

PERFORMANCE ANALYSIS OF INTERNAL MODEL CONTROLLER

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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Approved:



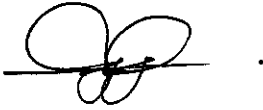
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June 2005

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.



Imran bin Jumain

ABSTRACT

The topic chosen for the Final Year Project is **Performance Analysis of an Internal Model Controller (IMC)**. The project is conducted by comparing the performances between the Internal Model Controller and the conventional PID Controller. A lot of studies of various controllers have been done. This is why the project is conducted where to have better understanding on the implementation of Internal Model Controller to any system. The purpose of the research is to present more evidence of IMC; some of the advantages and limitation.

The project has been conducted using the UTP pilot plant 6. The temperature loop (TIC 634) controlled by the control valve (FY631) is used throughout the project. This plant system currently utilizes the conventional PID Controller.

The empirical modeling technique (process reaction curve) has been chosen to be the modeling technique throughout the project period based on the analysis conducted during the first semester of the project.

The generated model becomes important when the author needs to design and implement the controller in order to minimize the error of the system. In other words, the controller is implemented to ensure the output response reaches its steady state value without experiencing large overshoot and longer settling time.

By comparing all the results and analysis, it shows that IMC has a better result in tuning. Only one variable, λ is tuned for IMC compared with PID which required tuning three (3) variables; proportional, integral and derivative. IMC can also be tuned to improve the performance of the system.

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LIST OF ABBREVIATIONS

No.	Abbreviation	Description
1	CV	Control Variable
2	DCS	Distributed Control System
3	FODT	First Order with Dead Time
4	FYP	Final Year Project
5	IAE	Integral Absolute Error
6	IMC	Internal Model Controller
7	MATLAB	Mathematics Laboratory
8	MV	Manipulated Variable
9	PETRONAS	Petroleum Nasional Berhad
10	PID	Proportional Integral Derivative
11	P&ID	Piping & Instrument Diagram
12	PPCS	Plant Process Control System
13	PRC	Process Reaction Curve
14	TIC	Temperature Indicator Controller
15	TT	Temperature Transmitter
16	UTP	Universiti Teknologi PETRONAS
17	%OS	Overshoot percentage

CHAPTER 1

INTRODUCTION

1.1 Background of Study

This project deals with application studies of the Internal Model Controller (IMC). Comparisons will be made between the basic IMC, conventional PID controller and also the IMC based PID controller. The author will also have to gain knowledge on several modeling techniques, such as empirical and statistical modeling methods.

At the early stage of the project, the author is require to study on theory of the system identification and familiarization of MATLAB command function to be used in the command window. It includes the familiarization on the system identification loop with recorded data, model structure, and also determination of the best model and best validation. Student will also be involved in several experimentations and analysis during the modeling.

Some theoretical knowledge learnt on the electrical & electronics engineering subjects such as Industrial Automation and Control System, Plant Process Control Systems, Control Systems I and II will be applied throughout the project. The basic knowledge of using MATLAB (Simulink), Distributed Control System and Heat Exchanger also will be used during the project period. .

1.2 Problem Statement

Some study and research on the Internal Model Controller have been done through the decades. The project requires the author to analyze the performance of the Internal Model Controller compared to other controller. The purpose of the research is to

present more evidence of IMC; some of the advantages and limitation. Currently all the UTP's pilot plants are utilizing the conventional PID Controller.

As the project goes on, the author required to implement the Internal Model Controller to one of the UTP's pilot plant and perform the analysis whether Internal Model Controller able to give a better performance compared with the conventional PID controller. The Drum Heat Exchanger Process Plant is chosen to implement the Internal Model Controller throughout the project period. So, at the end of the project, author should be able to identify whether the Internal Model Controller has a better performance than the conventional PID Controller.

1.3 Objectives

The objectives that to be achieved for the project are:

- To model the heat exchanger temperature control loop using the empirical modelling technique.
- To design the Internal Model Controller for the heat exchanger.
- To compare the performance of the Internal Model Controller with the conventional PID Controller.

