duration of the error. In this case, the controller's output is modified by the amount of error (number of times the proportional gain is reached) in the period specified by the constant time Integral (Ti) tuning parameter. By using integral control, the target is to obtain zero steady state error. Basic rule of thumb for using integral is too much integral effects would give unstable system or at least too many overshoots. The integral amount is total up with each pass through the calculation and becomes the controller bias (automatic reset). Some controllers state this parameter as repeats per minute while others use the reciprocal, minutes per repeat (T_i).

2.4.3 Derivative (Rate)

The derivative element in the controller acts upon the rate of change of error. If there exists the rate of change of error in the input of the controller, the controller will respond by adjusting its manipulated variable to counter the rate of change, thus hopefully able to correct the process variable before it strays very far from the set point. In simple explanation, derivative control is required to reduce the time taken for the process to reach steady state. The Time Derivative (T_d) tuning parameter determines the amount of derivative action.

If the derivative is based on the rate of change of error, the risk of having a rate of change of error will exist each time an operator makes a set point change. This results in a kick of the controller output, which will likely upset the process each time the set point is changes. Modern controllers calculate the derivative term based on the rate change of the process variable measurement.

The controller that used in observing the characteristic of a control system in practice is set at the conditions where the modes are used in combination with each other with the exception of the P mode that is used at every measurement. The proportional mode was used by its own or with the combination of the other modes. The following parts of this section describe the criteria and characteristic of each mode in study the exception of the P mode that has been elaborated on its own previously.

2.5 PID controller variation

2.5.1 Proportional Integral (PI)

The response of PI controller has about the same overshoot as proportional control however the period is larger. In spite of this, the response returns to the set point after certain period. The good thing about this controller is that it eliminates offsets.

2.5.2 Proportional Integral Derivative (PID)

PID controller gives better output compared to P, PI controller since the response of this controller mode has a lower overshoot and returns to the set point more quickly than response of the other types of controllers.

2.6 The characteristics of P, I and D controllers

Briefly, for a simple low-order system that can tolerate some offset, P control is satisfactory. However, the PI controller greatly recommended when we are facing with the application of a process that cannot tolerate offset. On the other hand, if the control is higher-order, the PID controller is needed to prevent large overshoot and long settling time.

In most modern control application, PI controller is often the choice because it eliminate offset and requires only two parameter adjustments. Even though the PID controller offers the combination of benefits that the other controller cannot produce on their own, tuning a PID controller is more difficult because of the three parameters involved that must be adjusted thus making the tuning procedure to be complicated. In addition to that, the presence of derivative action also could cause the controller output to be very edge if there is too much disturbance in the input signals.

Table 1: Effect of PID controller gain.

Controller	Rise time	Overshoot	Settling time
P	Decrease	Increase	Small change
I	Decrease	Increase	Increase
D	Small change	Decrease	Decrease

Table 1 shows the effects of each controller gains on a closed loop system. These correspondences might not be exactly accurate, because P, I and D controller gains are mutually related to each other. By changing one of the variables, it will affect the other two. For theoretical basis, the table should be used only as a reference when determining the gain values for P, I and D.

2.7 PID tuning

PID tuning is matter of selecting the right combination of P, I and D action to achieve the desired closed loop performance. This is done by adjusting the tuning constants, K_c, T_i and T_d. There are several methods for determining the optimum value of these gains. The methods are:

i. Trial and error

   The value of K_c, T_i and T_d are set by plugging in any appropriate values. Then, by making one or more tuning value to be constant, the other tuning value is either increased or decreased until the controller setting eliminates the consecutive error.

ii. Ziegler- Nichols [5]

   This method is very convenient when mathematical model of the plant is not known as well as the systems with known mathematical model. There are two main tuning methods recognized by Ziegler and Nichols, namely:

   - Open loop process reaction curve
   - Closed loop

2.7.1 Open loop

Open loop process reaction curve also known as Cohen & Coon method. This method derives all the tuning parameters from process reaction curve from a step input. The Cohen & Coon tuning rule assumes that S-shaped process reaction curve can be approximated by a process model consisting of a first order lag and a dead time as shown in Equation 18 and Figure 7.

Table 2: Cohen & Coon tuning parameters calculation.

Control Mode	Calculation (R=θ/τ)
P only	$K_p = \left[\frac{1}{R.K_c}\right]\left[1+\frac{R}{3}\right]$
P+I	$K_p = \left[\frac{1}{RK_c}\right]\left[\frac{9}{10}+\frac{R}{12}\right]$ $T_I = T_d \frac{(30+3R)}{(9+20R)}$
P+D	$K_p = \left[\frac{1}{RK_c}\right]\left[\frac{5}{4}+\frac{R}{6}\right]$ $T_D = T_d \frac{(6-2R)}{(22+3R)}$
P+I+D	$K_p = \left[\frac{1}{RK_c}\right]\left[\frac{4}{3}+\frac{R}{4}\right]$ $T_I = T_d \frac{(32+6R)}{(13+8R)}$ $T_D = T_d \frac{4}{(11+2R)}$

Table 2 gives all the formula to calculate the tuning parameters for each type of controller.

2.7.2 Closed loop

Unlike the open loop method which evaluates the system on a step response, closed loop method is evaluated based on the system at its limit of stability. The following procedures show how to apply this method:

1. Start any trending of PV.
2. Set the K_p and T_d to their minimum values and T_i time constant to its maximum value. Then place the controller in the Automatic state.
3. Increase the proportional gain in small steps. After each adjustment, observe the PV response to a SP change. When sustained oscillations are observed, note the value of the proportional gain and the period (in minutes) of the oscillations:

   G_u = proportional gain for sustained oscillations.

   P_u = period of oscillations (in minutes).
4. Calculate the controller settings as shown in Table X.
5. Make any final adjustment in K_p, T_i and T_d to obtain the desired PV response.

Table 3: Closed loop tuning parameters calculation.

Controller	K_p	T_i	T_d
P	0.5 G_u		
PI	0.45 G_u	P_u /2	
PID	0.6 G_u	0.5 P_u	0.125 P_u

Figure 9 shows the PID controller built in MATLAB SIMULINK.

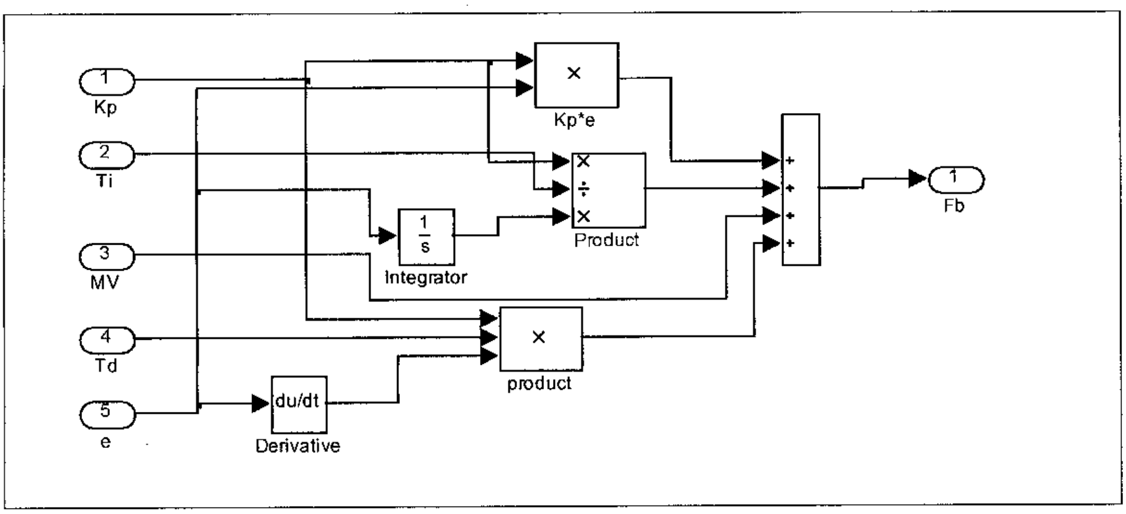

Figure 9: PID block built in MATLAB SIMULINK.

2.8 Fuzzy logic

Fuzzy logic was first introduced by Dr. Lotfi Zadeh [7] in his seminar paper in 1965. He proposed a methodology to deal with impression, which he called fuzzy sets. Fuzzy sets overcome the problems of crisp sets, where instead of only "true" and "false" or "yes" and "no," a membership of degree from "0" to "1" can be assigned to a set. The application of fuzzy logic to control systems, which are very popular currently, was first introduced by E.H. Mamdani [8] and his students in 1972. In fuzzy logic control applications, linguistic rules can be developed where, based on current conditions of the process, the next control actions can be formulated.

2.8.1 Set definition

Set can be defined as a collection of objects distinct and perfectly specified [9]. A part of set is a subset. For example, let's have a finite referential set:

E= {a,b,c,d,e}

We can form a crisp subset of E, for example:

A={b,d,e}

Or in other form:

A =

a	b	C	d	e
0	1	0	1	1

In above case, the element b belong to A, hence its degree of membership is 1. However, the element a does not belong to A, so its membership is 0. This property called a degree of membership. We can form a function, which represent this property.

$\mu_A(x) = 1$ if $x \in A$

0 if $x \in A$

This is a basic classical set theory. However fuzzy set is an extension of crisp set. Dr. Lotfi Zadeh [7] gave the following definition of fuzzy set:

A fuzzy set is a class of object with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function, which is assigned to each object a great membership ranging between zero and one.

Zimmerman [10] defined fuzzy set as a set that denoted by an ordered set of pairs, the first element of which denotes the element (x) and the second ($\mu_A(x)$) the *degree of membership*:

$A = \{(x, \mu_A(x) \mid x \in X\}$

Where $\mu_A(x)$ takes the values ranging from [0,1].

A= {(a, 0.4), (b, 0.2), (c,0), (d, 0.8) ,(e, 1)}

Fuzzy set can also be represented by linguistic variable, as follow:

H (height) = (very short, short, nice, tall, very tall)

2.8.2 Concept of fuzzy logic

A process control algorithm that based on Fuzzy logic is called Fuzzy Control. It is essentially embeds the intuition and experience of the operator. Generally, fuzzy control is similar to the expert system based on control. It is described by a set of IF... THEN... rules (called implication). The rule is described in Figure 10.

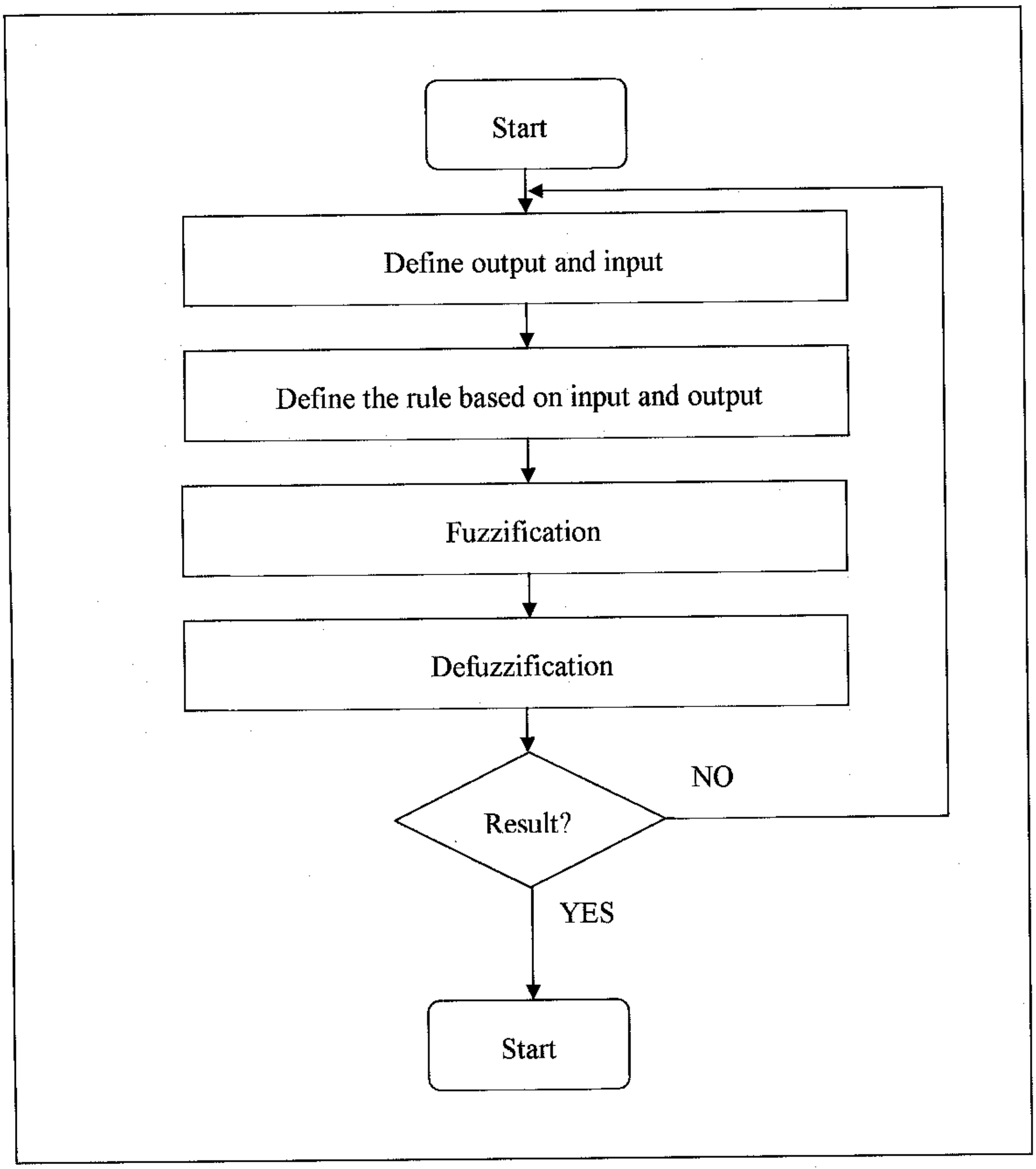

Figure 10: Flowchart of fuzzy logic.

Fuzzy Logic Controller (FLC) would normally take the reading of error (E) and the rate of change of error (ΔE/ dt) as the inputs and change in process variable (ΔPV) signal as the output. The controller then transforms the crisp values of (E) and (ΔE/ dt) into corresponding fuzzy values (usually there are several fuzzy values of E and (ΔE/ dt). From the knowledge of the controller, the fuzzy values of (E) and (ΔE/ dt) determine which particular rule or rules are to be fired through an inferencing algorithm. Several values of (ΔE/ dt). Several values of (ΔE/ dt) will then be obtained and a defuzzification mechanism will then transform these into one crisp value. The actual control signal obtained by adding (ΔE/ dt) to the past value of u, which is send to the plant.

2.8.3 Fuzzy Logic Controller (FLC)

Fuzzy control provides a formal methodology for representing, manipulating and implementing a human's heuristic knowledge about how to control a system [11]. Figure 11 shows the basic block diagram of FLC implementation.

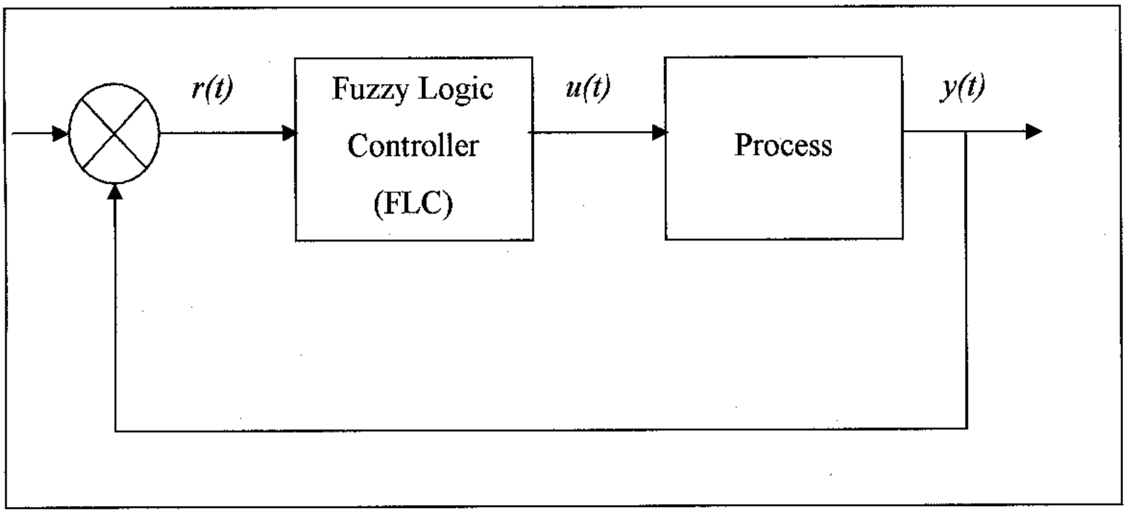

Figure 11: Block diagram of FLC implementation.

There are four main components of FLC [9]:

1. **Rule- Base.** (Set of IF-THEN rules), which contains a fuzzy logic quantification of the experts' linguistic description of how to achieve good control.
2. **Inference mechanism.** (also known as "inference engine"/ "fuzzy inference" system), which emulate the expert's decision making in interpreting and applying knowledge about how best to control the plant.
3. **Fuzzification interface.** Converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.
4. **Defuzzification interface.** Converts the conclusions of the inference mechanism into actual inputs for the process.

Figure 12 shows how the FLC architecture.

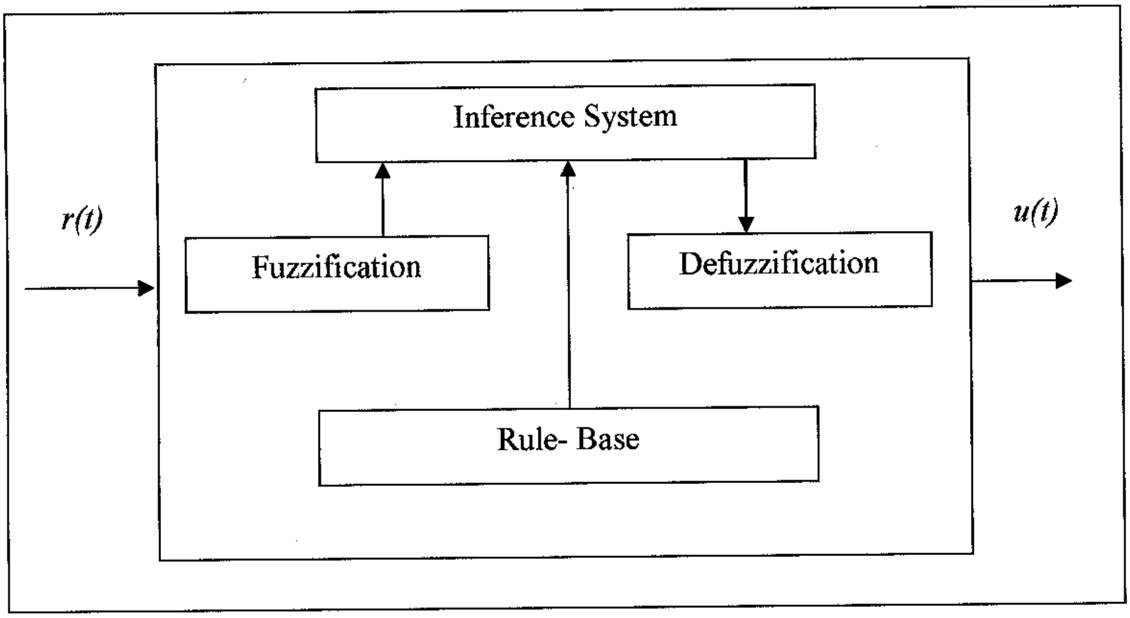

Figure 12: FLC architecture.

Example given by Rahmat, Norhisham [12] could give a better understanding on the FLC architecture.

Table 4: Basic Rule Base.

E&ΔE = U	VLE	LE	ZE	HE	VHE
VLE	VLE	VLE	VLE	LE	ZE
LE	VLE	VLE	LE	ZE	HE
ZE	VLE	LE	ZE	HE	VHE
HE	LE	ZE	HE	VHE	VHE
VHE	ZE	HE	VHE	VHE	VHE

VLE = Very low error LE = Low error ZE = Zero error HE = High error

VHE= Very high error

Based on Table 4, let's E and ΔE be the input labels. FLC output signal is U. Then the rule is as follows (example):

"*IF* **E** is **LE** AND **ΔE** is **LE** *THEN* **U** is **VLE**"

First step is to take E and ΔE and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. The inputs are always a crisp numerical values limited to the range of the input. Figure 13 shows the membership functions of the system.

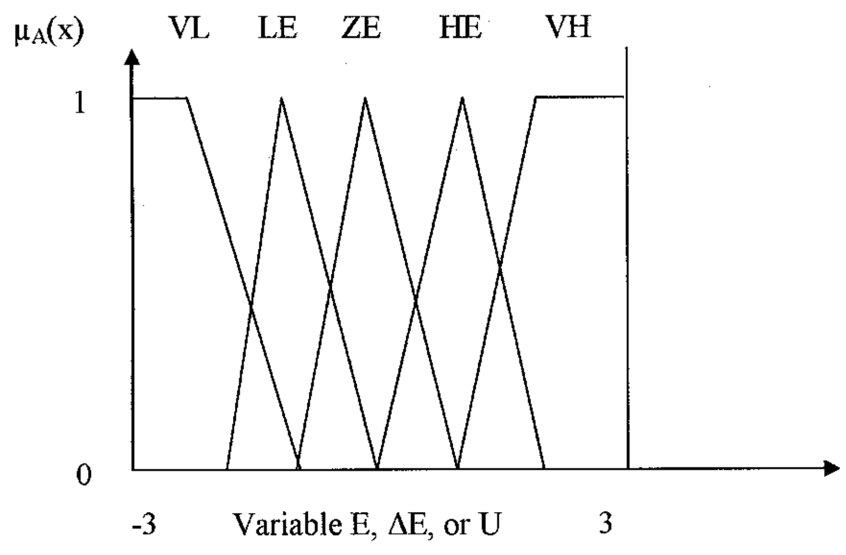

Figure 13: Membership functions.

Once the inputs have been fuzzified, the degree to which each part of the antecedent has been satisfied for each rule is known. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number will then be applied to the output function. Fuzzy operator is applied to the membership functions for "AND" or "OR" operators. For AND there are two built-in logical operators; MIN (minimum) and prod (product). Two built-in OR are max (maximum) and probor (probabilistic OR).

AND:

min(a,b) = {minimum of a and b}

prod (a,b) = a*b

OR:

max(a,b) = { maximum of a and b}

probor(a,b) = a+b - a*b

Example:

Let have next input values: $E = 0.2$ and $\Delta E = 1.4$ and the result for the membership function is as shown in Table 5.

Table 5: Degree of membership.

x=E	Degree of membership	x=ΔE	Degree of membership
$\mu_{VLE}(x)$	0	$\mu_{VLE}(x)$	0
$\mu_{LE}(x)$	0	$\mu_{LE}(x)$	0
$\mu_{ZE}(x)$	0.8	$\mu_{ZE}(x)$	0
$\mu_{HE}(x)$	0.2	$\mu_{HE}(x)$	0.6
$\mu_{VHE}(x)$	0	$\mu_{VHE}(x)$	0.4

$\mu_U(x) = \min \{\mu_{Ei}(x) \text{ AND } \mu_{\Delta Ei}(x)\}$

$5 \leq i \leq 1$

Based on Figure 13 and also the calculation of the membership function degree of membership, Table 6 is obtained.

Table 6: Table of Rule Base according to membership function.

E AND ΔE = U	VLE	LE	ZE	HE	VHE
VLE	0	0	0	0	0
LE	0	0	0	0	0
ZE	0	0	0	0.6	0.4
HE	0	0	0	0.2	0.2
VHE	0	0	0	0	0

The values are tabulated as in Figure 14.