1.4 Scope of Study

For the first phase, the study deals with modeling techniques for control system such as empirical modeling and statistical modeling. Data from the plants was recorded in the Plant Process Control System Laboratory. Part of the modeling work and simulation will be conducted using Simulink (MATLAB) software. At the end of the first semester, the author must be able to propose a model of the heat exchanger plant with the best accuracy reliability.

For the second phase, the author will undertake to design and simulate the Internal Model Controller. All the performances analysis also will be done throughout this period.

CHAPTER 2

LITERATURE REVIEW / THEORY

2.1 Heat Exchanger

Heat Exchanger is commonly found in PETRONAS chemical-processing plants. Of many heat exchanger designs, focus is given to the shell-and-tube-type; the one that is available at UTP Pilot Plant and has been used for plant data acquisition of the project. **Figure 1** below shows the internal design of the shell-and-tube-type heat exchanger.

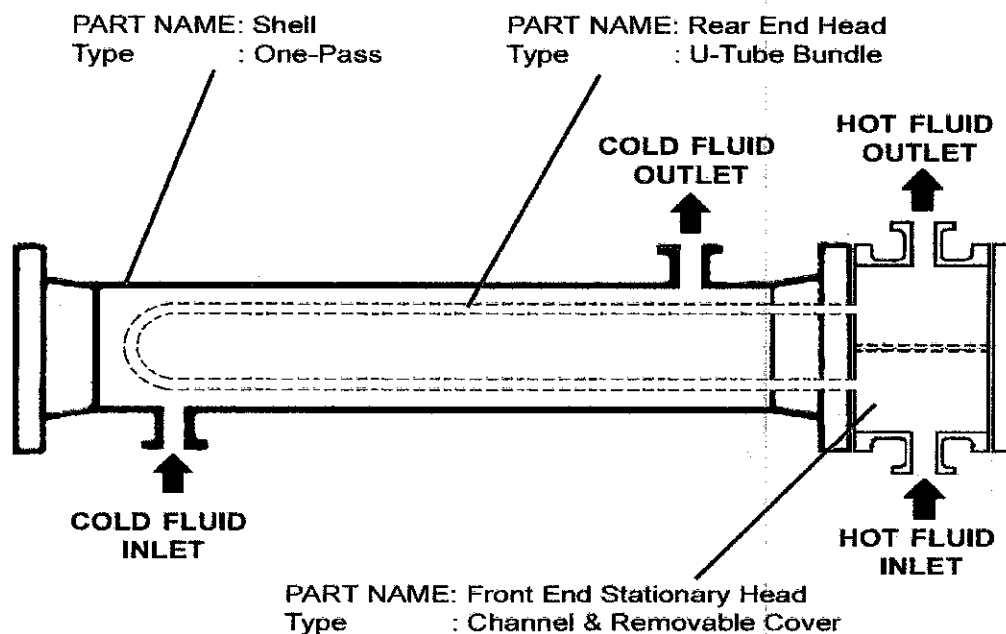


Figure 1 Shell-and-Tube-Type heat exchanger.

Generally, a typical shell-and-tube-type heat exchanger constitutes the bulk of unfired heat-transfer equipment. The hot fluid (water or steam) is used to transfer heat to the cold fluid, which in this case is the process fluid, at certain temperature as it flows

through the shell and made contact with the hot U-tube bundle. The heated process is then immediately cooled via a cooler (i.e. cooling tower) after it leaves the shell via the cold fluid outlet pipe.

In controlling the amount of heat exchange, the temperature of the cold fluid (controlled variable, CV) is measured at the cold fluid outlet pipe. Any deviation of the temperature measurement from its set point will result in the control valve at the hot fluid inlet pipe (manipulated variable, MV) being adjusted accordingly in order to increase or decrease the flow of the hot fluid into the front end part of the heat exchanger. Such action will bring the deviated temperature back to its set point. The control strategy used in achieving this objective is called feedback control.

2.2 Empirical Modelling

The process model, $G_p(s)$, is obtained empirically. Empirical model identification procedure is a very efficient modelling method specifically designed for process control. *The model developed using this method provide the dynamic relationship between selected input and output variables with $\pm 20\%$ model errors, and is limited to the first-order-with-dead-time models only.*

It is common to model an input – output response based on step responses. In this procedure, the process was first brought to a consistent and desirable steady state operating point, and then a step change is made in the input variable. An important decision at this point is the magnitude of the step change to make.

- If the step change in the change in input is too small, the measured output may not be sufficiently perturbed to develop a reliable model. This is particularly true if the measured output is noisy. Clearly, the magnitude of the step input must be enough so that the output signal to noise ratio is high enough to obtain a good model.
- If the step change in the input is too large, the output variable may change too much and does not reflect the true nature of the plant. This may also be

undesirable because of severe economic penalty. Also if the step input change is too large, non linear effect may dominate. That is, the operating condition may become significantly different than the desired condition.

2.3 Internal Model Controller Structure [2]

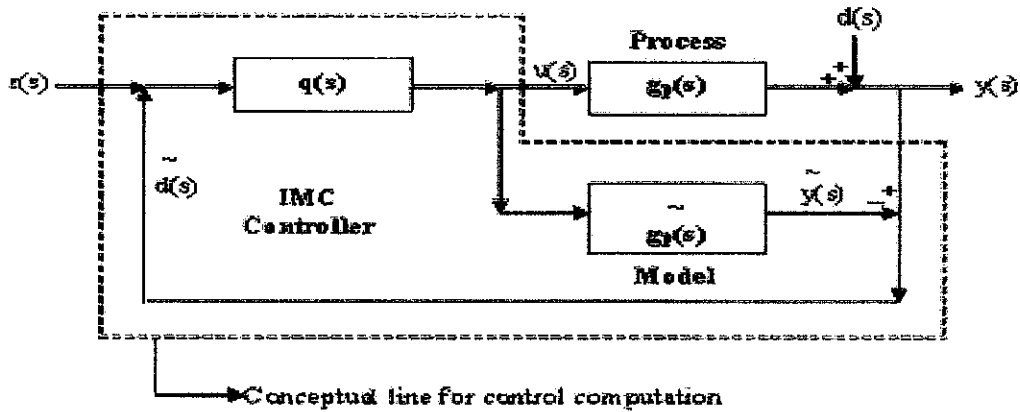


Figure 2 Standard IMC structure

The distinguishing characteristic of this structure is the process model, which is in parallel with the actual process (plant). Note that (\sim) is generally used to represent signal associated with the model. Lists of transfer function variable shown in the IMC block diagram are given below:

- $d(s)$ = disturbance
- $\tilde{d}(s)$ = estimated disturbance
- $g_p(s)$ = process
- $\tilde{g}_p(s)$ = process model
- $q(s)$ = internal model controller
- $r(s)$ = set point
- $\tilde{r}(s)$ = modified set point (correct for model errors and disturbances)
- $u(s)$ = manipulated input (controller output)
- $y(s)$ = measured process output

$\tilde{y}(s)$ = model output

Notice that the feed back signal is:

$$\tilde{d}(s) = (g_p(s) - \tilde{g}_p(s)) u(s) + d(s)$$

And the signal to the controller is:

$$\begin{aligned} \tilde{r}(s) &= r(s) - \tilde{d}(s) \\ &= r(s) - (g_p(s) - \tilde{g}_p(s)) u(s) - d(s) \end{aligned}$$

The reasons for feedback control include the following:

- Unmeasured disturbances
- Model uncertainty
- Faster response than the open loop system (with static controller)
- Closed loop stability of open loop unstable system.

There also some **limitation** in certain cases where:

a. Perfect model with no disturbance

If the model is perfect ($g_p(s) = \tilde{g}_p(s)$) and there is no disturbance ($d(s) = 0$), then the feedback signal is zero. The relationship between $r(s)$ and $y(s)$ is then

$$y(s) = g_p(s) q(s) r(s)$$

So, the relationship is the same with an open loop control system design.

b. Perfect model with disturbance effect

If the system perfect ($g_p(s) = \tilde{g}_p(s)$) and there is a disturbance, then the feedback signal is

$$\tilde{d}(s) = d(s)$$

This illustrates that the feedback is needed because of unmeasured disturbance entering the process.