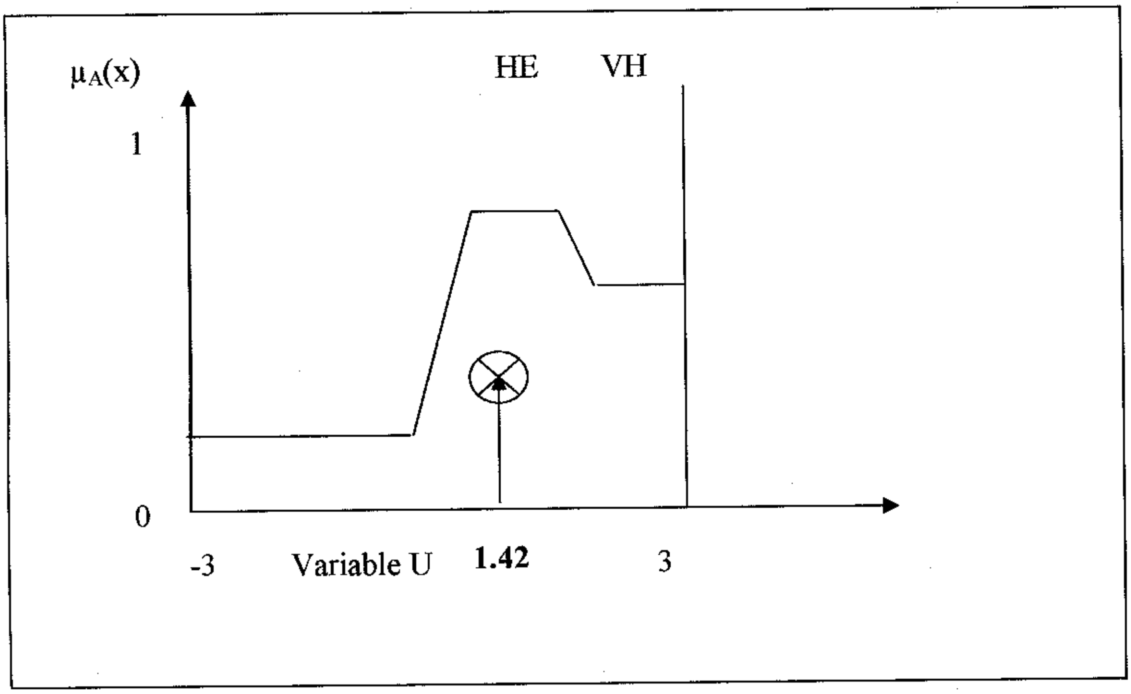

Figure 14: Result of aggregation.

The last step is to defuzzification. The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. As much as fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variable is generally a single number. However, the aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set. Perhaps the most popular defuzzification method is the centroid calculation, which returns the center of area under the curve. There are five built-in methods supported: centroid, bisector, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum. For this example, by using the centroid method, the output is 1.42.

2.9 Fuzzy Inference System (FIS)

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves all of the pieces that are described in the previous sections: membership functions, fuzzy logic operators, and if-then rules. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined.

2.9.1 Mamdani FIS

Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. Mamdani's method was among the first control systems built using fuzzy set theory. It was proposed in 1975 by Ebrahim Mamdani [11] as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators. Mamdani's effort was based on Lotfi Zadeh's 1973 paper on fuzzy algorithms for complex systems and decision processes [7].

Mamdani-type inference, as we have defined it for the Fuzzy Logic Toolbox, expects the output membership functions to be fuzzy sets (Figure 15). It does not have any specific equation. The development of Mamdani FIS is application specific.

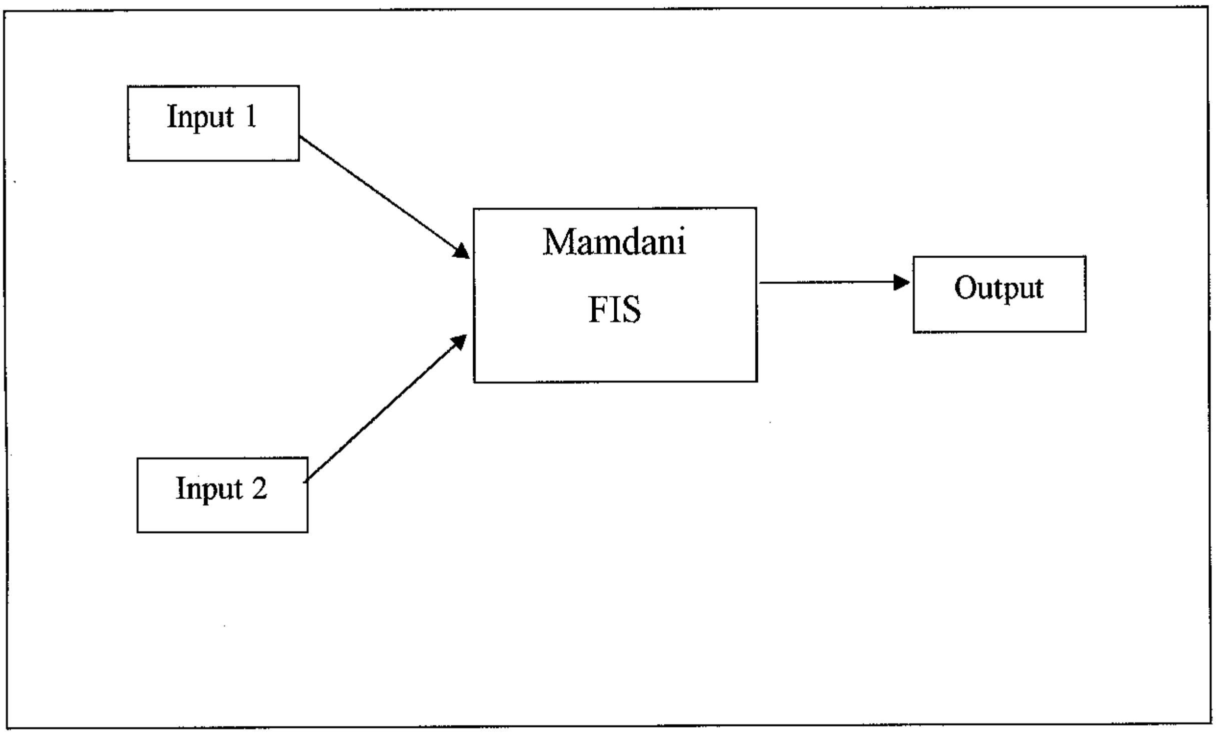

Figure 15: Mamdani FIS.

After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It's possible, and in many cases much more efficient, to use a single spike as the output membership functions rather than a distributed fuzzy set. This is sometimes known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of a two-dimensional function.

2.9.2 Sugeno FIS

Sugeno FIS is developed by Michio Sugeno [13], this type of FIS structure differs from its its Mamdani counterpart by having constant or linear equations fro output variable (input method still the same). The linear equations depend on the actual input value for its computation:

Constant $y = k$ k= measured experimentally/ calculated

Linear $y = m_1x_1 + m_2x_2 + ... + m_nx_n + c$

Where, $m_1, m_2, ..., m_n$= gradient to the nth input,

$x_1, x_2, ..., x_n$ = input variable value to the nth input

c = y-intercept y = output variable

Basically both of the FIS brings several unique advantages over another:

Advantage of Sugeno method:

- It's computationally efficient.
- It works well with linear techniques (e.g. PID control).
- It works well with optimization and adaptive techniques.
- It has guaranteed continuity of the output surface.
- It's well-suited to mathematical analysis.
- The membership functions could be developed by using the Advanced Neuro Fuzzy Inference System (ANFIS) provided with MATLAB thus make the FIS development easier.

Advantages of Mamdani method:

- It's intuitive.
- It has widespread acceptance.
- It's well-suited to human input.

2.10 Gain scheduling

A majority of feedback control techniques, including the venerable PID algorithm, relies on the principle of linearity that guarantees a Y % change in the process variable following an X % change in the control effort. The ratio or gain between X and Y will be fixed, whether the process is currently running at maximum capacity, minimum capacity, or somewhere in between. A controller need only know the value of that gain and the speed at which the process moves to select its control efforts appropriately.

Unfortunately, not all processes are strictly linear. Even the classic linear system comprised of a weight hanging from a spring will respond less and less to forces applied to the mass as the spring is stretched (or compressed) to the limits of its travel.

On the other hand, even nonlinear processes can be approximated as linear if X and Y are small enough. Consider, for example, a chemical process where a base is added to a solution to increase its pH. As the Figure 16 shows, the process reacts much more dramatically to the addition of the base when the pH is already in range B. A controller attempting to raise the pH all the way from range A to range C would proceed much too aggressively through range B if it assumed that the entire process were governed by a single low gain. Conversely, it would be much too conservative in ranges A and C if it assumed that the high gain of range B prevailed throughout.

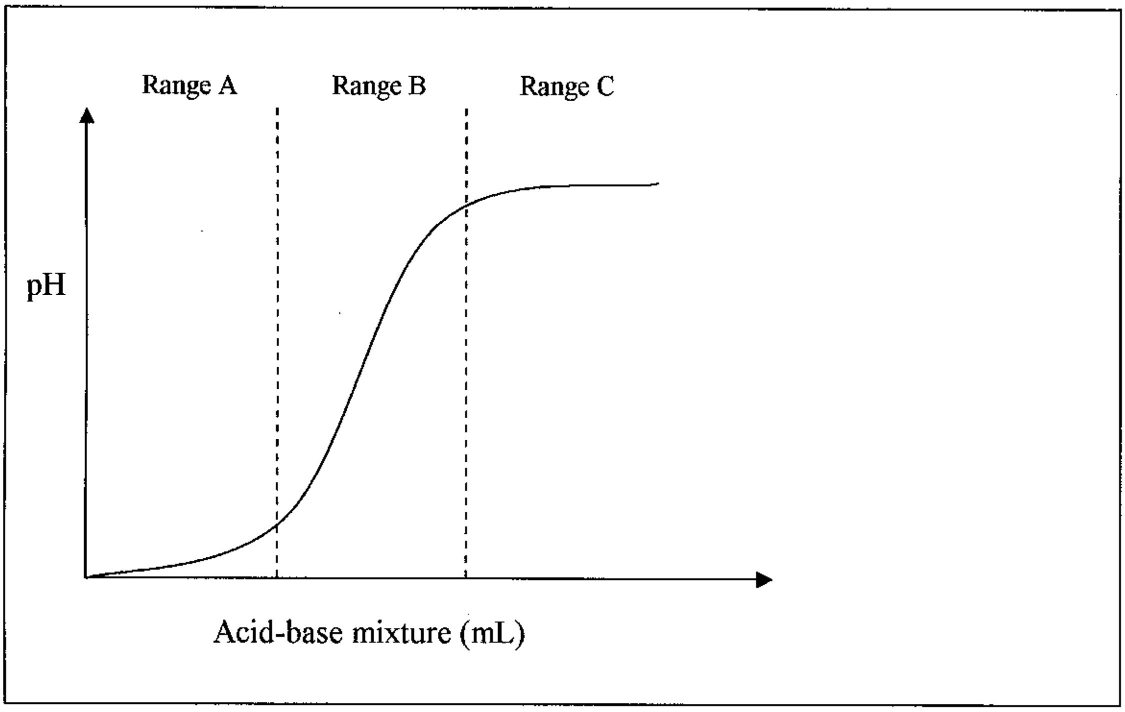

Figure 16: Different range with different gain value.

The classical solution to this problem is to operate the process entirely within one range or another (that is, keep X and Y low) or use a control algorithm that varies its gain as the process gain varies. If the variations in the process gain can be observed or inferred while the controller is in operation, it is fairly simple to update the controller's gain accordingly. This is often accomplished with a gain schedule- a look-up table that gives the controller gain appropriate for the current operating range as indicated by the value of the process variable.

In the pH control example, the gain schedule would have three entries corresponding to each of the three pH ranges. Each controller gain would be set according to a separate tuning test executed while the process operates in the corresponding pH range.

In the previous discussion, no problem was raised regarding the gain-scheduling. From Figure 16, it was showed that, there was no continuous transition from the ranges (e.g. fro range A to range B, etc).

To cater this problem, fuzzy logic system would be useful to ensure a smooth transition among the ranges.

For pH problem, Karr [14] has proposed the range for strong acid strong base (SASB) neutralization process. From the idea, the membership functions of the fuzzy controller could be developed easily.

CHAPTER 3

METHODOLOGY & PROJECT WORK

3.1 Mathematical model

Mathematical model is obtained by combining several block diagrams previously discussed in section 2.3. Figure 17 shows the block diagram for uncontrolled process while Figure 18 shows the whole mathematical model completes with the PID controller.

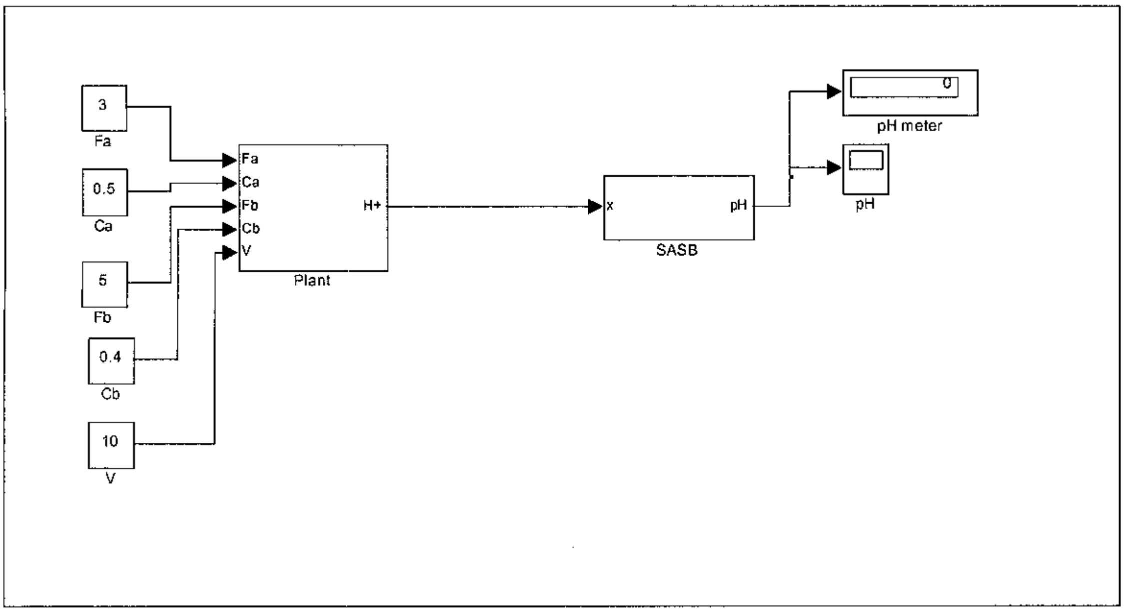

Figure 17: The SIMULINK block to simulate the uncontrolled pH neutralization process.

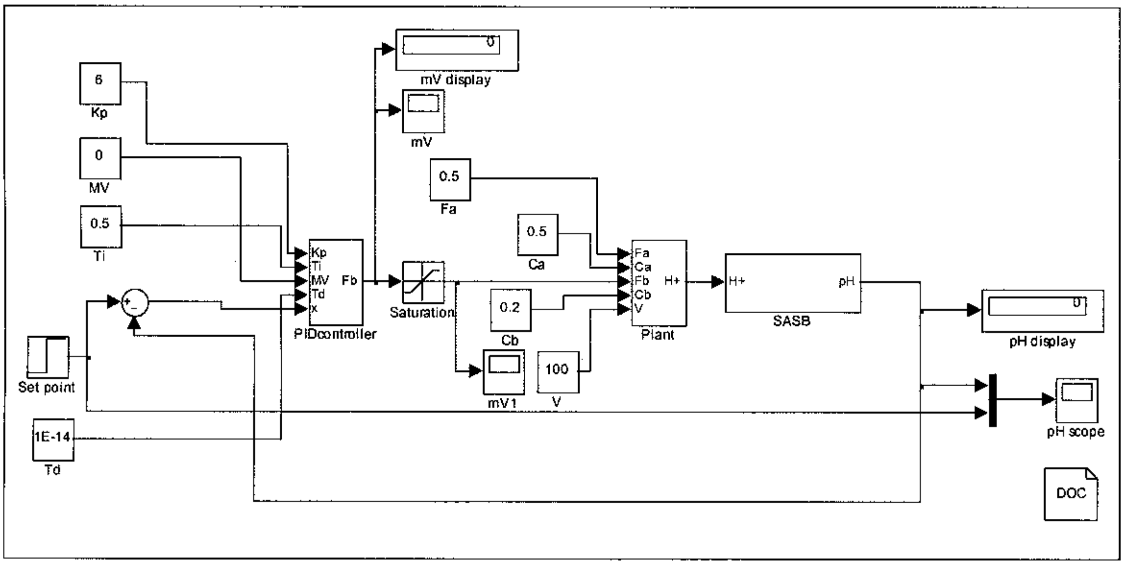

Figure 18: The SIMULINK block to simulate mathematical model with PID controller.

The Plant block in Figure 18 is the same block as shown in Figure 5 while the SASB block in the same as in Figure 2. The result from the simulation from Figure 18 is shown in Figure 19.

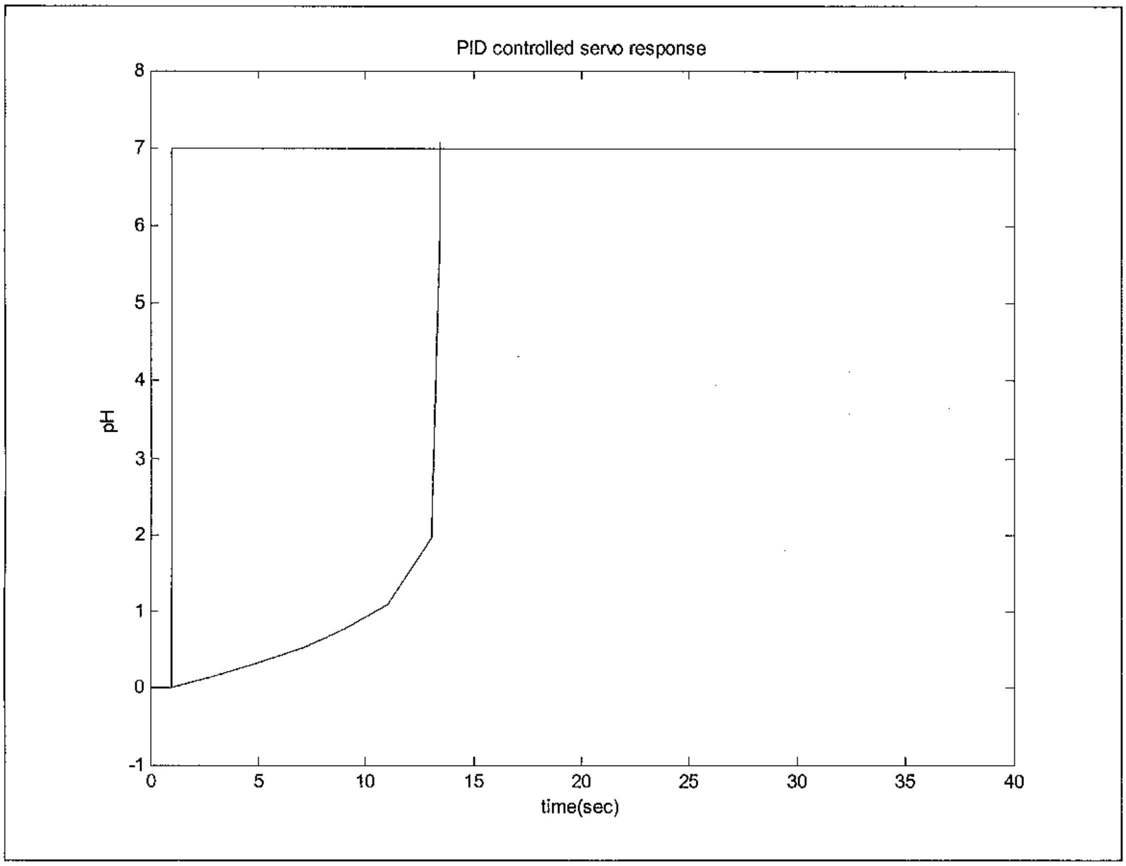

Figure 19: The simulation result based on P+I only controller with the mathematical model of pH neutralization process.

3.2 Empirical model

3.2.1 Empirical data

Empirical model is obtained by using Method I Ziegler Nichols as discussed previously in section 2.3.

From several lab experiments, several set of data are collected to determine all the required parameters to that it can be simulated in MATLAB SIMULINK. The data are obtained from the Process Control System Laboratory sessions. The procedure for the Lab is attached in Appendix I. The data is shown in Table 7. The PID tuning constant is obtained from the Cohen-Coon formula for open-loop tuning as shown in Table 2.

Table 7: Empirical data from lab experiment.

Measurement	SET 1	SET 2	SET 3
Process Reaction Curve, $G_p(s)$			
Change in Manipulated Variable, δ	0.1	0.1	0.2
Change in Control Variable, Δ	0.7	0.455	0.667
Apparent dead time, θ (sec)	0.15	1.3	0.649
Apparent time constant, τ (sec)	0.162	0.94	0.351
Process gain, K_c	7	4.55	3.33
$R=\theta/\tau$	1.08	1.38	1.85
Tuning Parameter, $G_c(s)$			
Proportional, K_p	0.15	0.16	0.795
Integral time, T_i (sec/repeat)	1.103	1.21	1.067
Derivative time, T_d (sec/repeat)	0	0	0

3.2.2 Simulation

Those set of data are then is simulated in the MATLAB SIMULINK as shown in Figure 20. The results are shown in Figure 21, 22 and 23.

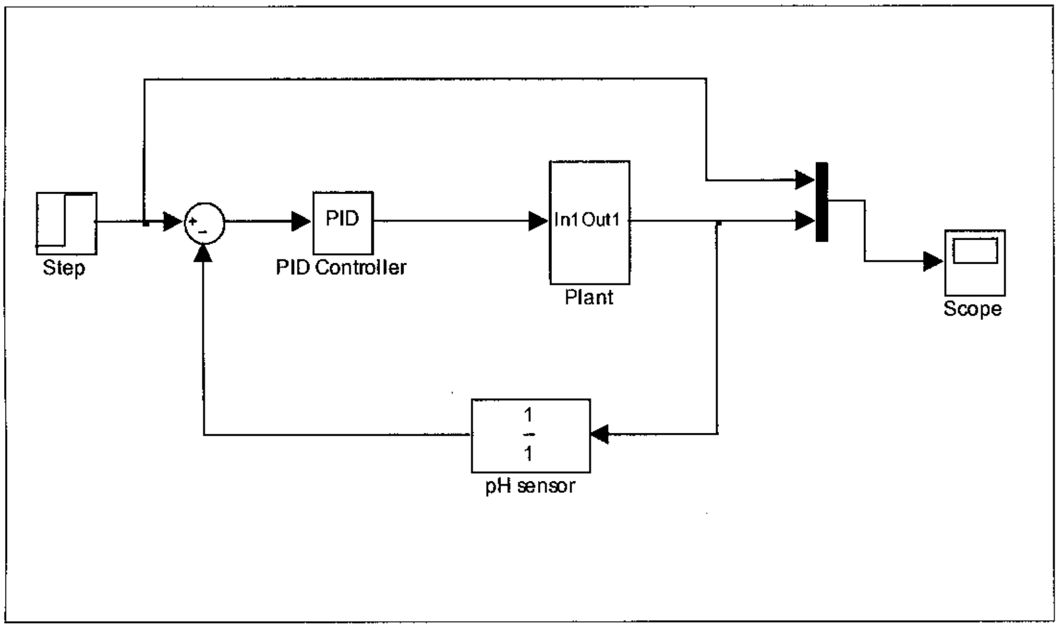

Figure 20: MATLAB simulation block diagram for empirical model.