c. Model uncertainty with no disturbance

If there are no disturbances ($d(s) = 0$) but there is model uncertainty ($g_p(s) \neq \tilde{g}_p(s)$), which is always the case in the real world, then the feedback signal is

$$\tilde{d}(s) = (g_p(s) - \tilde{g}_p(s)) u(s)$$

This illustrates that feedback is needed because of model uncertainty. The close loop relationship is thus:

$$y(s) = \left(\frac{g_p(s) q(s)}{1 + q(s)(g_p(s) - \tilde{g}_p(s))} \right) r(s) + \left(\frac{1 - \tilde{g}_p(s)q(s)}{1 + q(s)(g_p(s) - \tilde{g}_p(s))} \right) d(s)$$

2.4 IMC-Based PID (Equivalent Feedback Form to IMC)

The derivation of standard feedback equivalence to IMC is using the block diagram manipulation. Begin with the IMC structure shown in **Figure 3**; the point of comparison between the model and process output can be moved as in **Figure 4**. **Figure 4** can be rearranged to the form of **Figure 5**. As the result the IMC structure can be rearranged to the feedback control structure, as shown in **Figure 6**. The reformulation is advantageous because the PID controller often results when the IMC design procedure is used. The feedback from must be used for unstable process.

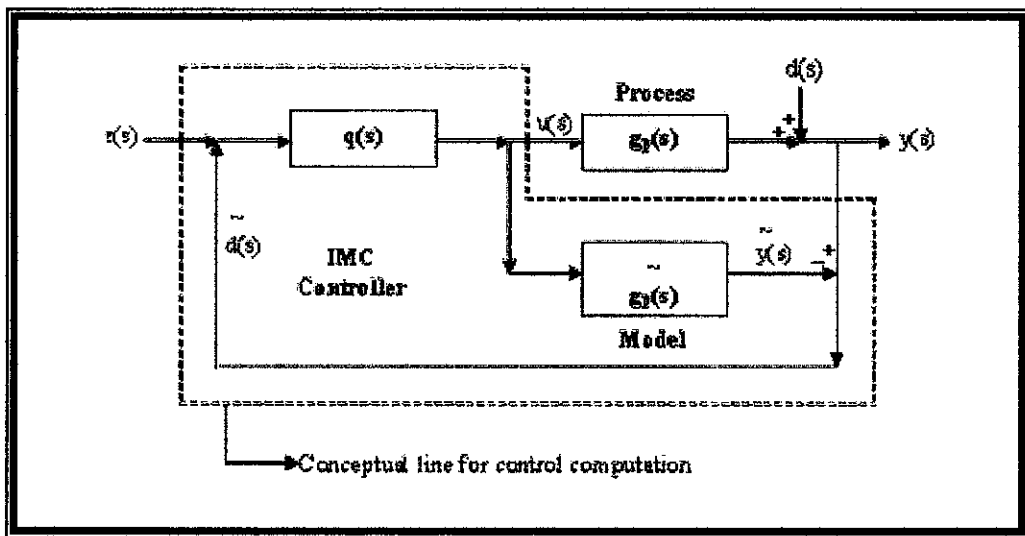


Figure 3 IMC structure

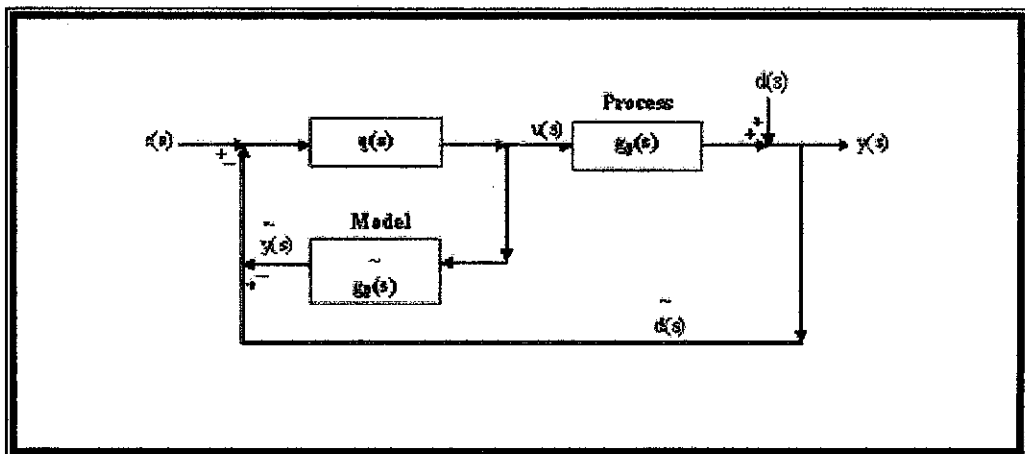


Figure 4 Cosmetic change in IMC

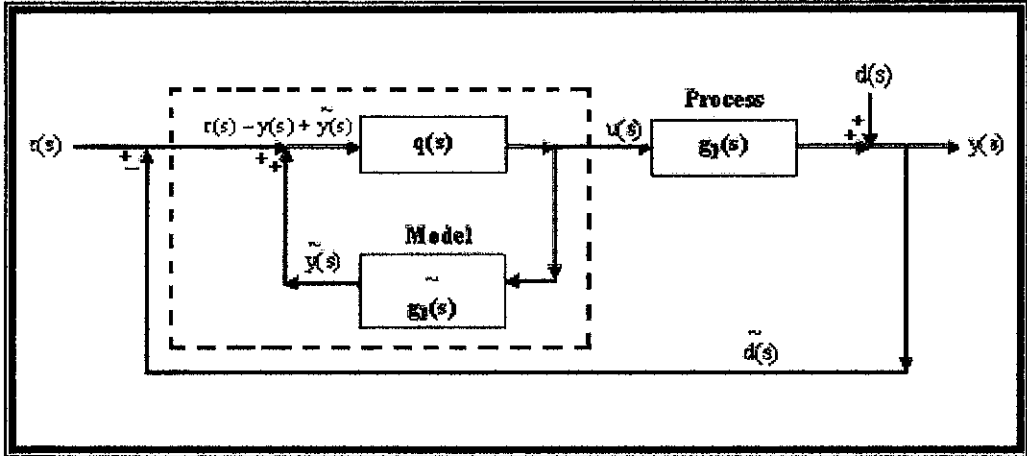


Figure 5 Rearrangement of IMC structure

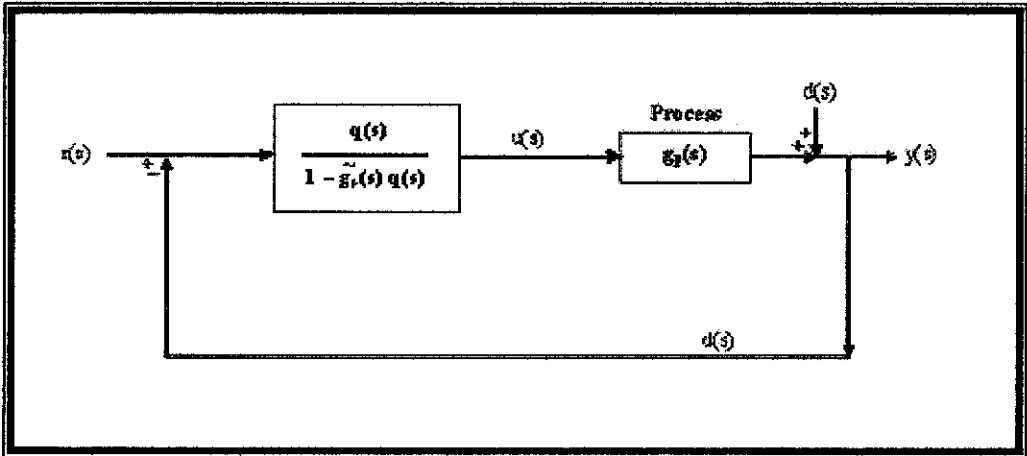


Figure 6 Standard feedback diagram illustrating the equivalence with IMC

CHAPTER 3

METHODOLOGY

The procedures of the project should be identified to have an appropriate management for the Final Year Project schedule and to make sure that the project flow is more systematic.

3.1 Literature Review

Literature review plays significant impact to strengthen the basic knowledge about anything related to the project. Internet is the main source for the study, as well as books, journals, articles and reports done by any researcher in this field. MATLAB need to be revised in order to familiarize with the coding (syntax) and Simulink application.