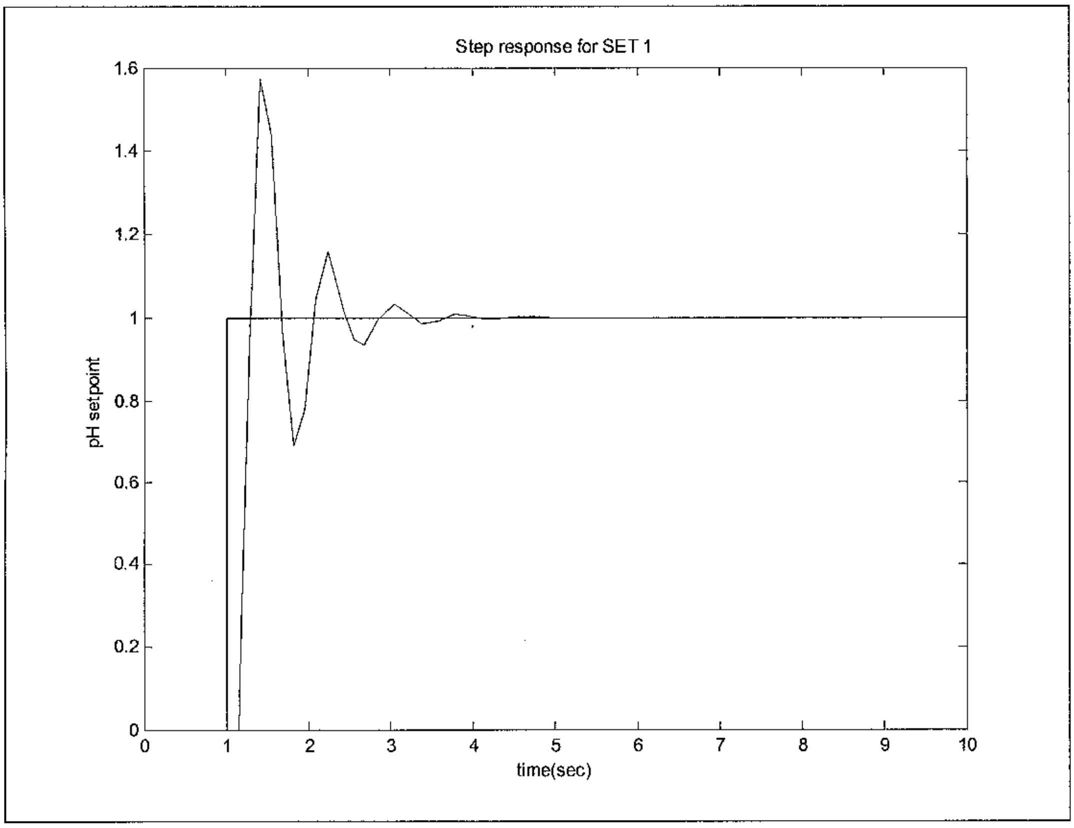

Figure 21: Simulation result from SET 1.

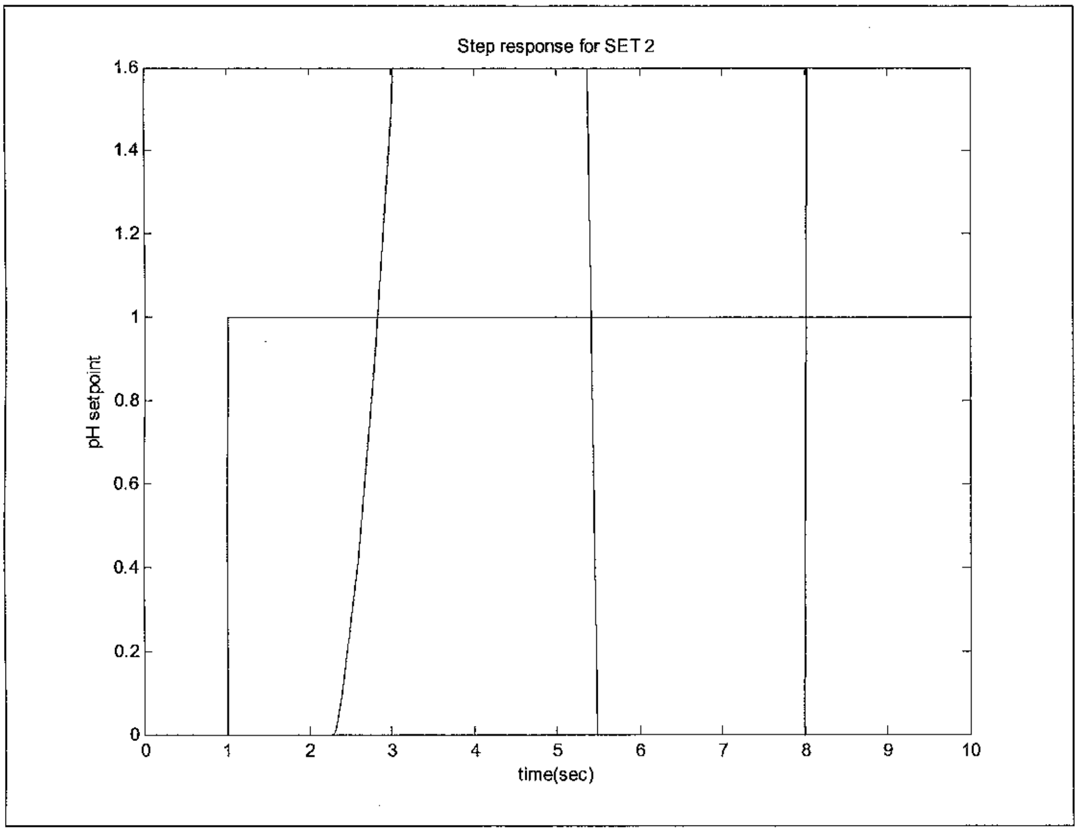

Figure 22: Simulation result from SET 2.

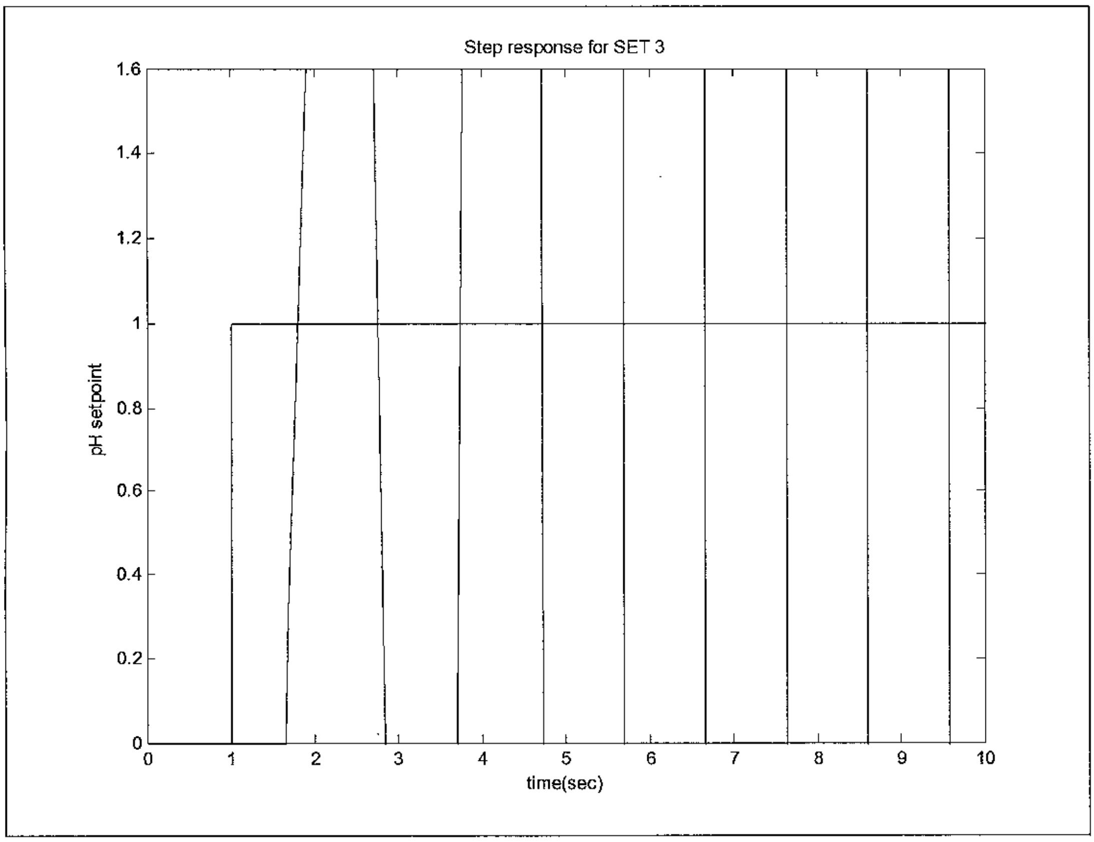

Figure 23: Simulation result from SET 3.

3.3 Gain table

From the PID controlled closed loop as shown in Figure 18, the gain table of the process was developed.

To develop the gain table, trial and error is the standard procedure for any fuzzy logic controller design. However there are several rules of thumb. For example, let's see Figure 24 which is the titration curve of neutralization process.

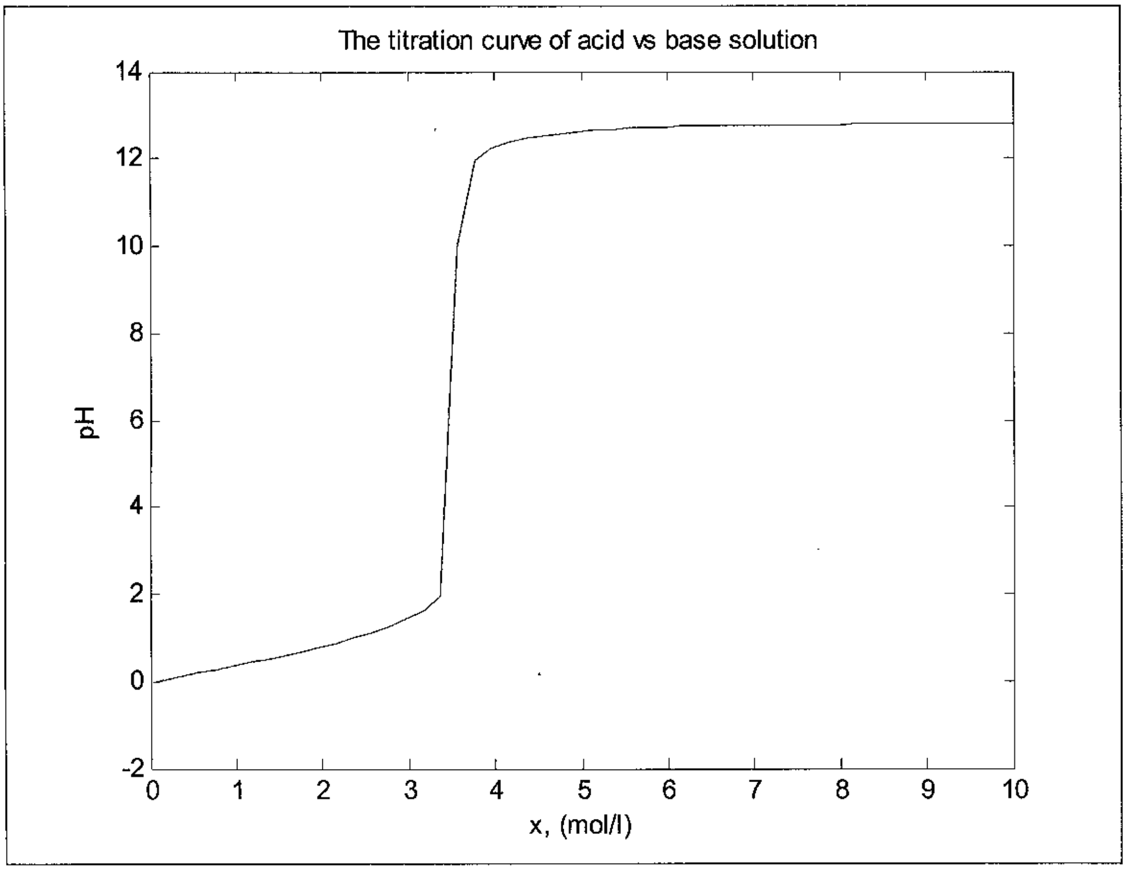

Figure 24: pH neutralization titration curve.

From the titration curve, we could see that the linearity exist for the pH ranging approximately from 5 to 9, hence we could conclude that for this range the gain should be a single constant value. Secondly based on [2], to control accurately under these conditions you need a switchable gain to vary dependent on the pH value you want to control to. The gain factor drops by a factor of 10 per pH unit of neutrality. Therefore a low gain is required near a pH value of 7 and high gain at a higher or lower pH value. Based on [14], there should be 7 membership functions required to control any neutralization process between strong acid and strong base.

The third rule is based on the method of open loop tuning for any PID controller. Basically, we start K_p with low value and T_i with high value (e.g. 9999). The aim of this step is to obtain the best value of K_p and T_i for specific value of pH set point.

Based on the established rules, for example for set point of pH 7:

$K_p = 10 \quad T_i = 1020$

After several trial and error procedures, the gain table is successfully developed. The table is shown in Table 8 tabulated in graphical form shown in Figure 25.

Table 8: The plot for K_p and T_i versus pH set point.

pH set point	Kp	Ti
1	76	0.5
2	72	990
3	52	1200
4	50	663
5	14	685
6	14	851
7	14	1020
8	14	1180
9	14	1350
10	52	4300
11	52	4300
12	72	4300

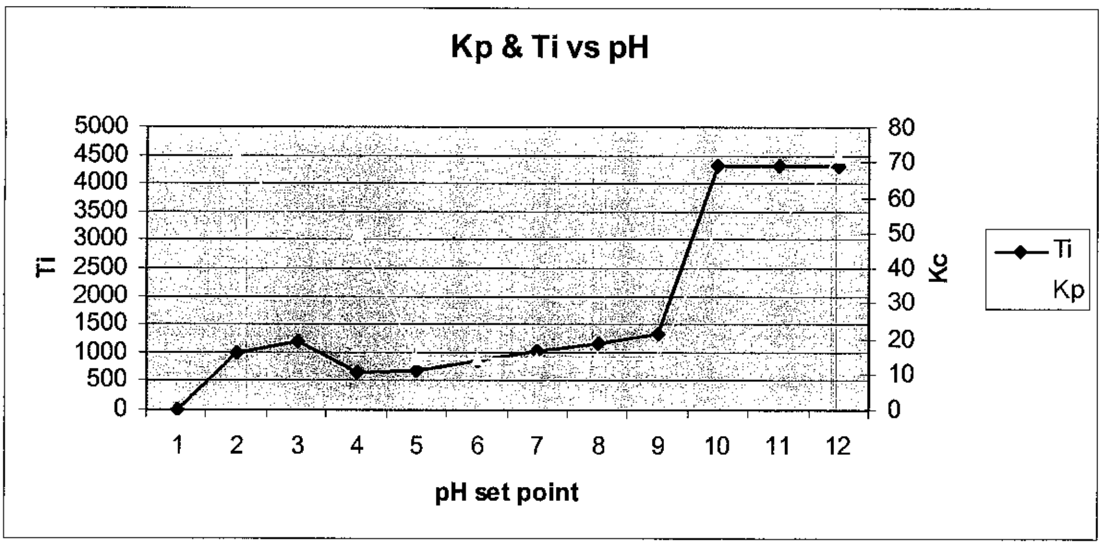

Figure 25: The plot for K_p and T_i versus pH set point.

3.4 ANFIS method

Besides the idea presented above, ANFIS was also used in order to design controller to replace the whole PID controller in the empirical and mathematical model. This method is based on the methodology proposed by Hazrin Hany [15] where only one fuzzy controller is used to replace the PID controller for the closed loop transfer function as shown. The idea behind this design is quite simple. The FLC will replace the PID controller after the FLC is well-trained to imitate the PID controlled response. Appendix II shows the ANFIS Graphical User Interface (GUI) used in the design works.

3.4.1 Empirical model

The FIS for the closed loop is constructed by using ANFIS GUI provided by MATLAB. Figure 26 shows how the data are collected from the existing model based on the successfully tuned closed-loop. The closed-loop was perfectly tuned for its K_c and T_i. From this successfully set-up, then the data are collected. The result from the PID controlled was shown in Figure 27.

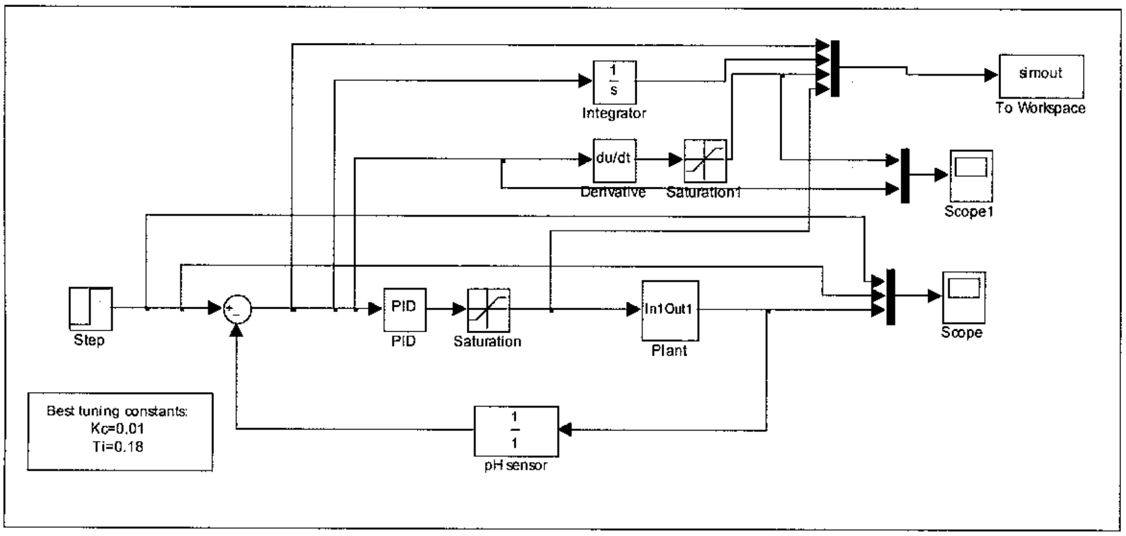

Figure 26: The setup to obtain the FIS for empirical model.

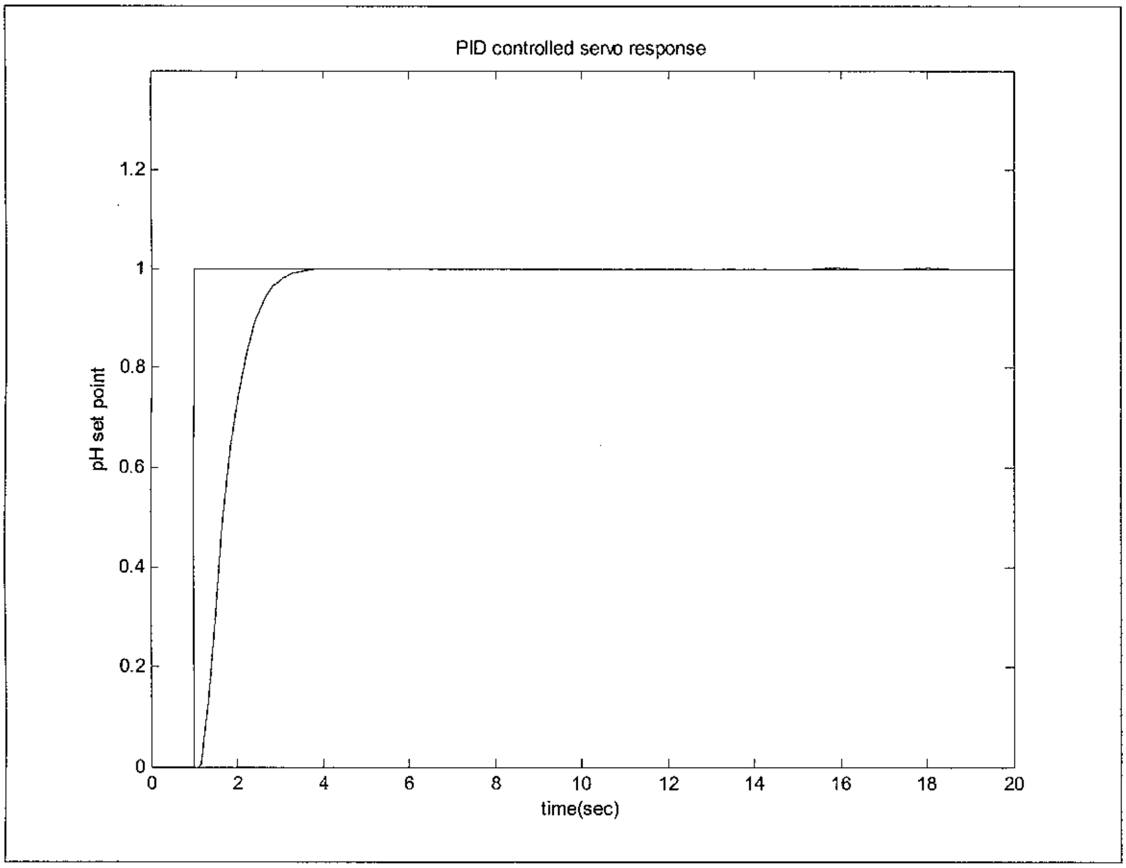

Figure 27: Result from PID controlled process.

The FIS obtained is saved as *'empirical.fis'* file to be used in the simulation later.

3.4.2 Mathematical model

The same method used for empirical model is used for mathematical model. Figure 27 shows the arrangement to collect the data to be used for training purposes in ANFIS GUI.

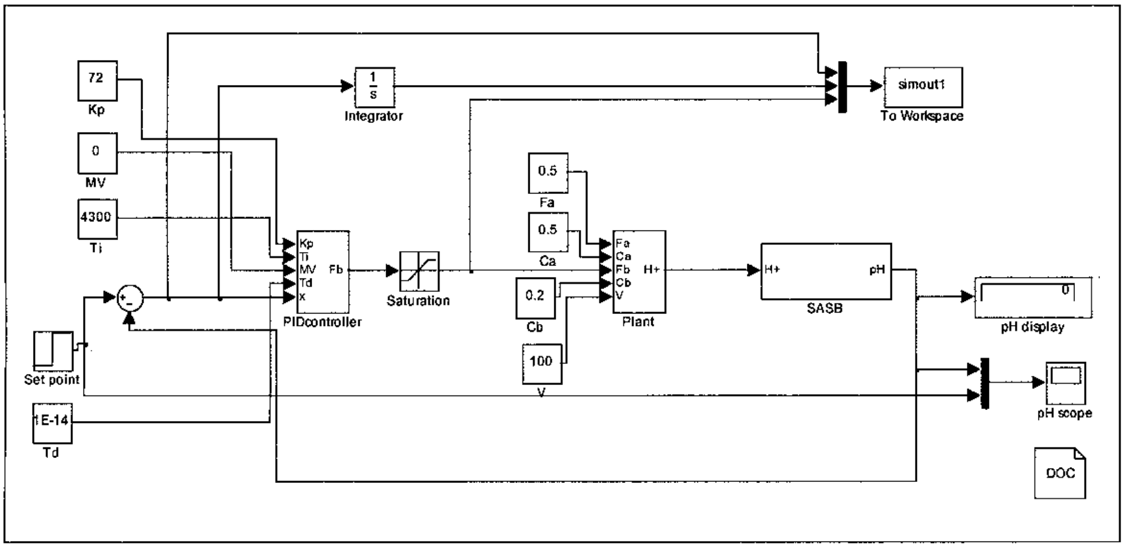

Figure 28: The setup to obtain the FIS for mathematical model.

The best setting for K_p and T_i for mathematical model is obtained from Table 8 for pH 10 to 12. The FIS obtained is saved as *'math.fis'* file to be used in the simulation later.

3.5 Gain-scheduling method

3.5.1 Fuzzy Inference System (FIS) for K_p

After obtaining the gain table as shown in Table 8 and Figure 25, the membership functions of the each controller parameter could be developed. Figure 29 shows how the controller would control the process.

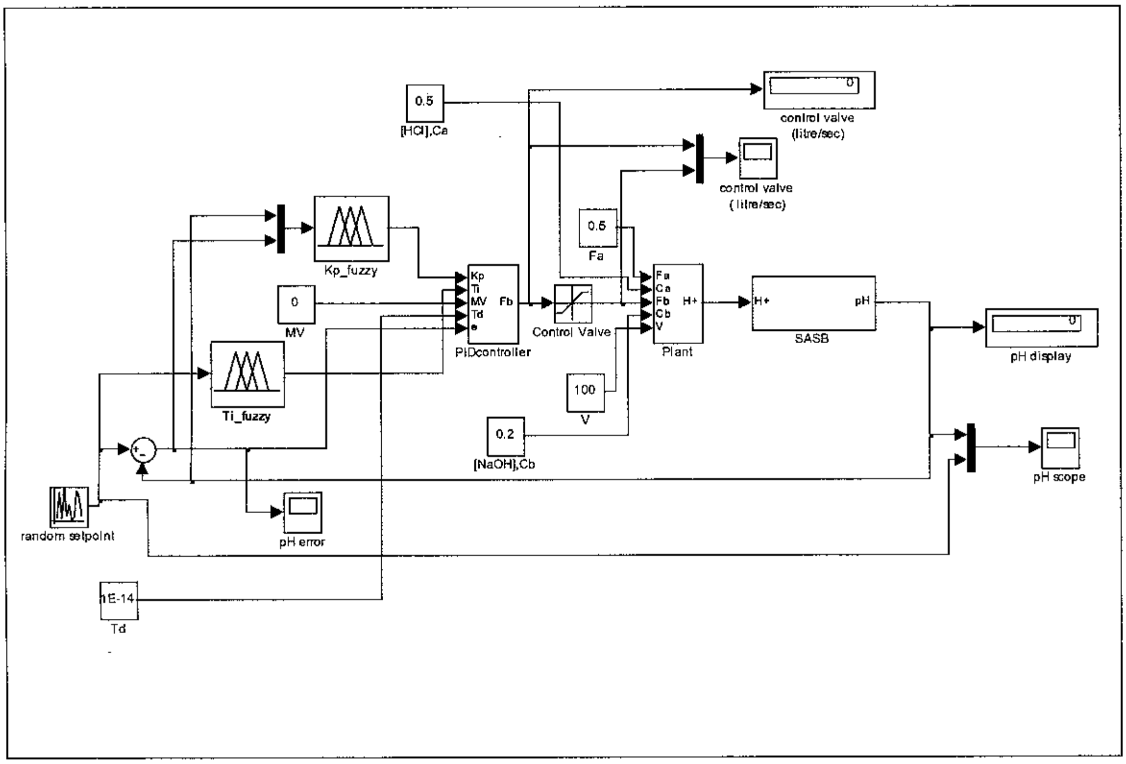

Figure 29: The process loop controlled by two fuzzy logic controllers.

For this development, the Fuzzy Logic Toolbox provided in MATLAB/SIMULINK is used. The Graphical User Interface of the toolbox could be accessed by typing *'fuzzy'* at the command prompt.

For K_p, the fuzzy rules as given by Karr [14] and also Nio Tiong Ghee; Kumaresan, S.; Liau Chung Fan [16] are applied. Based on their rules, the inputs required for K_c tuning are the error signal from the controller (E) and also the set point (SP). Figure 30 shows the logic of input/output relationship of the K_c controller and the rules are shown in Table 9.

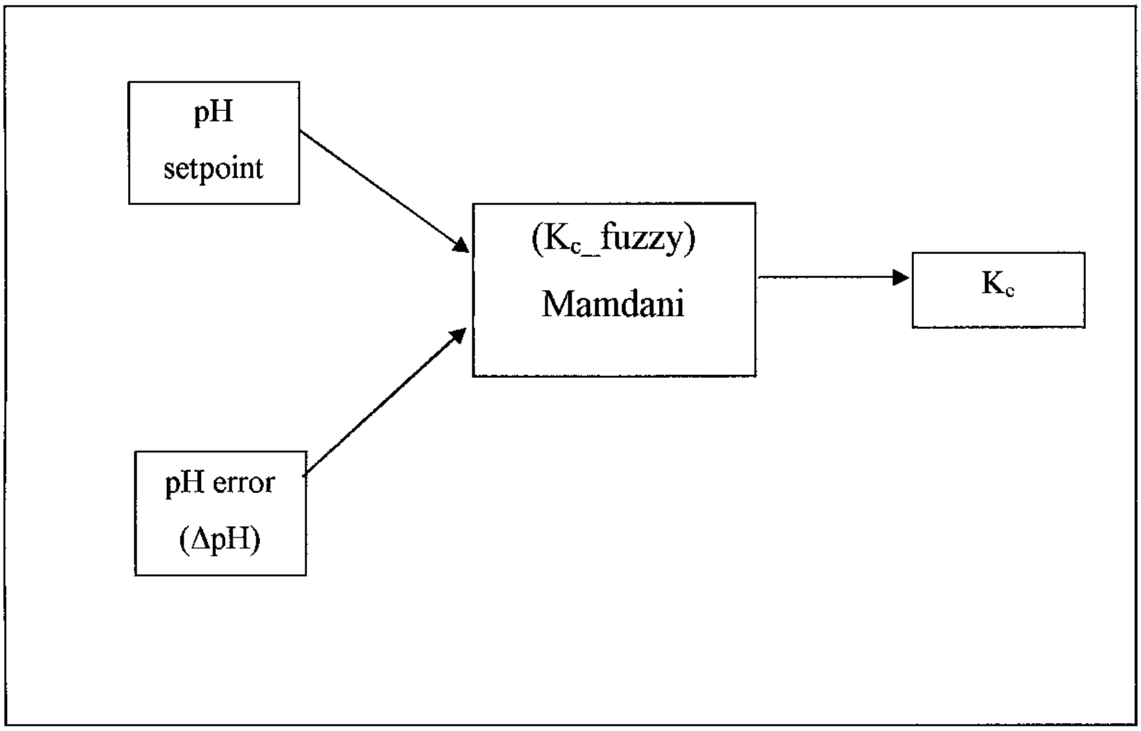

Figure 30: The input-output relationship for K_c controller.

Table 9: Fuzzy rules for K_p.

pH	ΔpH		
	Small (S)	Large (L)	Negative (NegL)
Very Acidic (VA)	Normal (N)	Very Large (VL)	Very Large (VL)
Acidic (A)	Not So Small (LES)	Not So Large (LEL)	Not So Large LEL)
Mildly Acidic (MA)	Very Small (VS)	Small (S)	Small (S)
Neutral (N)	Very Small (VS)	Very Small (VS)	Very Small (VS)
Mildly Basic (MB)	Very Small (VS)	Small (S)	Small (S)
Basic (B)	Not So Small (LES)	Not So Large (LEL)	Not So Large (LEL)
Very Basic (VB)	Normal (N)	Very Large (VL)	Very Large (VL)

From Table 9, each membership function is as shown in Table 10. However, it must be noted that, those range is subject to changes during the actual design of the controller later. For pH set point, the membership type is trapezoidal.

Table 10: Membership function pH ranges.

Membership function	pH range
Very Acidic (VA)	1 to 3
Acidic (A)	2.5 to 5
Mildly Acidic (MA)	4.5 to 7
Neutral (N)	6.5 to 8
Mildly Basic (MB)	7.5 to 10
Basic (B)	9.5 to 12
Very Basic (VB)	11.5 to 14

Membership function for ΔpH is shown in Table 11. The membership type is trapezoidal and triangle.

Table 11: Membership function ΔpH ranges.

Membership function	Error range (ΔpH)
Negative Large (NL)	-10 to 0
Small (S)	-1.5 to 1.5
Large (L)	0 to 10.

Last but not least is the membership functions for the output; K_p. Table 12 shows the rough arrangement. Since K_p, the membership type is Gaussian type; the range would be rearranged in the GUI to fit the input later. The range given below is only the average value for each membership function. For Gaussian type, the function must be specified as the average and also the standard deviation.

Table 12: Membership function K_p ranges.

Membership function	Gain K_p range
Very Small (VS)	4 to 18
Small (S)	25 to 35
Not So Small (LES)	50 to 60
Normal (N)	70 to 80
Not So Large (LEL)	100 to 105
Very Large (VL)	127 to 134

Table 13: FIS properties for K_p.

Properties	Method
And	Min
Or	Max
Implication	Min
Aggregation	Max
Defuzzification	Som

Based on the information provided above, the FIS is developed. The FIS must then be tested on the controller by trial and error basis. Appendix III shows all the fuzzy GUI interfaces related to K_p fuzzy rules.

3.5.2 Fuzzy Inference System (FIS) for T_i

For Ti, the information provided by Nio T. G., Sivakumar K., Liau C. F. [14] is used. For T_i, the Sugeno type is used instead of Mamdani. The relationship between the input and output is either constant or linear. The relationship is developed directly from the gain table for T_i as shown in Table 1. For Ti, the input is the pH set point while the output is the integral time, T_i as shown in Figure 31.

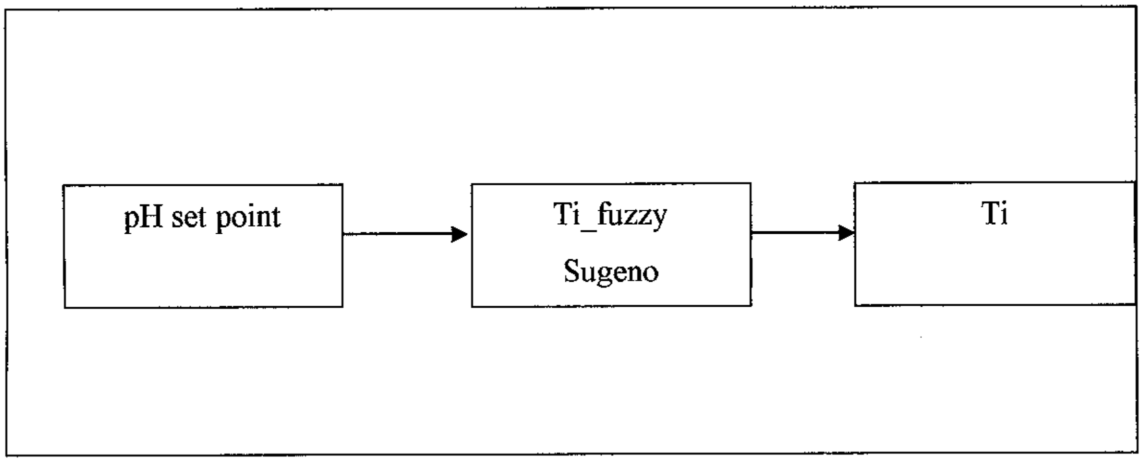

Figure 31: Sugeno FIS for T_i controller.

From Table 8, the linear relationships could be summarized into 7 different equations. The input-output relationships are summarized in Table 14 and 15. X represents the input while y represents the output. Appendix IV shows all the fuzzy GUI interfaces related to T_i fuzzy rules.

Table 14: Input region for T_i membership functions.

Membership function	Relationship
Super Acidic (SA)	[1 2 2.5 2.55]
Very Acidic (VA)	[2.55 2.6 2.9 2.95]
Quite Acidic (QA)	[2.95 3 4 4.05]
Acidic (A)	[4.05 4.1 4.4 4.45]
Mildly Acidic to Basic (MA2B)	[4.45 4.5 9.0 9.05]
Quite Basic (QB)	[9.05 9.1 9.9 9.95]
Very Basic (VB)	[9.95 10 12 12.05]

Table 15: Output function for T_i membership functions.

Membership function	Relationship
Super Acidic (SA)	$y = 760x - 530$
Very Acidic (VA)	$y = 1200$
Quite Acidic (QA)	$y = 555x - 465$
Acidic (A)	$y = -1733x - 8700$
Mildly Acidic to Basic (MA2B)	$y = 167x - 149$
Quite Basic (QB)	$y = 3350x - 28660$
Very Basic (VB)	$y = 4300$

CHAPTER 4

RESULT & DISCUSSION

4.1 ANFIS method

To test the 'empirical.fis' and 'math.fis' obtained from section 3.4, the arrangement as shown in Figure 32 (empirical) and Figure 34 (mathematical) are used. The results of both simulations are shown in Figure 33 (empirical) and Figurer 35 (mathematical) respectively.

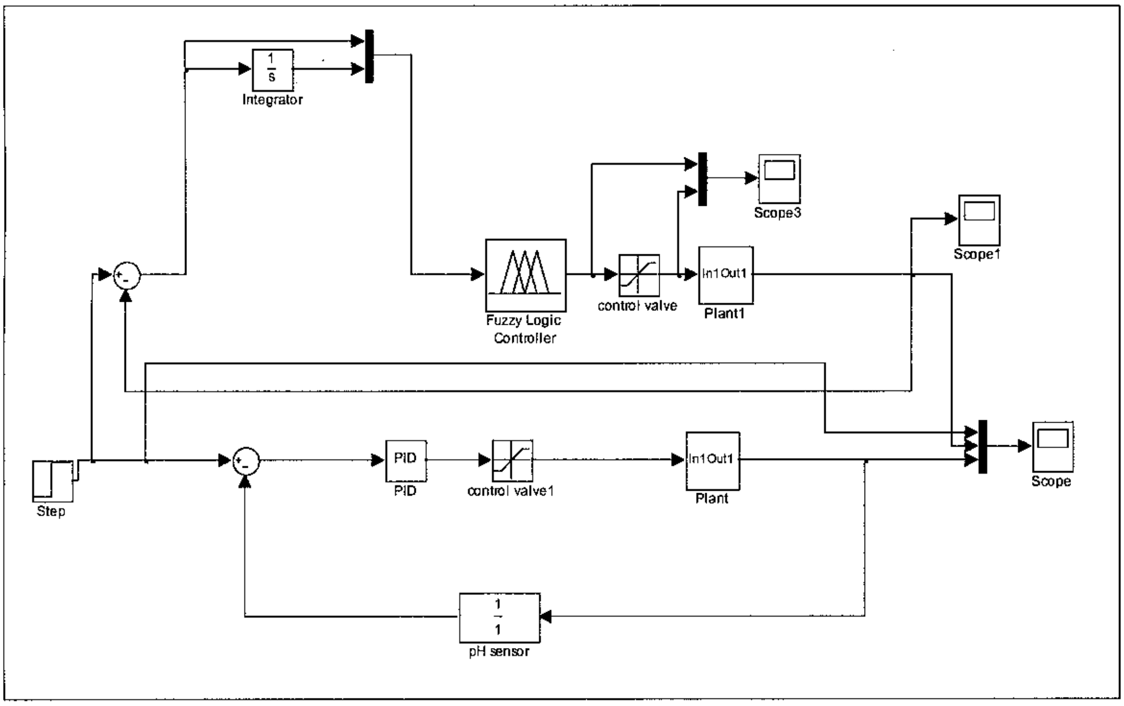

Figure 32: ANFIS implementation for <u>empirical model.</u>

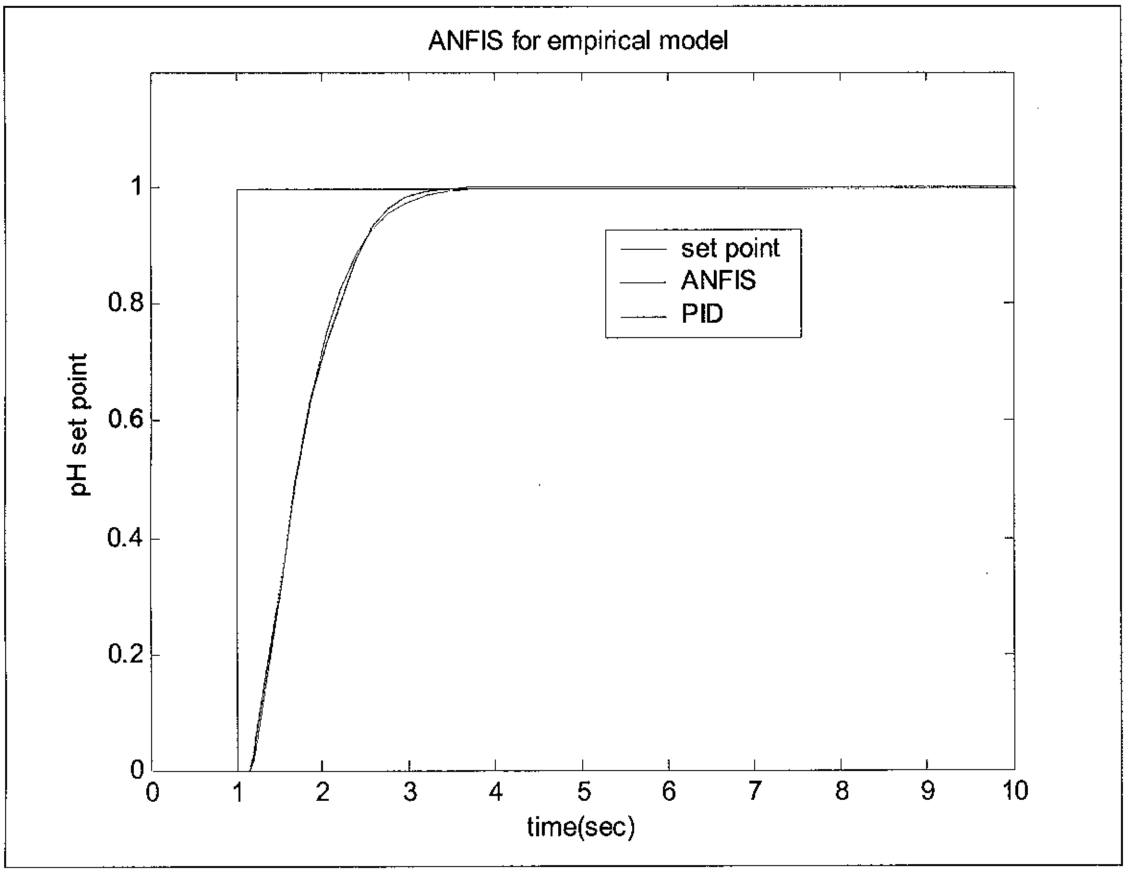

Figure 33: The simulation result for <u>empirical model</u>. Blue (set point), Red (PI controller), Green (ANFIS).

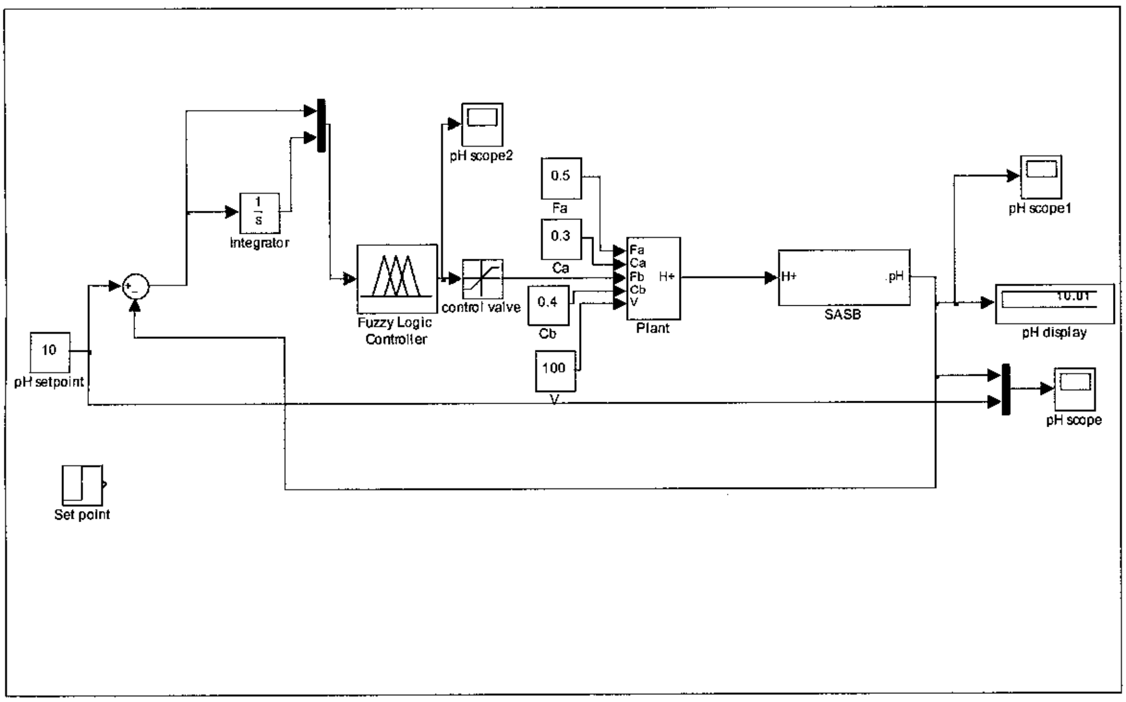

Figure 34: ANFIS implementation for <u>mathematical model</u>.

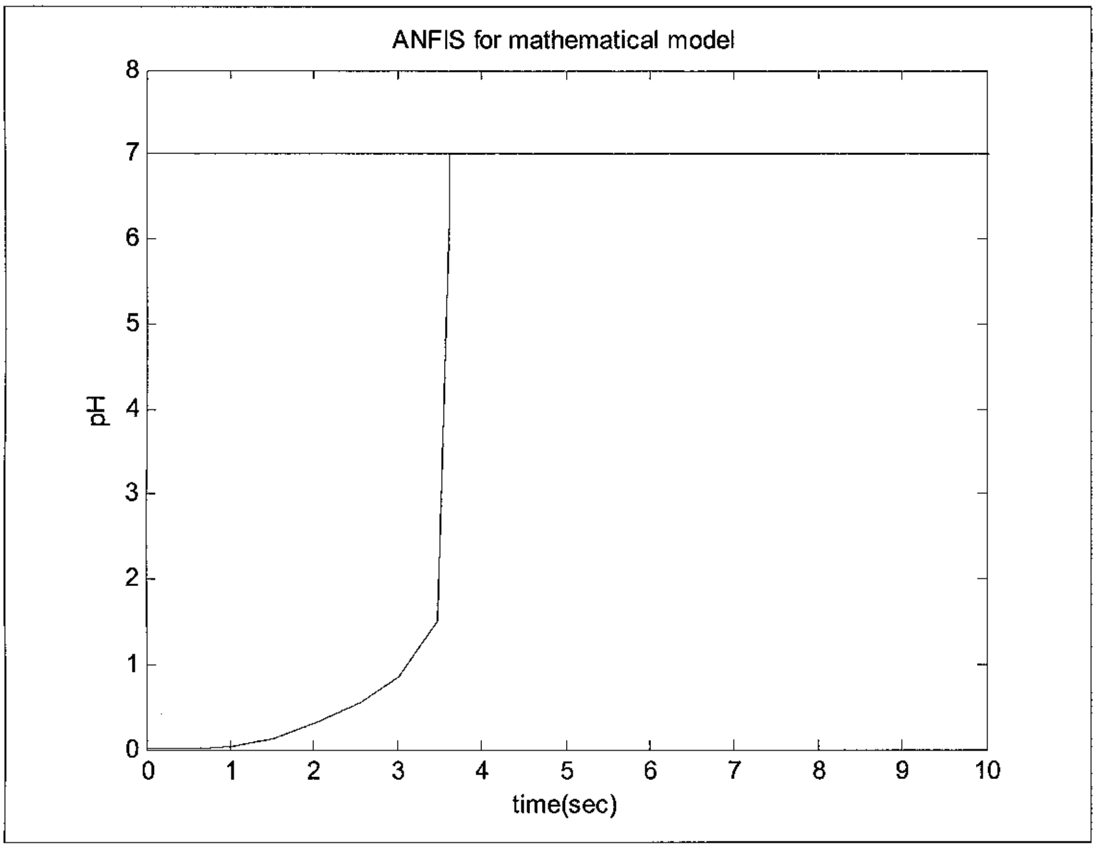

Figure 35: The result from ANFIS implementation for mathematical model at pH=7.

4.1.1 ANFIS for empirical model

From the simulation result shown in Figure 34, the result was very impressive. The FLC controlled output follow the set point successfully. The settling time is approximately 3.5 seconds. The time lag is approximately 1.2 seconds with an over damped response.

It must be noted here that the controller only act for a limited range of pH which is approximately from pH 10 to 12 based on the experiment conducted in the laboratory during the process modeling. The result shows that the set point is 1 which represents the output for any value between the given ranges.

Both the PID controlled and FLC controlled responses are over damped response. The response type could be determined based on the operator discretion. The basic idea is the FLC will follow the response from the PID based on the training done in ANFIS GUI.

However based on the training, for a given over damped PID controlled response, the FLC output could be designed to produce under damped response as shown in Figure 36. It could be accomplished by changing the type of membership function during the ANFIS training. In this design, Bell membership function would give the under damped response while Trapezoidal membership function would give the exact response as PID.