The author also required to understand the plant loop process (Heat Exchanger temperature control – TIC634). The temperature at TT634 is controlled by the flow at control valve 631). The P&ID or the loop diagram is shown in **Appendix A**.

3.2 Project Planning

Since this project has been planned for two semester work, the project plan should be scheduled in such a way that can fix the time for the two semesters. The author and supervisor can easily monitor the progress of the project. For the first semester, the study will cover the modeling techniques for the heat exchanger plant by using the empirical and statistical modeling. Most of the plants works will be done in the Plant Process Control System Laboratory. Some of the modeling and all the simulation will be based on the Simulink (MATLAB) software.

For the first phase, author should be able to state the best method to have the accurate transfer function of the heat exchanger plant.

By right for the second phase, author has to deal with the modeling, designing, and simulation of the controller. At the end, the performance analysis should be done to compare the performance of both conventional PID controller and IMC.

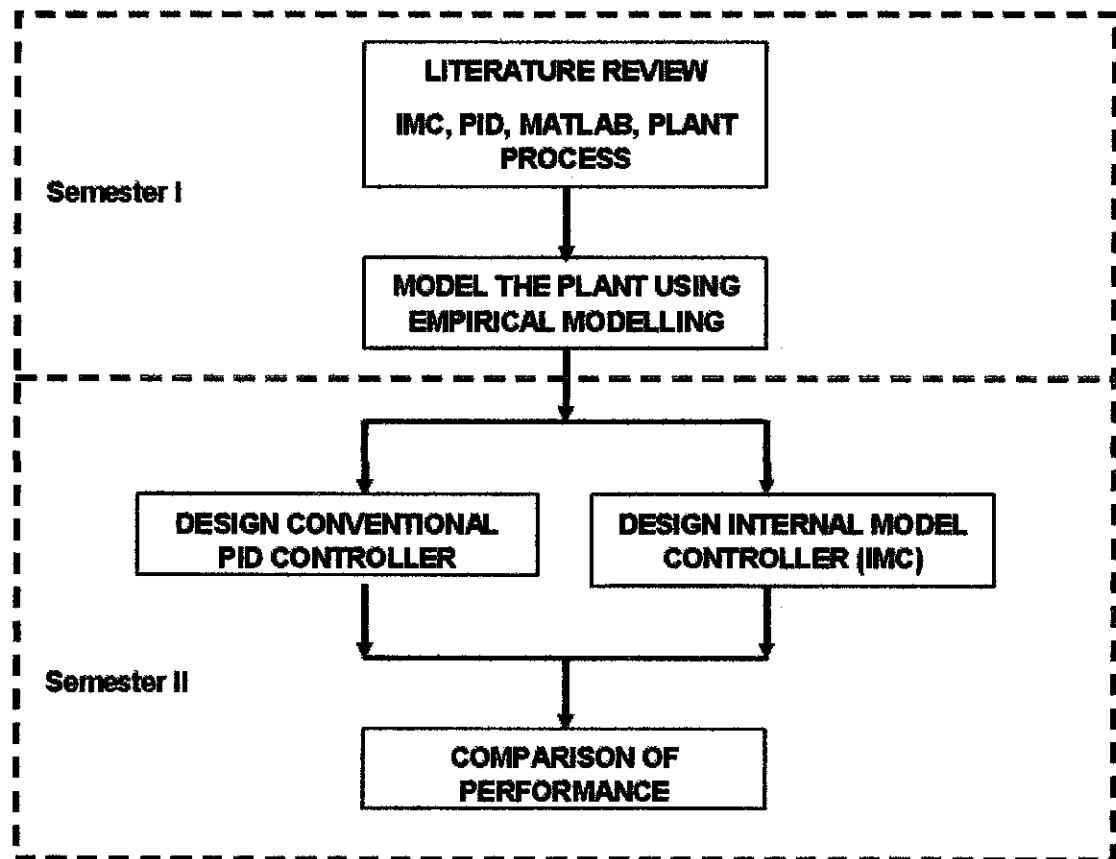


Figure 7 Project methodology

3.3 Tools and Equipment Used

MATLAB is the main software that is used in this simulation. The UTP pilot plant which is Plant 6 (Heat exchanger temperature control loop) in the plant process control system (PPCS) Laboratory will be used throughout the project period. The Distributed Control System (DCS) used by the laboratory is manufactured by Pc Automation Sdn. Bhd. The manual procedure to setup the loop control is attached in the **Appendix B**.