As the FLC is designed for the specific plant only, the FLC is not possible to be implemented to other similar pH neutralization plants. Therefore, mathematical modeling could be used to portray the whole ANFIS implementation for any pH neutralization plants.

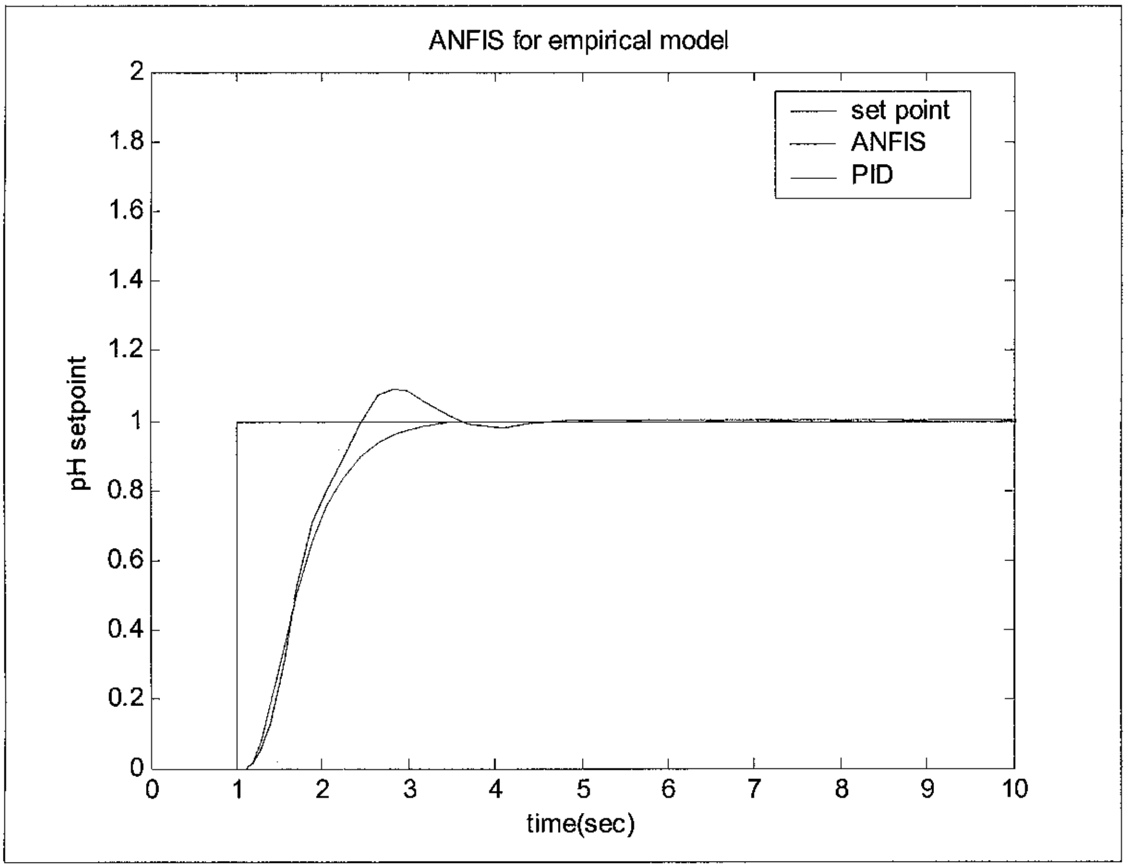

Figure 36: Underdamped FLC response from overdamped PID response.

4.1.2 ANFIS for mathematical model

Figure 34 shows the result of ANFIS implementation for mathematical model at 7 pH. The result is also very impressive, the settling time is approximately 3.5 seconds.

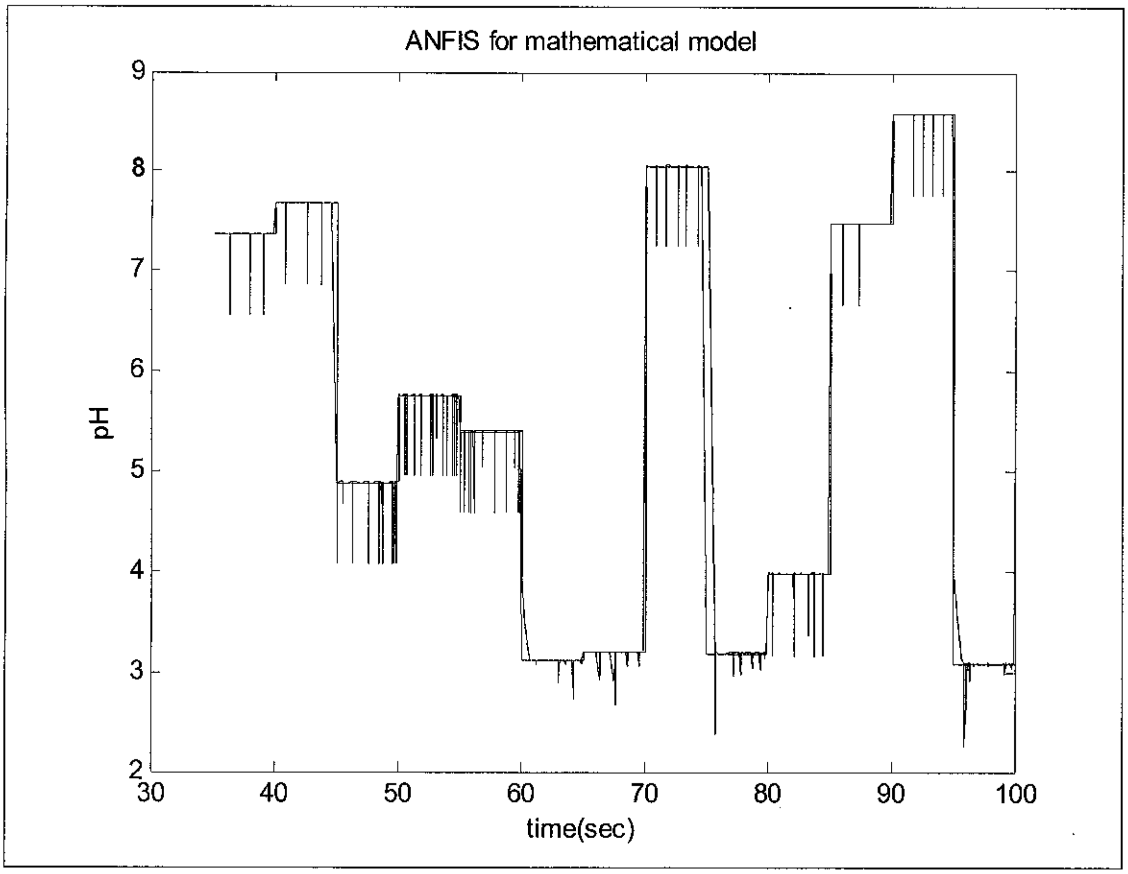

Figure 37: ANFIS for mathematical model for random set points range between 3 to 11 pH.

Figure 37 shows the output for random set points range between 3 to 11 pH. The result was not quite good since there are so many spike signals that could lead to fault alarms at the operator workstation. However, the pH output still follows the random set points.

Based on the explanation from Hazaril [17], for pH process, a special control valve/ pump known as 'dosing pump' is required to prevent the normal spikes in the pH process. In this mathematical model, since the control valve is not modeled based on the 'dosing pump,' therefore the spikes could not be avoided. Therefore for the analysis on the ANFIS implementation for mathematical model, the result could be accepted by neglecting the spikes.

To design the FLC for mathematical model by using ANFIS, the training was performed by using the highest set point of the plant which is at pH 12. As compared to empirical model design, the training was performed by using random set point from 0 to 1.

4.2 Gain-scheduling method

For gain-scheduling method, the FIS files developed in section 3.5 will be tested on servo and regulator problem.

4.2.1 Servo problem

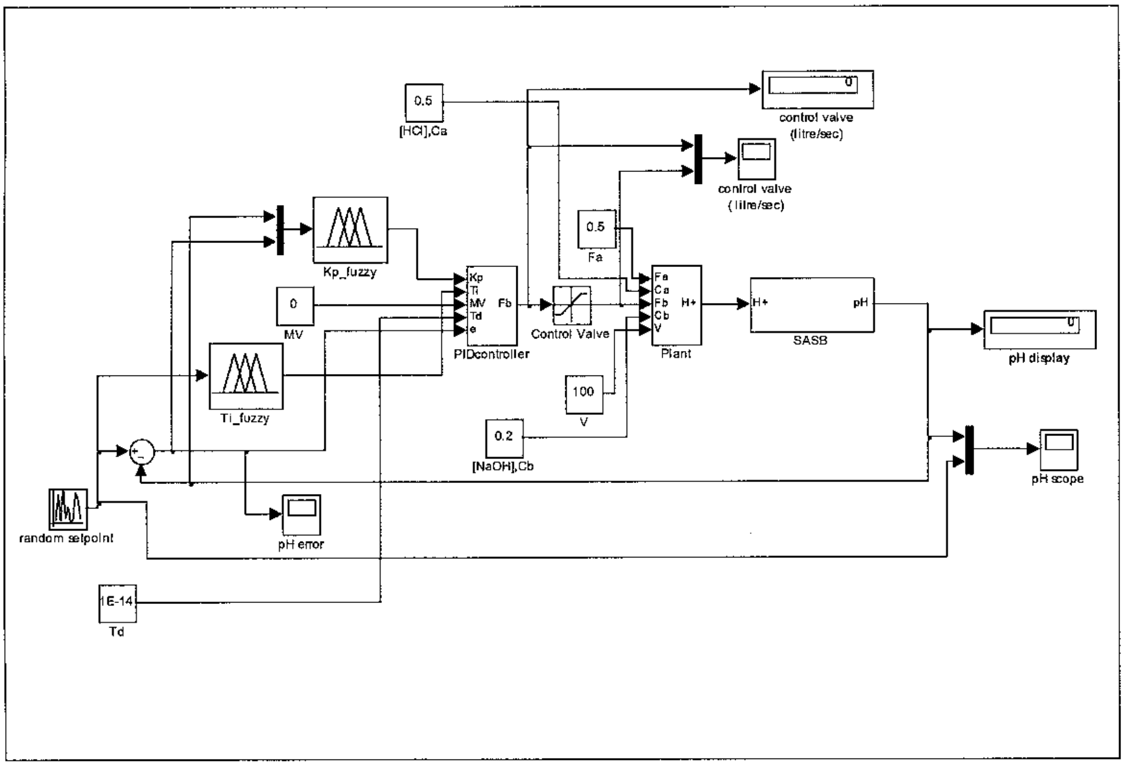

Figure 38: Block diagram for testing servo problem. The random number generator was used between pH 3 and 11.

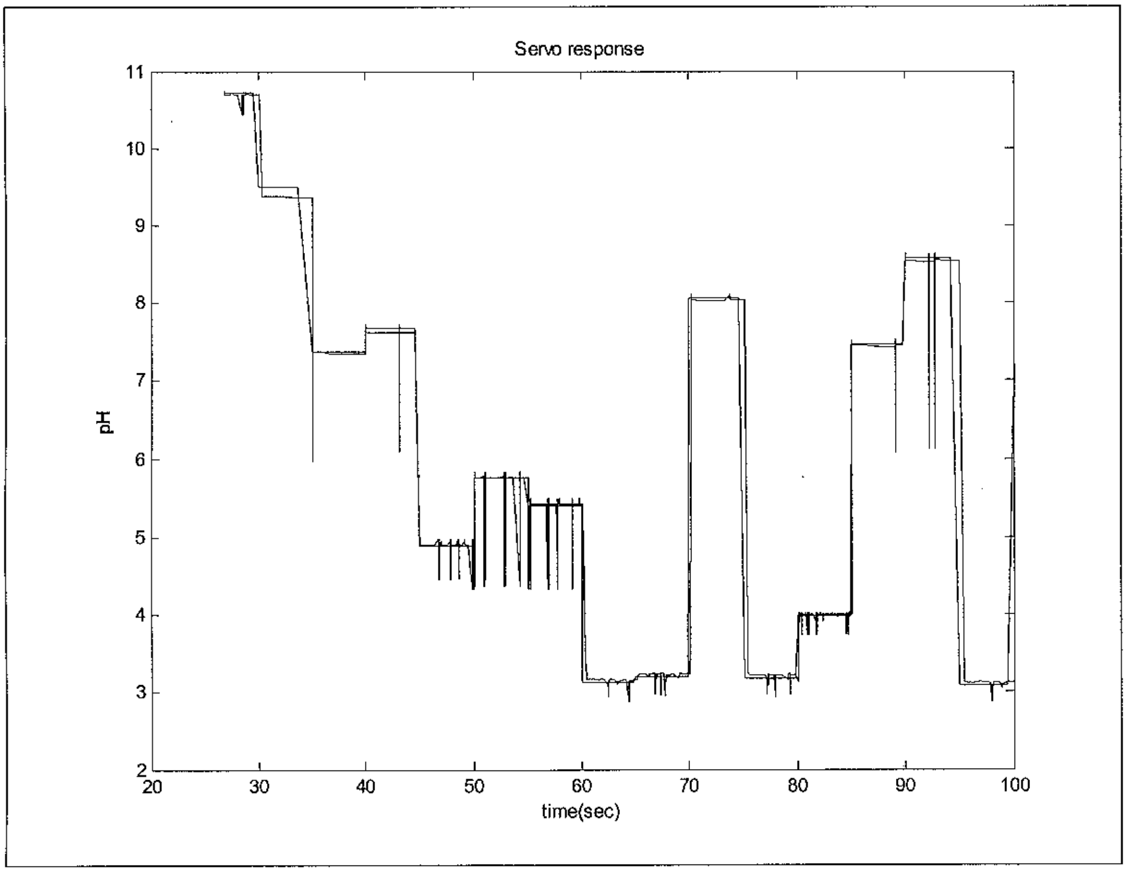

Figure 39: The result from the servo problem simulation. Green (Set point), Blue (Process variable).

For servo problem, the FLC for K_p and T_i are simulated against a uniform random number generator for pH between 3 and 11 in 100 seconds duration as shown in Figure 38. The result was shown in Figure 39.

The output is almost similar to the output from the ANFIS implementation for mathematical model. There are still some spikes in the signals despite successfully follow the random set point changes. The occurrence of the spikes was explained in section 4.1.2.

4.2.2 Regulator problem

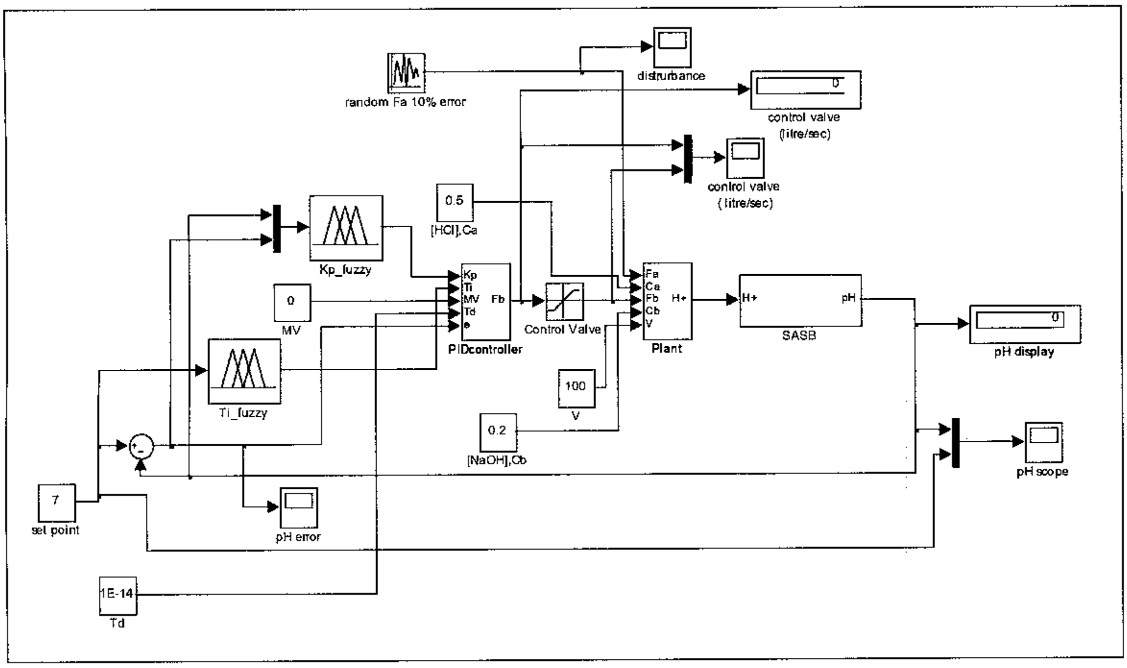

Figure 40: Block diagram for testing regulator problem. The random number generator was used to vary the acid flow, F_a at ±20% variation.

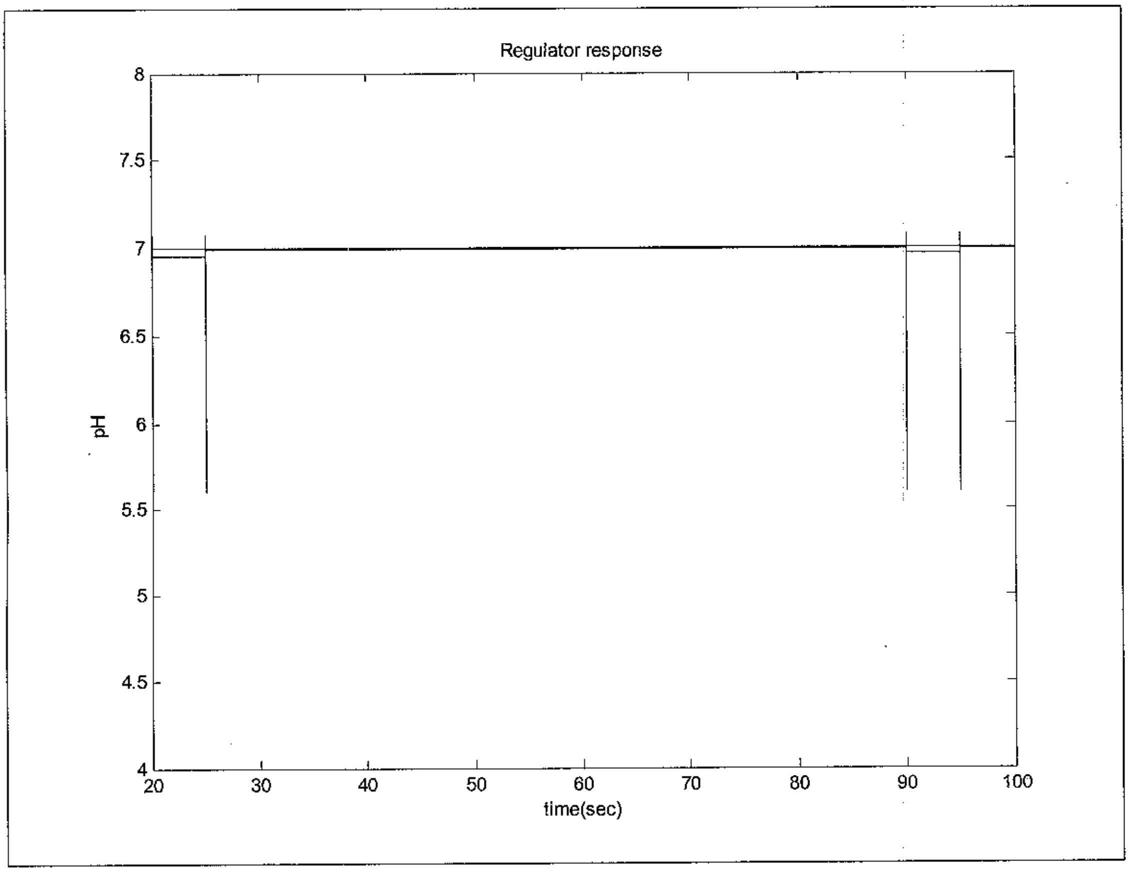

Figure 41: The result from the regulator problem simulation. Green (Set point), blue (Process variable).

For regulator problem, the FLC for K_p and T_i are simulated with ±20% disturbance in acid flow, F_a in 100 seconds duration as shown in Figure 40. The result was shown in Figure 41.

From the result, it shows that the controller manage to marginally reject the disturbance effects. The process variable still maintains around the set point value, although quite fluctuating with the occurrence of spikes.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

From the project, there are several conclusions could be made. Firstly on the behaviour of the pH neutralization process itself. From the study, it really shows that the process is highly nonlinear. Although the work is only for Strong Acid- Strong Base (SASB) only, but according the work done by Ylen Jean Peter [18], the other weak or strong acidic and basic interaction also will give the same nonlinear behaviour.

Therefore, for high variation of pH in the set point, normal PID controlled would not be sufficient. One possible method is to use gain scheduling technique. Gain scheduling technique could be further upgraded to achieve more robust controller by using FLC.

There are two methods for FLC design, either by using ANFIS tool or gain-scheduling method. The main difference between those two methods is, the former one require less effort to design the Fuzzy Inference System (FIS) since the use of ANFIS GUI was very helpful in order to design such controller. Besides that, ANFIS implementation directly replaces the PID controller from the process loop while in the gain-scheduling method, the PID controller is not permanently replaced, however, the FLC is used to vary the PID input parameters; K_p and T_i.

In this project, ANFIS is implemented for both the empirical and mathematical models of pH neutralization process. Empirical model is a linearized model of the process for the Analytical & Chemical Pilot Plant located in the Process Control & Instrumentation Laboratory (23-00-06).

ANFIS design for empirical and mathematical model gives a very impressive result. For the empirical model, ANFIS successfully follow the predetermined PID response. For the mathematical model, by neglecting all the spikes around the set points, the result is also acceptable.

Gain-scheduling method is a very tedious method since it required to be started from the lowest level of the design approach. Everything must be started from the beginning. The output response from gain-scheduling method approach is almost similar to the ANFIS implementation (Compared the output from Figure 37 and 39).

For the regulator problem, the simulation proves that for ±20% error in the acid flow, F_a, the controlled variable still capable to catch up with the set point.

From ANFIS implementation, the best inference would be the FLC could be used to replace PID controller in the process loop to control a wide range of pH value. However, if the designers decide to maintain the PID controller for any reason, they still might do that by using the gain-scheduling method approach. The reason for maintaining the PID controller could be due to the robustness of PID controller.

In overall, FLC could be used as an alternative to PID controller. FLC could be implemented with various configurations depending on the designers' requirements.

5.2 Recommendation

The most important continuation of this project is nothing else but to physically implement the controller to the physical pH neutralization plant.

To physically implement the controller, one possible method was to use relevant Data Acquisition (DAQ) to obtain the signal from the Distributed Control System (DCS) workstation into the MATLAB. MATLAB already pre-included set of PID algorithm that is suitable for industrial process application in addition to the FLC. The tuning tasks must also be performed in MATLAB. To obtain the signal from the DCS, the interface provide by MATLAB such as Real-Time Workshop tools provided in the SIMULINK packages.

Secondly is on the 'dosing pump' model. It is also recommended to redevelop the mathematical model of the process by integrating the 'dosing pump' model so that all the spikes could be eliminated and hence better and accurate output response would be acquired.

In addition to FLC, there are many new developments in other artificial intelligent (AI) methods for process control such as Neural Network, Genetic Algorithm and total Neural-Fuzzy integration (in fact that is ANFIS originated from). Therefore, it should be great ideas to start using these methods.

On the other hand, other conventional methods of process control such as feed forward-control, cascade-control might also be ventured to see their effective. These methods provide some advantages due to common availability in commercial PID controllers.

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Appendix I

Laboratory Experimental Procedure

EXPERIMENT 4:

PH CONTROL IN A CSTR

4.1 OBJECTIVE OF THE EXPERIMENT

(i) To study the pH control pilot plant and prepare a P & I diagram.

(ii) To tune a liquid flow control loop by ultimate gain method.

(iii) To tune a pH control loop by the process reaction curve method.

(iv) To study the closed loop characteristic of the pH control loop of the CSTR.

4.2 INTRODUCTION AND THEORY

pH is defined as $\log_{10}H^+$ and is a measure of the acidity or alkalinity of a liquid. The pH scale is from 1 to 14. with 7 as the pH of neutral water. A value of the pH lower than 7 designate as acidic solution. pH control is important for many chemical processing applications and in pollution control.

In the present experiment the acid flow is under PID flow control while the CSTR pH is controlled by a PID loop controlling the alkaline flow. The loop will be tuned by the ultimate gain method (refer Experiment 3, Table 3.1). The pH control loop will be tuned by the process reaction curve method. (refer to Experiment 2, Table 2.1)

4.3 EXPERIMENTAL EQUIPMENT

The schematic diagram of the experiment set-up is shown in the figure 4.1. Acid solution pumped from tank VE100 by pump P100 into CSTR VE120. The alkaline solution from tank VE110 is pumped by pump P110 into the same CSTR, VE120. The CSTR is equipped with a stirrer and pH transmitter AT122. If desired further neutralisation may be carried out in a second CSTR VE130, or the final neutralisation tank VE140. Besides pH dissolve oxygen can also be measured in a tank VE140.

The major control hardware includes the following:

Flow transmitter	FT120, FT121, FT130
Conductivity transmitter	CT110, CT100
pH transmitter	AT122, AT130, AT140
Dissolved oxygen transmitter	AT141

Flow controller	FIC120, FIC121
pH controller	AIC122, AIC 130
Control valves	FCV120, FCV121, FCV130

The simplified diagram for the flow control and pH control are shown in Figures 4.2 and 4.3 respectively.

4.4 PROCEDURE

The experiment has the following three part:

(i) Tuning flow loop in the acid flow path.
(ii) Tuning pH control loop.
(iii) Operating closed loop pH control.

4.4.1 Start-up

1 Switch on power to the Local Control Panel.
2 Turn the selector to DCS to run the experiment under DCS control. Set it to local if the experiment to be run under local control by using the multi loop controller only.
3 Switch on the main air supply compressor at the compressor room. Wait for the compressor to stop before starting any experiment. This is to ensure that the main instrument air supply to the system is sufficient before running any experiment.
4 Switch on the DCS server and clients. The entire system to start-up automatically. When prompted, key in your user name and password to log in. Consult the supervisor for the correct user name and password.

4.4.2 Preparation of Acidic process stream

1 Fill the acid storage tank with water (up to ½ tank).
2 Use the manual pump provided for acid to pump about 10% of the acid solution into the storage acid tank. Caution: Always add acid to water. Do no add water to the acid.
3 Stir the final solution to ensure homogeneity.

4.4.3 Preparation of Alkaline process stream

1 Fill the alkaline storage tank with water. (up to ½ tank).
2 Use the manual pump provided for alkaline to pump about 30% of the acid solution into the storage acid tank. Caution: Always add alkaline to water.
3 Stir the final solution to ensure homogeneity.

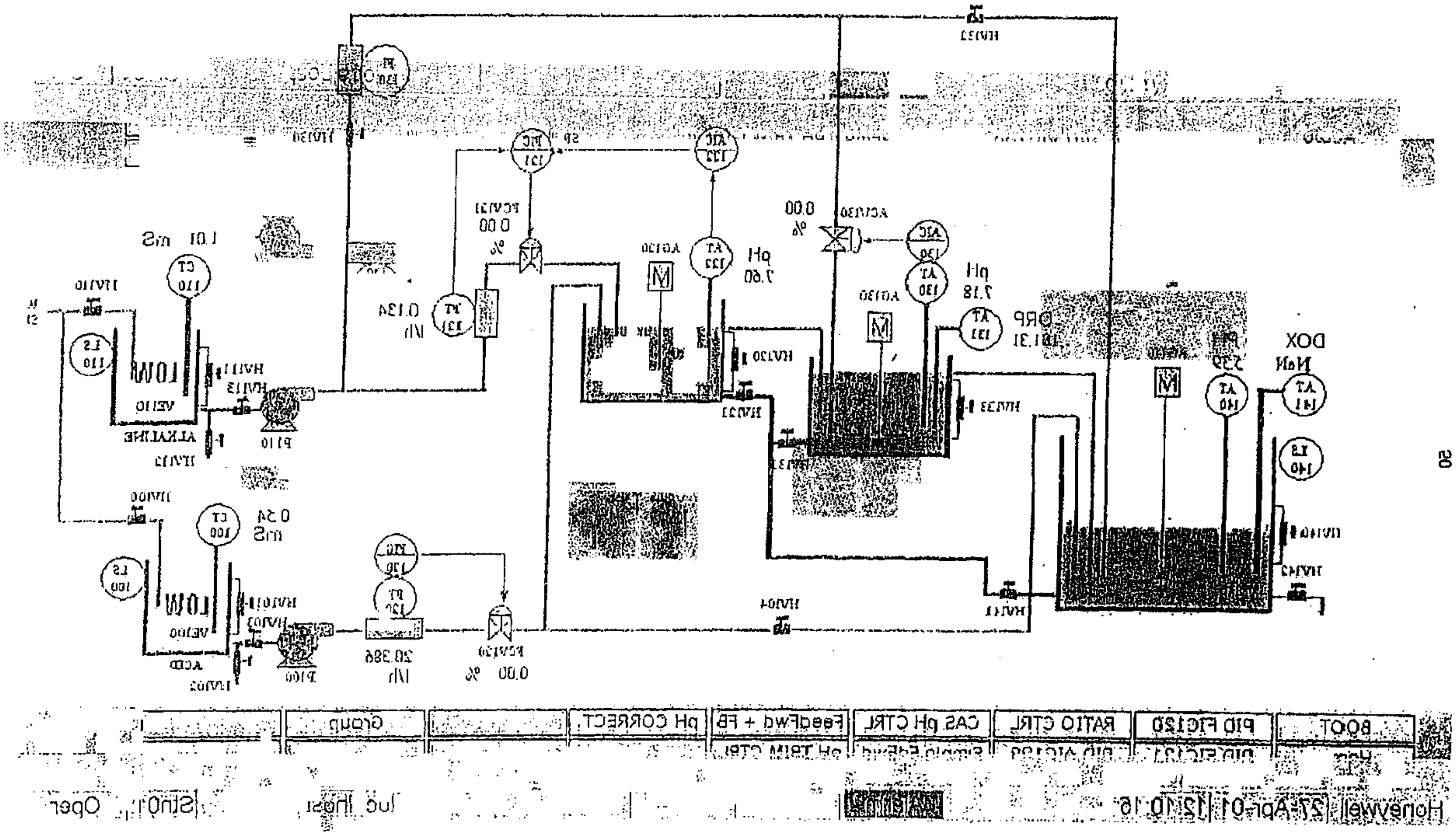
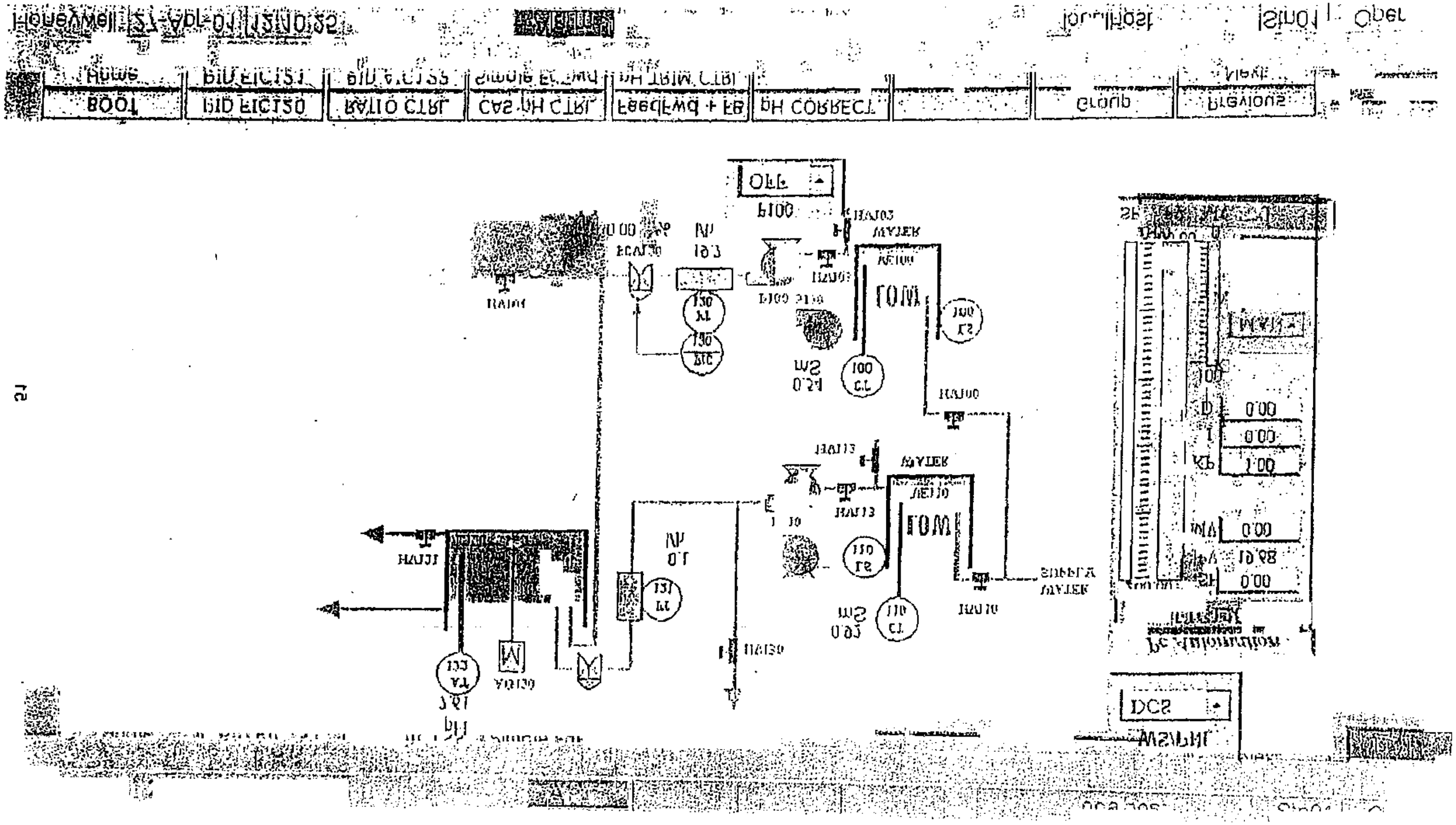


Figure 4.1: CSTR pH control

Figure 4.2: Flow Control Loop



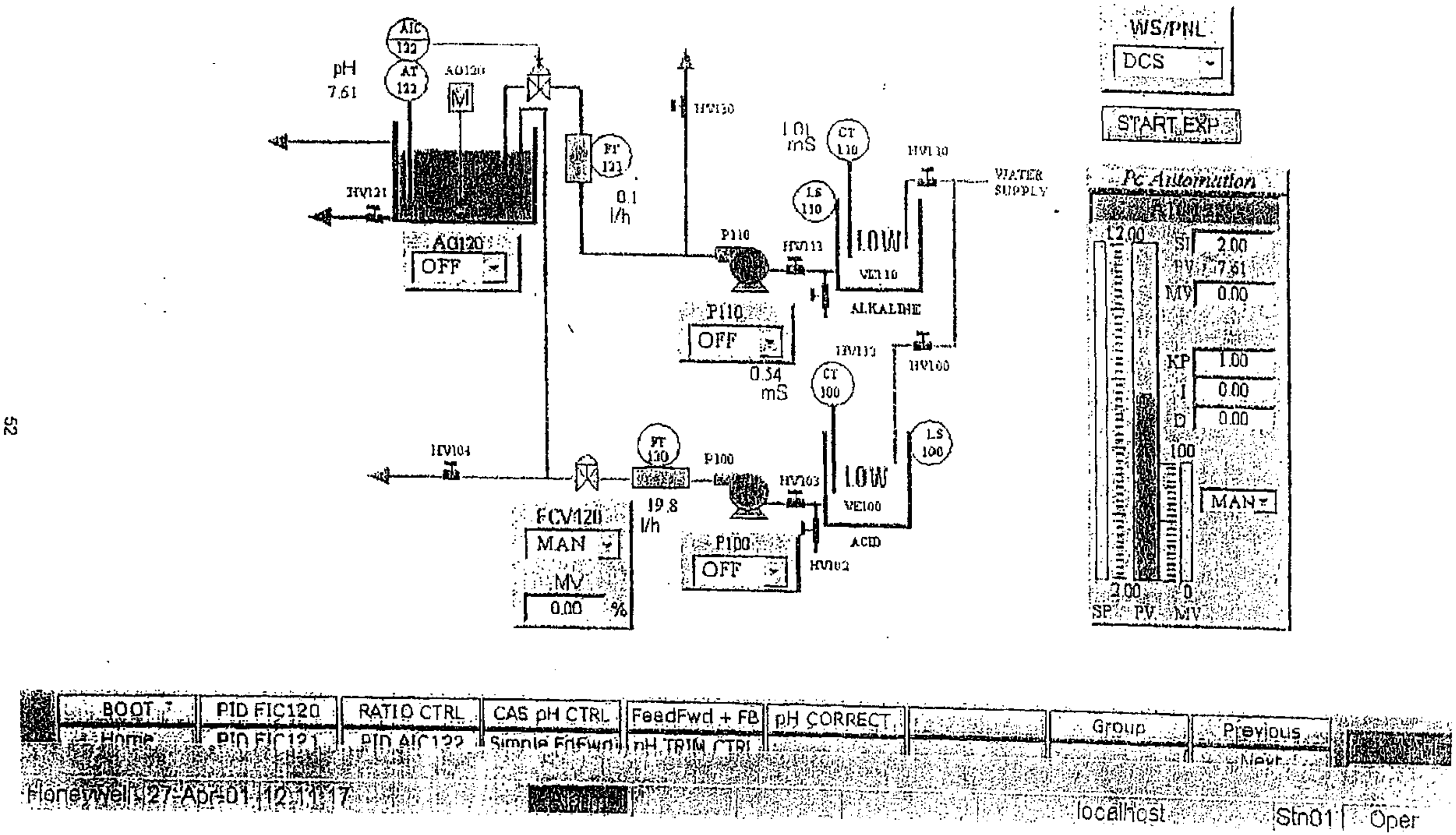


Figure 4.3: pH Control

4.4.4 Start Up

Table 4.4: Preparation and Start-Up

STEP	ACTION	REMARKS
1	Ensure that all Utility Services are ready (i.e. Switch on Power Supply to Control Panel and Switch on Air Supply Systems to the Pilot Plant.	
2	At the Local Control Panel, turn the selector switch to 'DCS'.	
3	Fill the vessel VE100 with water until it is about half full.	
4	Ensure that the DCS is ready (i.e. It is communicating properly with the control panel).	
5	At the computer and the 'Chemical Processing Over-View' display, click on the button [PID FIC 120].	Display for 'Experiment 1 – Simple PID flow Control (FIC 120)' will appear.
6	From the WS/PNL select combo-box, choose DCS. This will transfer control of the pilot plant to the DCS.	Click on drop down box and select 'DCS'.
7	From the Control select combo box, choose FIC120.	
8	At the Controller Faceplate (FIC120) set the controller to MANUAL mode.	Click on drop down box and select 'MANUAL'.
9	Close the control valve FCV120 manually (0%) i.e. a) Setting Control Mode to 'MANUAL', then b) At the MV data entry field, key in 0 and press [Enter].	Same operation to Open/Close other control valve manually.
10	Adjust the Hand Valves at the Pilot Plant as follows: Open Hand Valve HV103 Close Hand Valve HV102	Hand valves to be Open/Closed Fully.

4.4.5 Closed Loop Tuning of Flow Loop

Table 4.5: Closed Loop Tuning Method for Flow Control Loop

STEP	ACTION	REMARKS
1	At the FIC120 Controller Faceplate, set the P, I and D parameters as follows: - Gain (K_p) = 2.0 - Integral time (I) = 9999 - Derivative time (D) = 0.0	Before setting any variables, click on 'OPER' icon (on lower right side) and type 'MNGR'.
2	Adjust the Controller Set Point (SP) to 0.1 m^3/h	Set SP = 100
3	Set the Controller Manual Mode and Open the Control Valve FCV120 by 86%	Set Controller Manipulated Variable, MV = 86%
4	Start the Pump P100 via DCS	Click on drop down box and select 'ON'
5	Slowly adjust the Control Valve FCV120 to bring the Process Variable (PV) to almost equal to the SP	Adjust MV
6	Observe the PV from the Trend Window and wait until it has stabilised to a constant value	
7	Set the Controller to AUTO mode	
8	Wait for the PV to stabilised	
9	Make a small step change to SP (e.g. increase the set point by 10% i.e. to 110)	
10	Observe the PV from the Trend Window. If the PV response is not oscillatory, adjust the control Gain (K_P) value until it become oscillatory	Set controller to MANUAL mode, adjust SP and MV to initial values and double K_p value. Repeat Step 7, 8 and 9.

11	If the PV response is oscillatory, observe whether the magnitude of PV is increasing or decreasing. If it is increasing reduce the controller gain by 1.5 times. If it is decreasing increase the controller gain by 2 times. Aim to obtain an oscillatory response with almost constant amplitude.	
12	When constant amplitude oscillation is achieved allow at least 3 oscillation cycles to be recorded and freeze the trend window.	
13	Print out the PV response curve.	Print in colour
14	Stop pump P100 and set the controller FIC120 to MANUAL mode.	
15	Using the printed graph obtained from section above, measure and tabulate the relevant values as required. K_u is the ultimate gain of the controller (the controller gain at which constant amplitude oscillation is acquired). T_u is the ultimate amplitude oscillation of PV	Refer Table 4.6
16	Based on the equations for Closed Loop Tuning for PI, calculate the required controller tuning parameters.	Refer Table 3.1
17	Key in the calculated tuning parameters at the FIC120 controller faceplate.	Set $K_p = K_c$ and Integral $= T_i$.

Table 4.6: Tabulation of Results- Results for Closed Loop Tuning

Measurement	Test 1	Test 2	Test 3	Average
Ultimate Controller Gain, K_u				
Time for 3 Oscillation periods or more (minute)				
Calculations:				
Ultimate Period, T_u (time taken for one Oscillation period) (minute)				
Tuning Parameters:				

Gain, K_c				
Integral Time, T_I (minute/repeat)				
Derivative Time, T_D (minute/repeat)				

4.4.6 pH Control

Table 4.7: Preparation for pH Control

STEP	ACTION	REMARKS
1	Ensure that all Utility Services are ready (i.e. Switch on Power Supply to Control Panel and Switch on Air Supply Systems to the Pilot Plant.	
2	Adjust the Hand Valves at the Pilot Plant as follows: Open Hand Valve HV103 Close Hand Valve HV102 Close Hand Valve HV112 Open Hand Valve HV113	Hand valves to be Open/Closed Fully.
3	At the Local Control Panel, turn the selector switch to 'DCS'.	
4	Ensure that the DCS is ready (i.e. It is communicating properly with the control panel).	
5	At the computer and the 'Chemical Processing Over-View' display, click on the button [PID AIC 122].	Display for 'Experiment 4– Simple PID pH Control (AIC 122)' will appear.
6	From the WS/PNL select combo-box, choose DCS. This will transfer control of the pilot plant to the DCS.	Click on drop down box and select 'DCS'.
7	From the Control select combo box, choose pH AIC122	
8	At the FIC120 Controller Faceplate: - Set the controller to AUTO mode. - Set its output to 100% (fully open). - Set its P, I and D values obtained from Experiment 1.	Set MV = 100, K_p, I and D accordingly.

9	Open HV100 and HV110 to fill vessels VE100 and VE110 with water until each of them is about ¼ full.	
10	Close HV110 when the water level at VE110 is ¼ full.	
11	When the water level at VE100 is about ¼ full, start pump P100 via DCS to fill the reaction vessel VE120. Continue to fill VE100.	
12	When the water level at the reaction vessel VE120 is above its agitator blades stop pump P100.	
13	Close HV 100 when the water level at VE100 is ¼ full.	
14	At the vessel VE100 use the hand pump provided to add concentrated sulphuric acid into it [Note: do not add water into concentrated acid instead add acid to water]. Observe the reading of the conductivity meter. Stop adding acid when the conductivity of the solution is approximately 100 micron-Siemen.	The students are advised to wear eye protection goggle and rubber gloves when dealing with acid solution.
15	At the vessel VE110 use the hand pump provided to add concentrated caustic soda (Sodium hydroxide) solution into it. Observe the reading of the conductivity meter. Stop adding acid when the conductivity of the solution is approximately 100 micron-Siemen.	The students are advised to wear eye protection goggle and rubber gloves when dealing with acid solution.
16	At the AIC122 Controller Faceplate, set the controller to MANUAL mode.	Click on drop down box and select 'MANUAL'.
17	Close the Control Valve pHCV12 manually (0% open).	pHCV12 is the same Control Valve as FCV121.
18	Ensure that all tanks are properly covered.	

Table 4.8: Start-Up

STEP	ACTION	REMARKS
1	Start agitator AG120 via DCS.	

2	At the FIC120 Controller Faceplate: - Adjust the Controller Set Point to 0.05 m^3/h	Set SP = 50
3	Start pump P100 via DCS.	

4.4.7 Identification of pH Process

Table 4.9: Process Identification for pH Control Loop

STEP	ACTION	REMARKS
1	At the AIC 122 Controller Faceplate, manually Open Control Valve pHCV122 to 10%.	Set MV = 10.
2	Start pump P110 via the computer.	Click on drop down box and select 'ON'.
3	Observe the pH curve from the Trend Window and wait until it has stabilised.	
4	Adjust the output of controller AIC122 to obtain a stable pH value (AT122) between 6.5 and 7.5.	Set SP = 7.
5	At the Controller Faceplate (AIC122) make a Step change of between 10 to 20% to the control valve FCV121 manually.	Set SP = 7.7. Adjust controller MV.
6	Observe the pH curve (AT122) from the Trend Window and wait until it has stabilised to a new constant value and freeze the trend window. .	This is the process Reaction curve.
7	Print out the pH trend curve.	Print in colour.
8	Stop both the pumps P100 and P101, and the agitator AG120 via DCS. Then set the controllers FIC120 and FIC121 to MANUAL mode.	

Table 4.10: Result Analysis for pH Control Loop

STEP	ACTION	REMARKS
9	Compare the process value curve with a set of expected process Reaction Curve provided in Figure 2.6.	
10	Identify the process response with the corresponding Reaction Curve.	
11	Make several measurements as per the Reaction Curve chart.	Refer to Table 4.11.
12	Sketch a Block Diagram to represent the process and describe the characteristic of this process.	Dead time, Capacity/Rate of Rise, Time Constant, Noise.
13	Using the printed graph obtained from section above (process analysis) above, measure and tabulate the relevant values as required. Refer table 4.9.	Note: dB_u and dM are changes from the 1st stable output to the 2nd.
14	Based on the equations for Open Loop Tuning, calculate the required controller tuning parameters. Refer table 2.1.	
15	At the AIC122 controller faceplate. Key in the calculated controller tuning parameters.	

Table 4.11: CSTR Model

Type of model	Time constant, T_1	Time constant, T_2	Decay time, τ
First Order			
First Order with decay time			
Second order			
Second order with decay time			

Table 4.12: Results for Open Loop Tuning

Measurement	Test 1	Test 2	Test 3	Average
Change in Manipulated Variable, dM				
Change in Ultimate Value, dB_u				
Slope, S				
Apparent Dead Time, T_d				
Calculations:				
Apparent Time Constant, $T = dB_u / S$				
Steady State Process Gain, $K_p = dB_u / dM$				
$R = T_d / T$				
Tuning Parameters:				
Gain, K_c				
Integral Time, T_i (minutes/repeat)				
Derivative Time, T_D (minutes/repeat)				

4.4.8 pH Control Performance

Table 4.13: Control Loop Performance Test for pH Control Loop

STEP	ACTION	REMARKS
1	Repeat the Start-up procedure for this experiment.	
2	At the AIC122 Controller Faceplate: - Set the controller to MANUAL mode - Set its output to 10% Set its P, I and D values obtained from Experiment 4B or Experiment 4C.	
3	Start pump P110 via the computer	
4	Set both the Controller (FIC120 AND AIC122) to Auto mode.	
5	Wait for the Process Value (PV) of FIC120 AND AIC122 to stabilise.	
6	Make a small step change to the Set Point of FIC120 Controller of between 10% to 20%.	
7	Observe the Process Value (PV) of the pH controller AIC122 from the Trend Window and look for some typical response characteristic. Refer to guide lines.	Refer Siborg (1989).
8	Capture the importance process response and print out the trend curve.	Print in colour.
9	Stop both the pumps P100 and P110 and the agitator AG120 via the computer then set the controllers FIC120 and AIC122 to manual mode.	

Table 4.14: Tabulate and Analyse Results

STEP	ACTION	REMARKS
10	Using the printed graph obtained from section above (process analysis) above, measure and tabulate the relevant values as required.	Refer Table 4.15 Seborg (1989).
11	Describe the Characteristic of the process response.	
12	Discuss the functions of each controller tuning parameters P, I and D.	
13	Suggest any improvement to the process control loop and its total error.	

Table 4.15: Closed Loop Response

Characteristic	Test 1	Test 2	Test 3	Average
Initial value of SV				
Final value of SV				
ΔS				
Gain				
Rise Time				
Overshoot				
Decay ratio				
Period				
Response Time				

4.5 INTERIM REPORT

The interim report should contain:

(viii) P & I diagram of process.
(ix) Flow control loop tuning data and results.
(x) Process Reaction Curve experimental data.
(xi) Suggested Process Model.
(xii) Cohen-Coon Setting Calculations.
(xiii) Closed Loop Response Characteristic.
(xiv) Answers to review questions.

4.6 REVIEW QUESTIONS

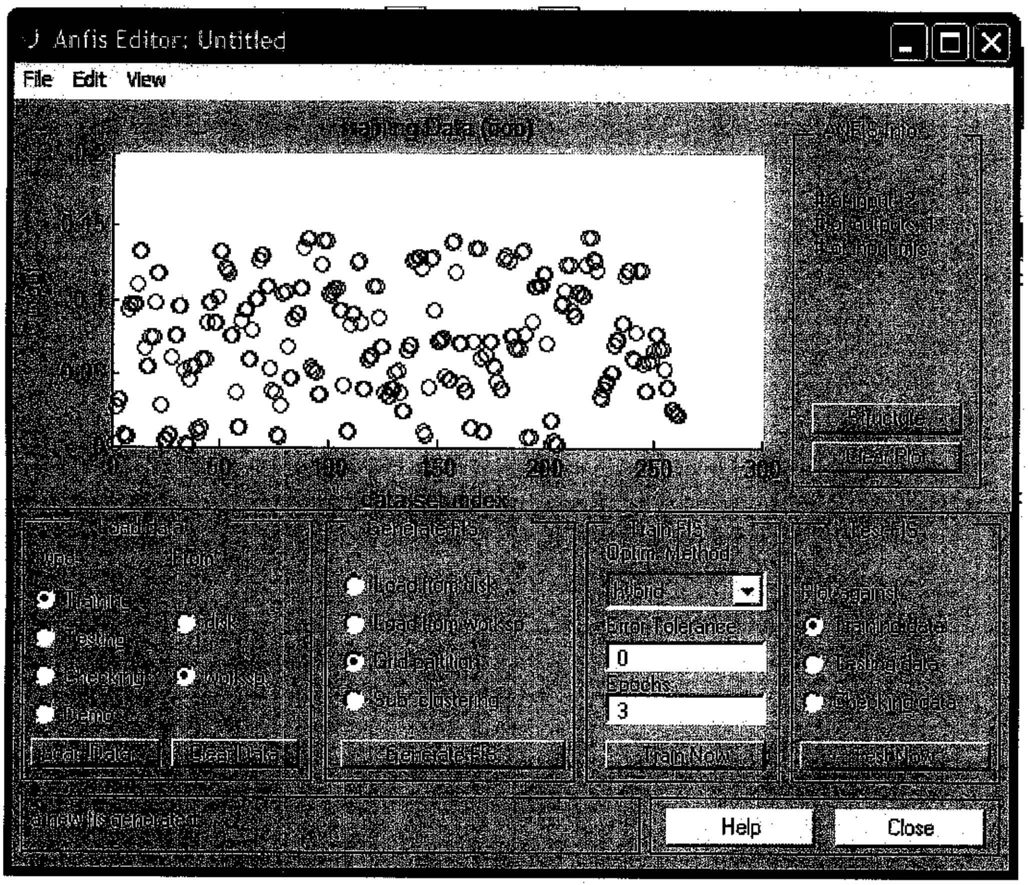
(i) Sketch the titration curve of a strong acid- strong base.
(ii) What is meant by process gain?
(iii) Do you expect any difficulty in controlling the pH at a value 7?
(iv) Give one example each of a
   (a) strong acid
   (b) strong base
   (c) weak acid
   (d) weak base

2.7 REFERENCES

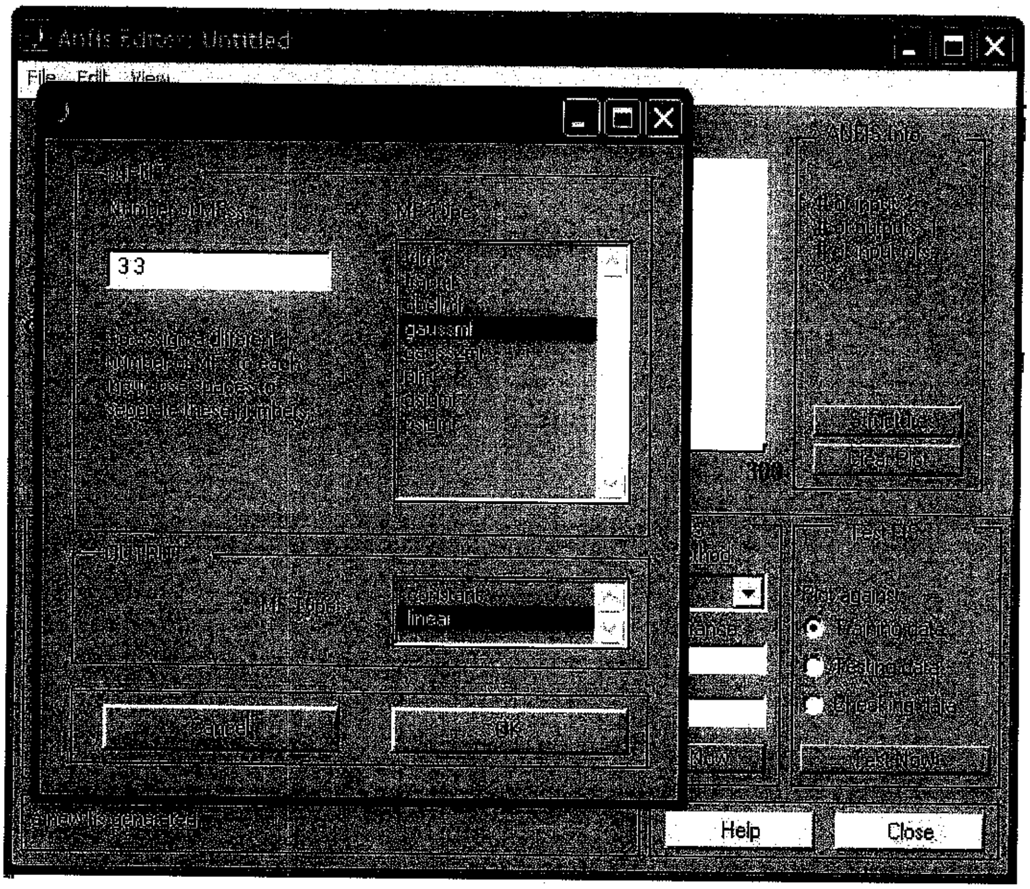
Seborg D.E., T.F. Edgar and D.A. Melliechamp. *Process Dynamics and Control*. John Wiley and Sons, New York, 1989. pg: 116-118, 164-173.

Appendix II

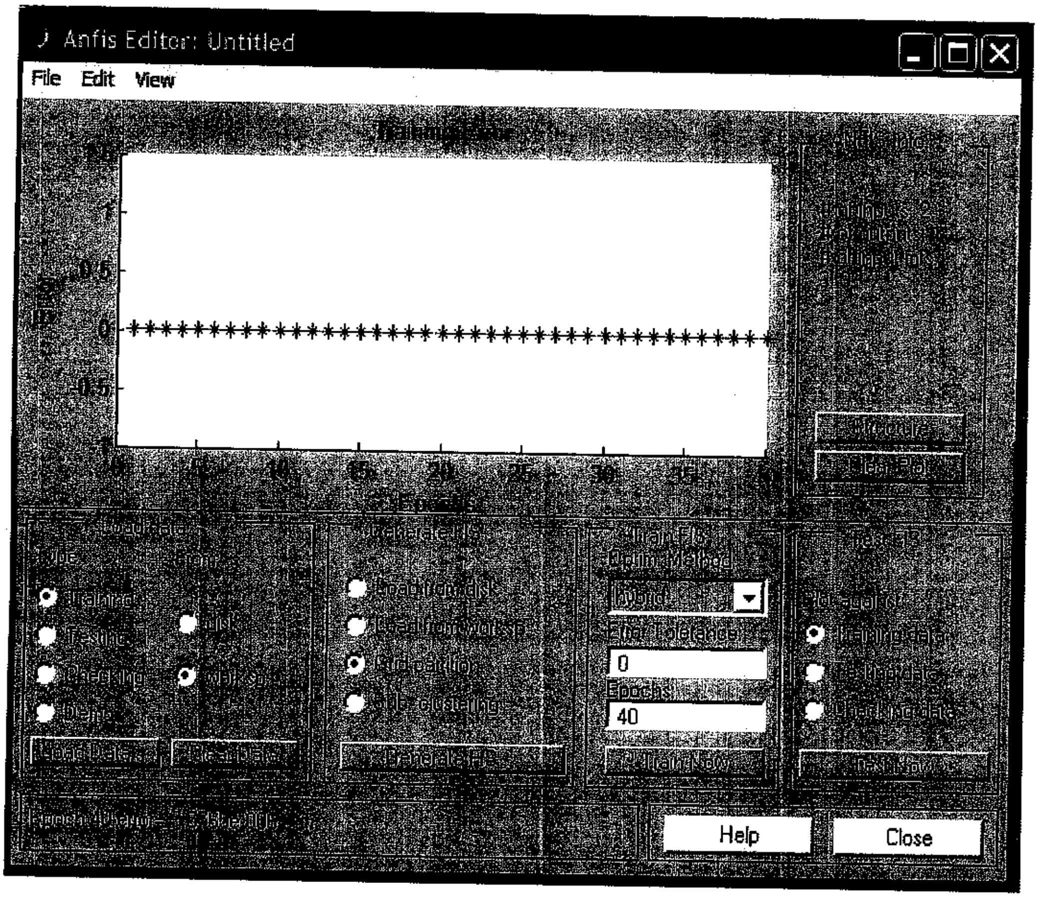
ANFIS GUI



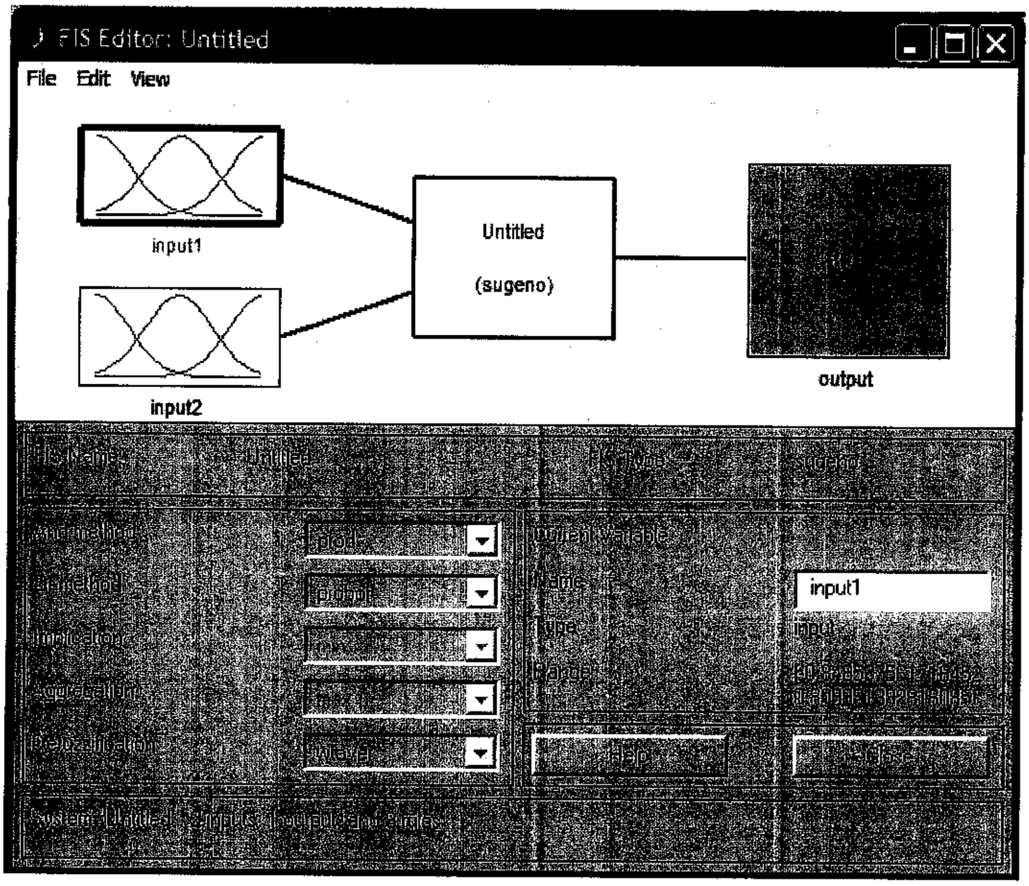
II.1: Loading the training data.



II.2: Setting up the membership functions for the training.



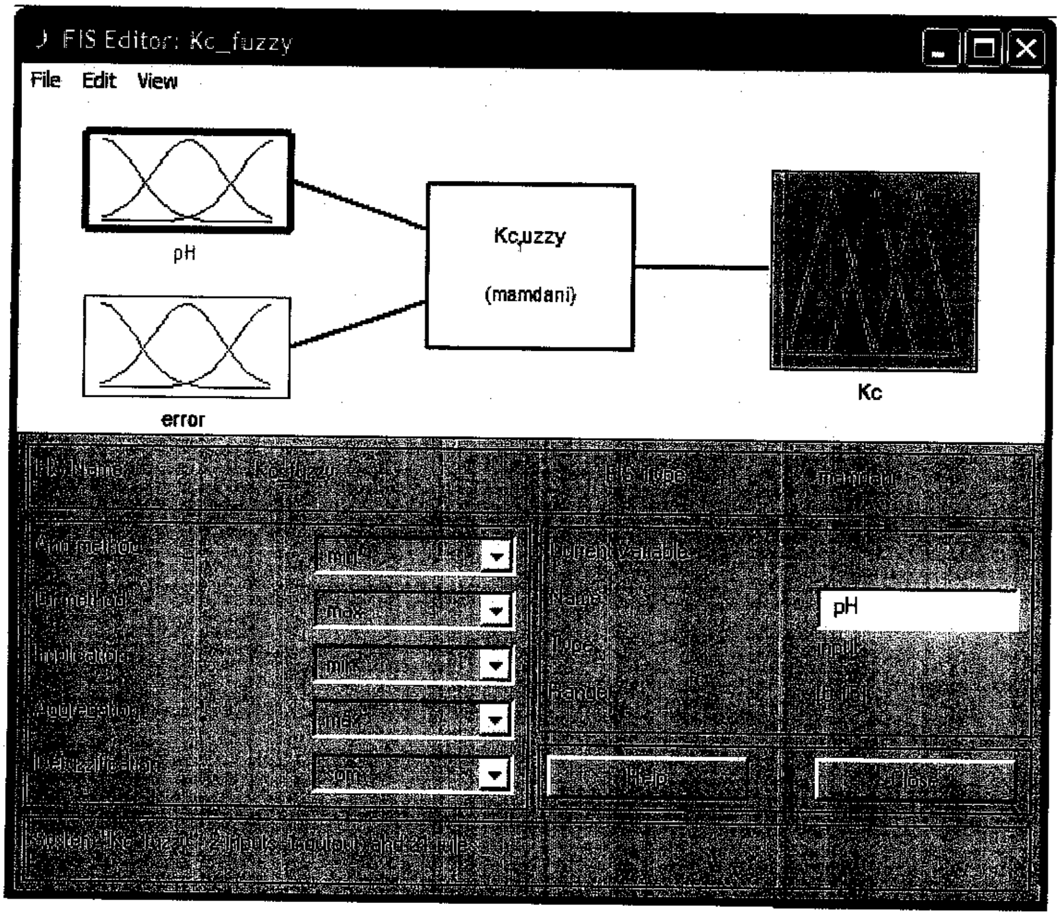
II.3: Result from the training.



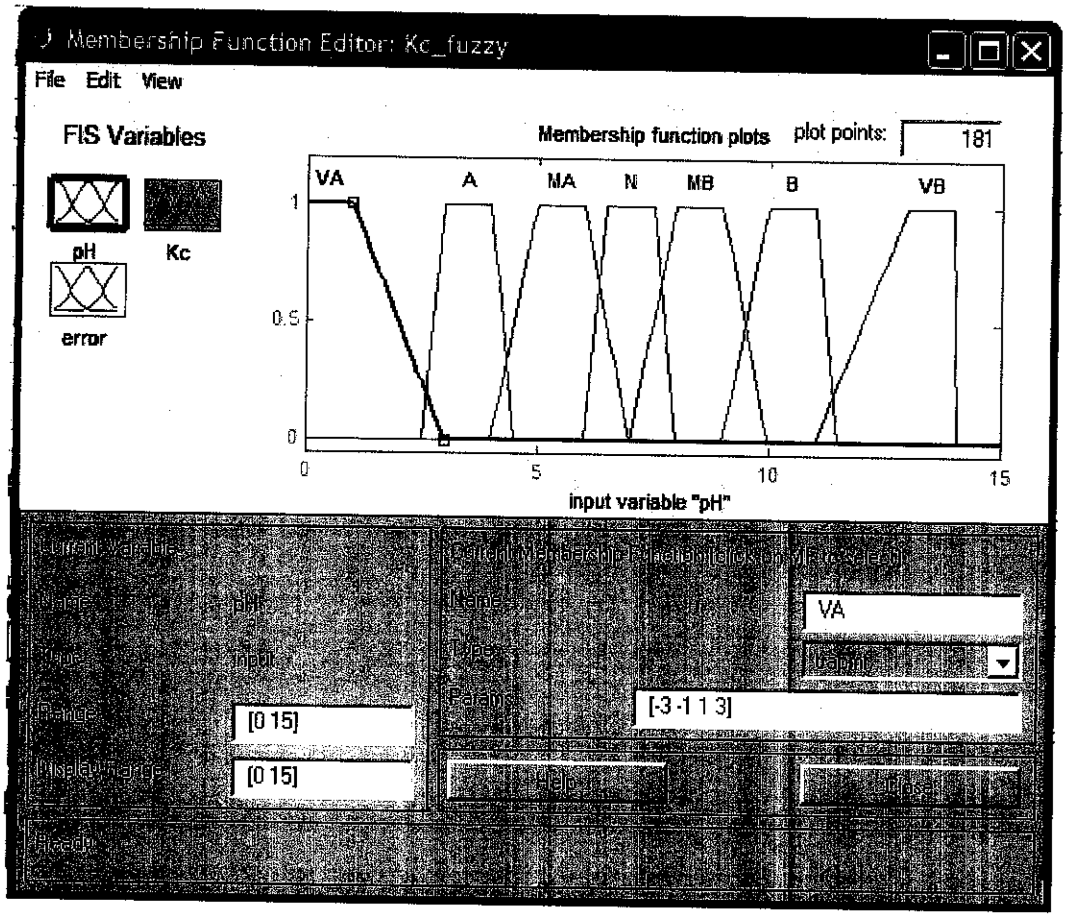
II.4: The Fuzzy Interference System (FIS) from the ANFIS training.

Appendix III

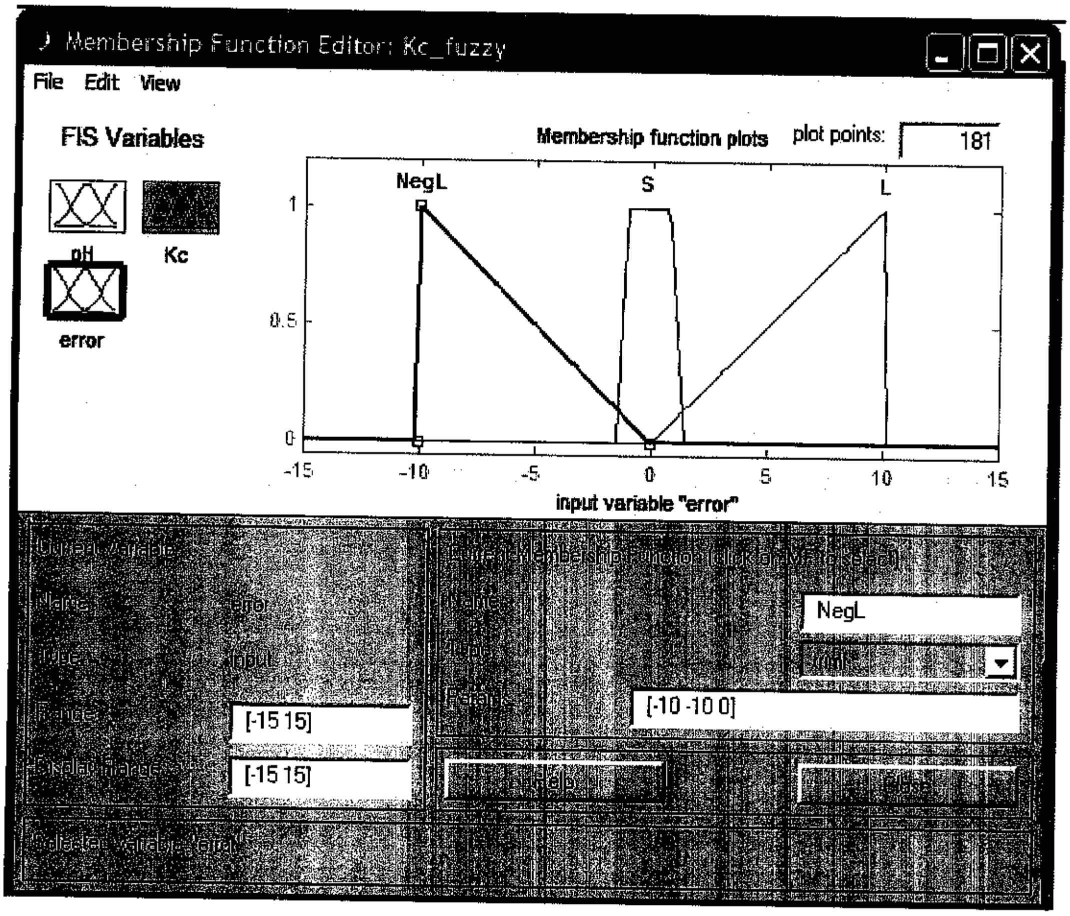
K_p fuzzy rules



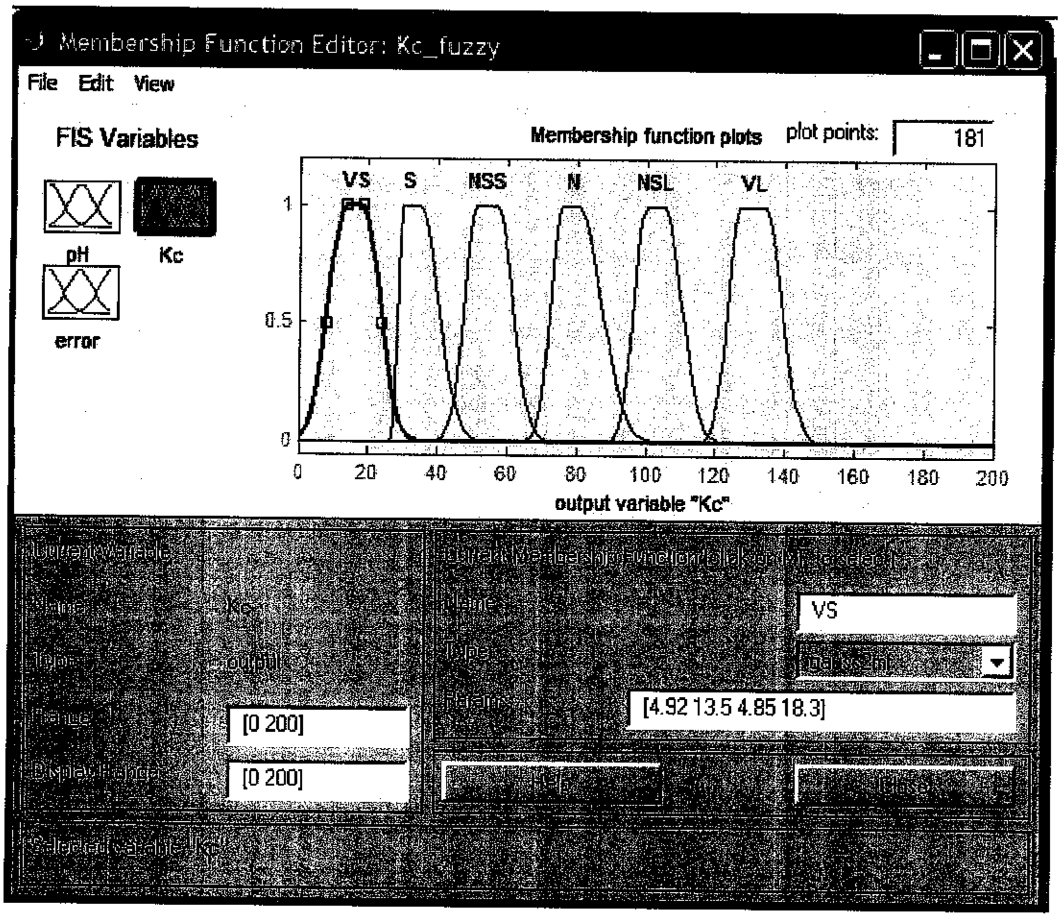
III.1: Fuzzy Inference System (FIS) for K_p.



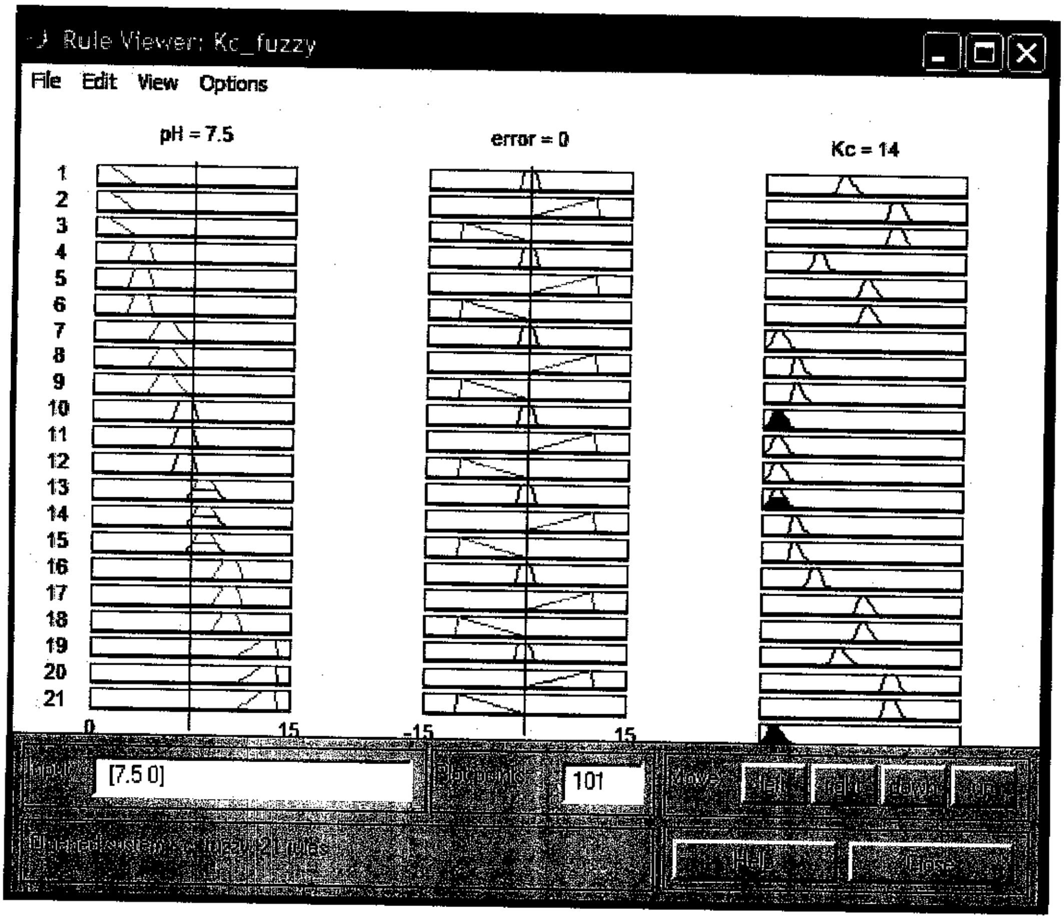
III.2: The membership functions for input pH.



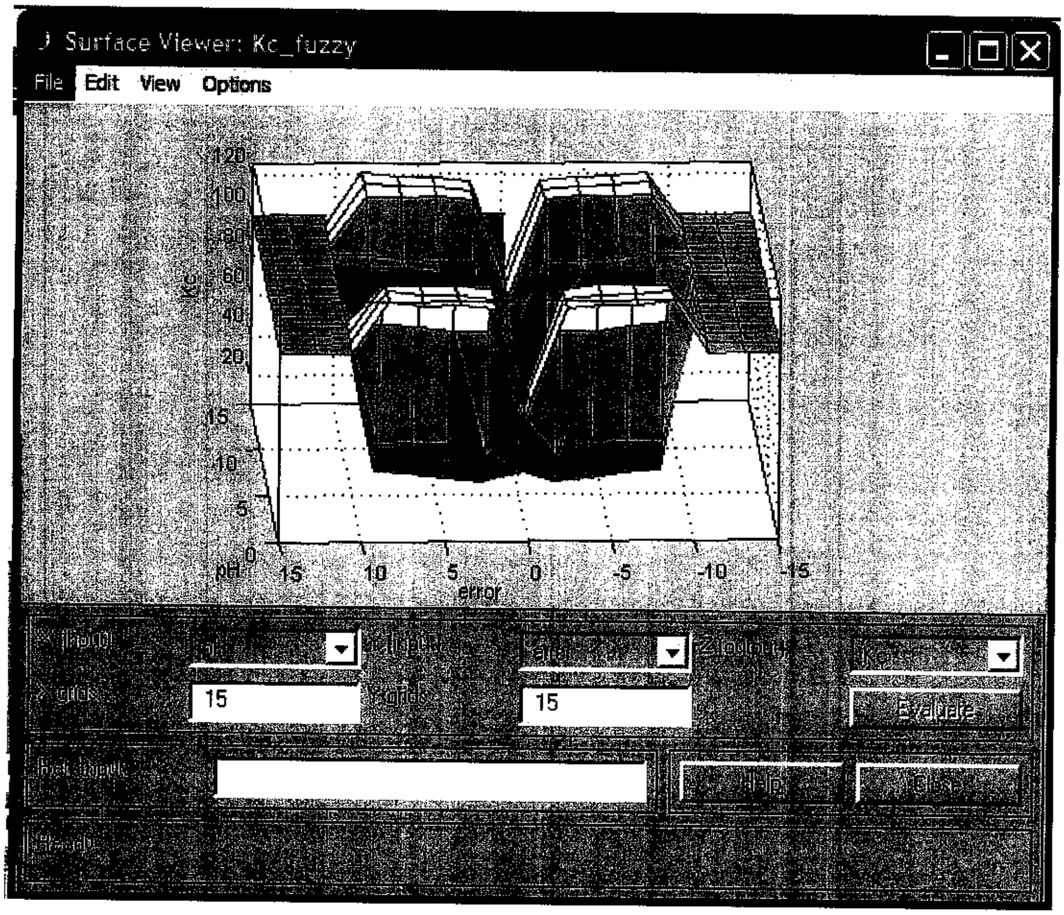
III.3: The membership functions for input error pH.



III.4: The membership functions for output K_p.



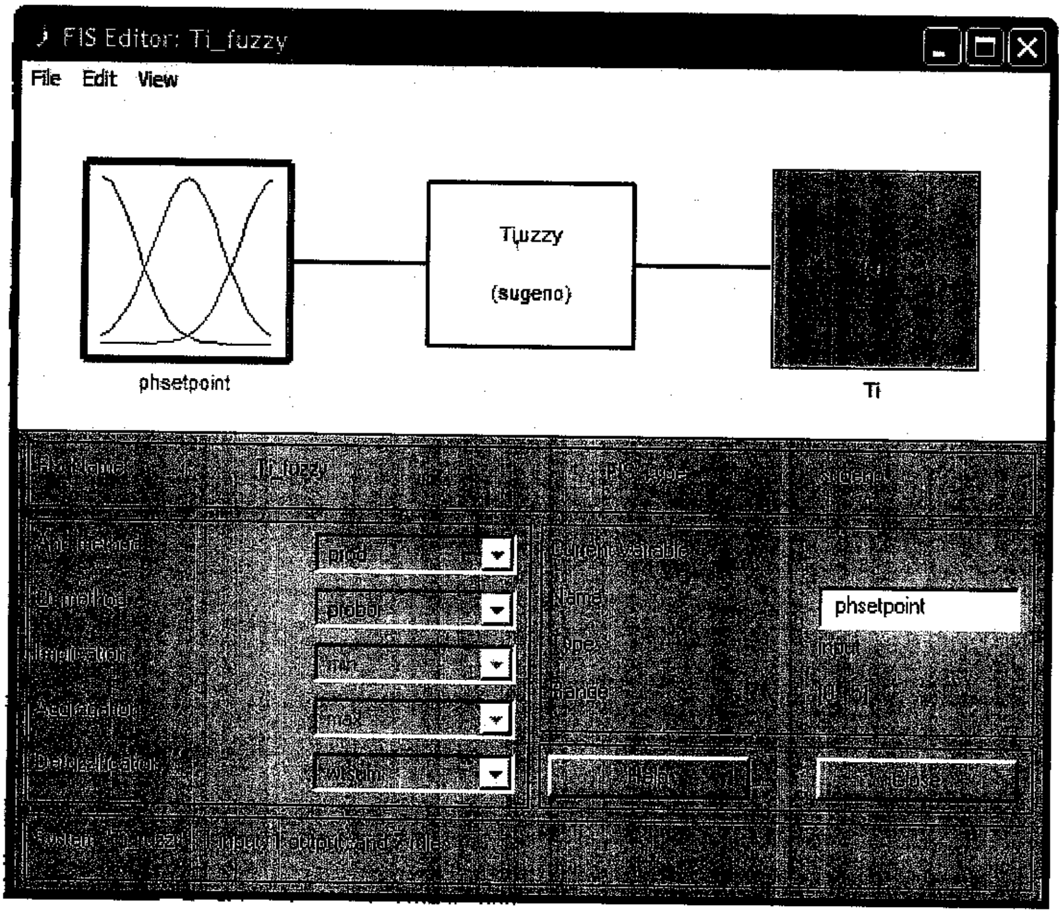
III.5: The rules based on the K_p FIS.



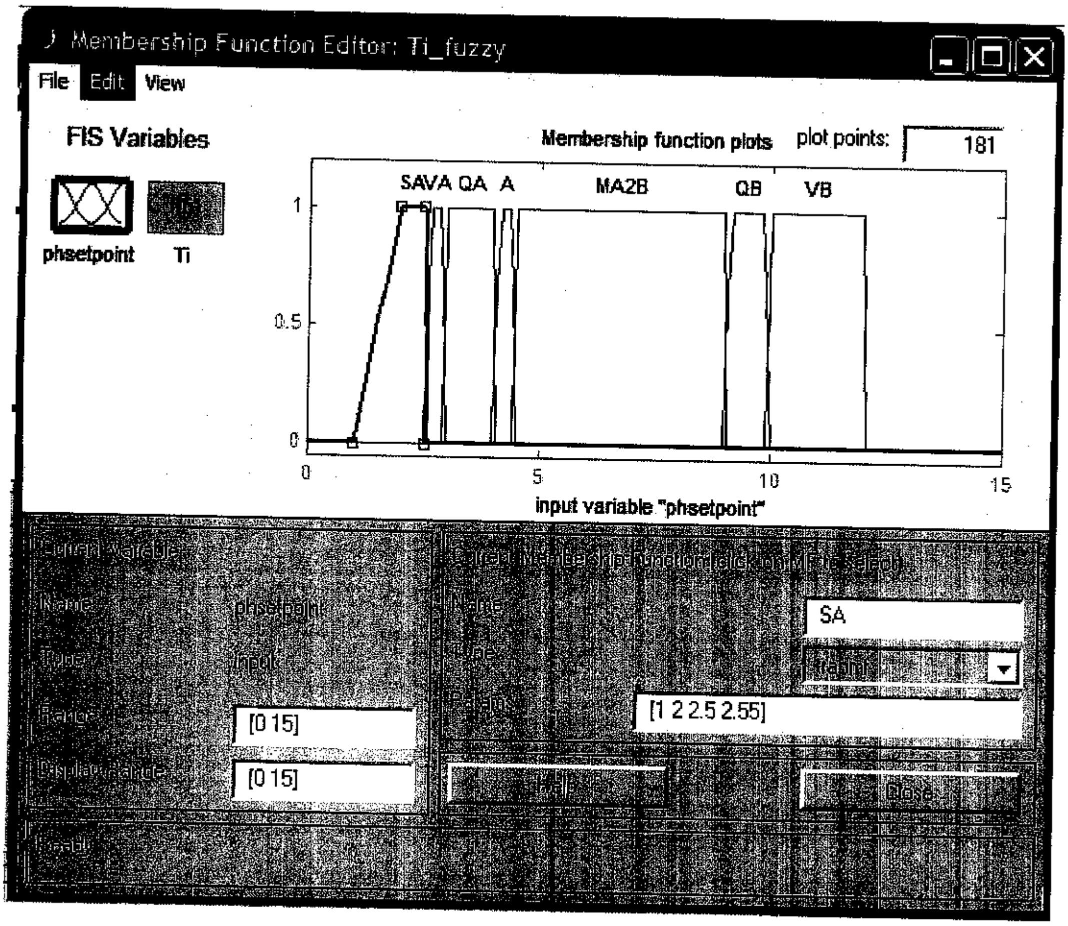
III.6: 3-dimentional view of the input-output relationships of pH, error pH and K_p.

Appendix IV

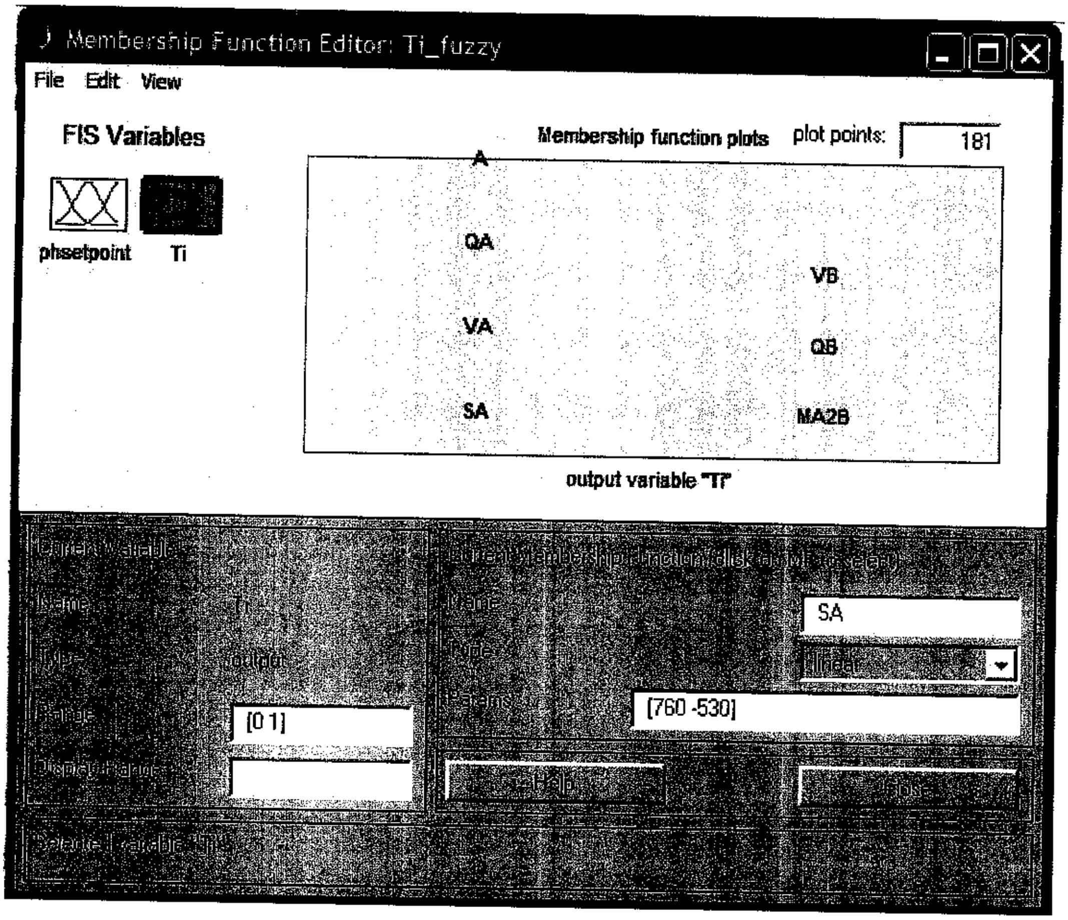
T_i fuzzy rules



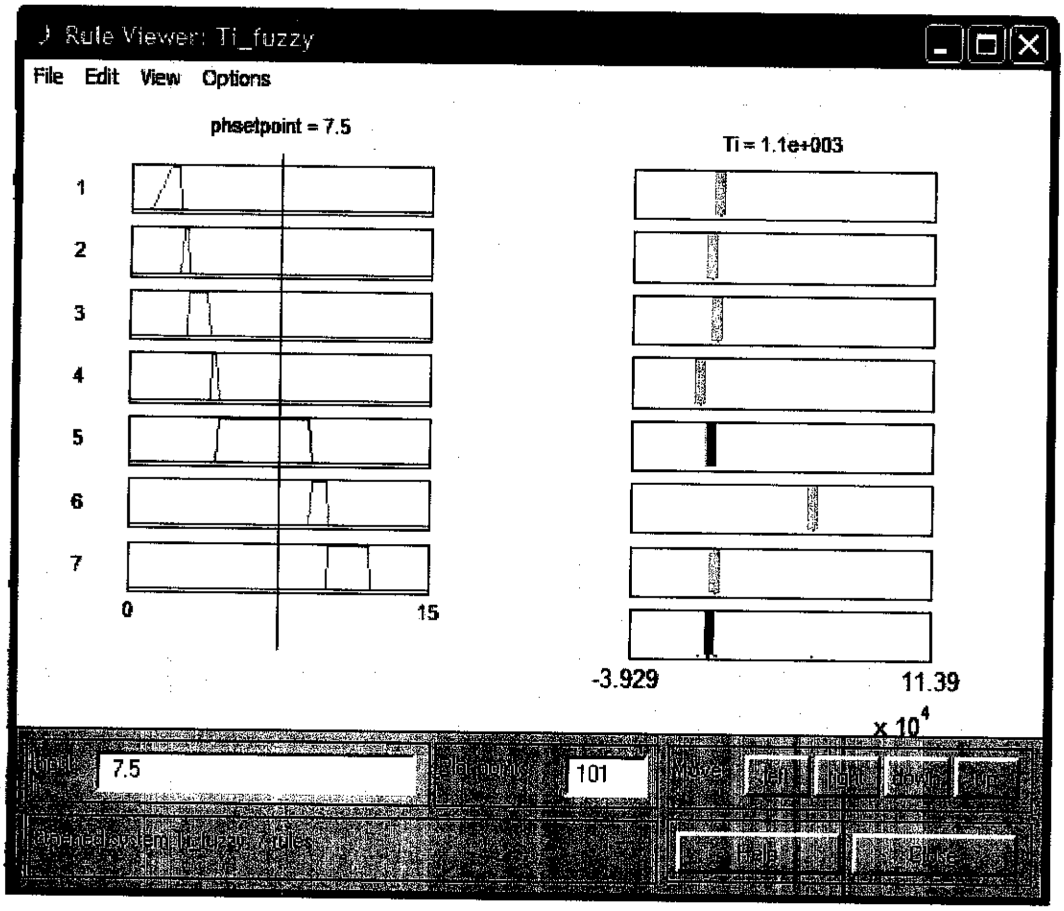
IV.1: **Fuzzy Inference System (FIS) for T_i.**



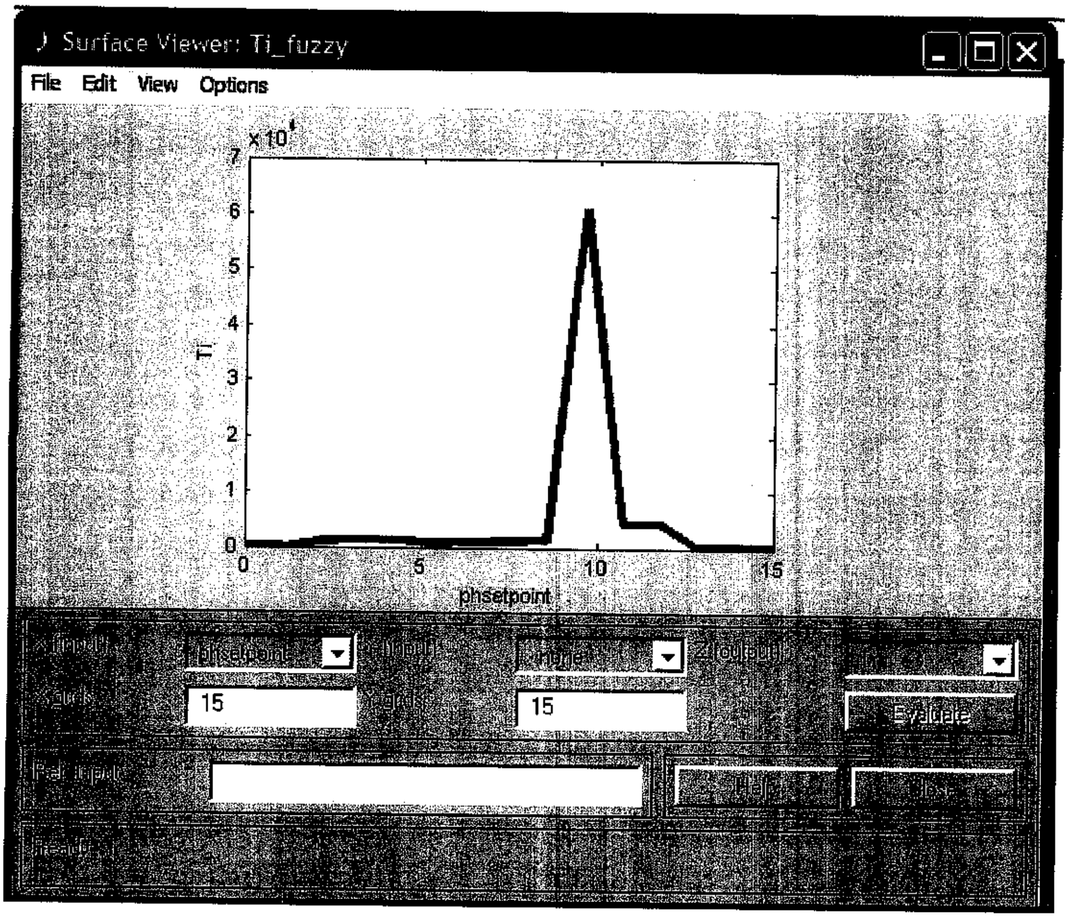
IV.2: The membership functions for input pH set point.



IV.3: The membership functions for output T_i.



IV.4: The rules based on the T_i FIS.



IV.5: 2-dimentional view of the input-output relationships of input pH set point and T_i.