i. Experimental design

An important yet an often underestimated aspect of empirical modelling is the need for proper experimental design. Since every method requires some type of input perturbation, the design determines its shape and duration. It also determines the base operating conditions for the process, which essentially determine the condition about which the process model is accurate. The magnitude of the input perturbation is determined. The design requires a priori information about the process and its dynamic responses. The result of this step is a complete plan for the test which should include

1. A description of the base operating conditions.
2. A definition of the perturbations.
3. A definition of the variables to be measured, along with the measurement frequency.
4. An estimate of the duration of the experiment.

ii. Plant experiment

The experiment should be executed as close to the plant as possible. Large disturbances during the experiment can invalidate the result. Therefore, plant operation should be monitored during the experiment since the experiment is designed to establish the relationship between one input and output, changes in other input during the experiments could make the data unusable for identifying dynamic model. The data collected from the plant is restructured into tabular form which is attached in the **Appendix J**.

For an open loop system, a small change for the manipulated variable (as input) is introduced to generate the dynamic response of process variable (as output). MV was manually increased by 20% control valve opening (TIC634) and the temperature curve (TT 634) was observed. The process dynamic curve for TT 634 is shown in the **Appendix C**.

iii. Determine model structure

The initial structure is selected based on prior knowledge of the unit operation, perhaps based on the structure of the fundamental model, and based on patterns in the experimental data collected. The goal is not to develop a model that exactly matches the experimental data. Rather, the goal is to develop a model that describes the input-output behavior of the process adequately for use in process control.

iv. Parameter estimation

At this point a model structure has been selected and data has been collected. Two methods are used to determine values for the model parameters so that the model provides a good fit to the experimental data. One method uses graphical technique; and the other one uses statistical principles. Both methods provide estimates for parameters in transfer function models, such as gain, time constant and dead time for the first order with dead time model.

v. Diagnostic evaluation.

Some evaluation is required before the model is used for control. The diagnostic level of evaluation determines how well the model fits the data used for parameter estimation the diagnostic evaluation can used two approaches:

1. Comparison of the model prediction with the measured data.
2. Comparison of the results with any initial process variable

vi. Model verification

It is appropriate to emphasize once again that the model develops by this procedure relates the input perturbation to the output response of the process,

including all equipment between the input and output. Thus the typical model includes the dynamics of valves, sensors and other related process equipment.

Two objectives must always be balanced in performing the experimental procedure, especially in a real plant environment:

1. Maintenance of safe, smooth and profitable plant operation, for which a small experimental input perturbation is required.
2. Development of an accurate model for process control design that will be improved by a relatively large input perturbation.

The Process reaction curve is probably the most widely used method 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 input and output response data until the process again reaches steady state.
4. Perform the graphical process reaction curve calculation.

3.4.2 Process Reaction Curve [1]

The process reaction curve is probably the most widely used empirical method for identifying the dynamic model. The process reaction curve method involves the following four steps:

1. Process is allowed to reach the steady state.
2. A step change is introduced in the input variable.
3. Input and output response data is collected until the process again reaches steady state.
4. Graphical process reaction curve calculation is performed.

The graphical calculations is determined the parameters for the first order model with dead time. The form of the model is as follows, with $X(s)$ denoting the input and $Y(s)$ denoting the output, both expressions in deviation variables:

$$Y(s) / X(s) = K_p e^{-\theta s} / \tau s + 1$$

Where:

$$K_p \text{ (gain)} = \Delta / \delta$$

$$\delta = \text{input change}$$

$$\Delta = \text{magnitude of the steady state change in the output}$$

$$\tau = \Delta / S$$

$$S = \text{maximum slope}$$

$$\theta = \text{intercept of maximum slope with initial value}$$

There are two different graphical techniques in common use. **Method I** uses the graphical calculation shown in **Figure 1**. The values determined from the graph are the magnitude of the input change, the magnitude of the steady state change in the output and the maximum slope of the output versus time plot.

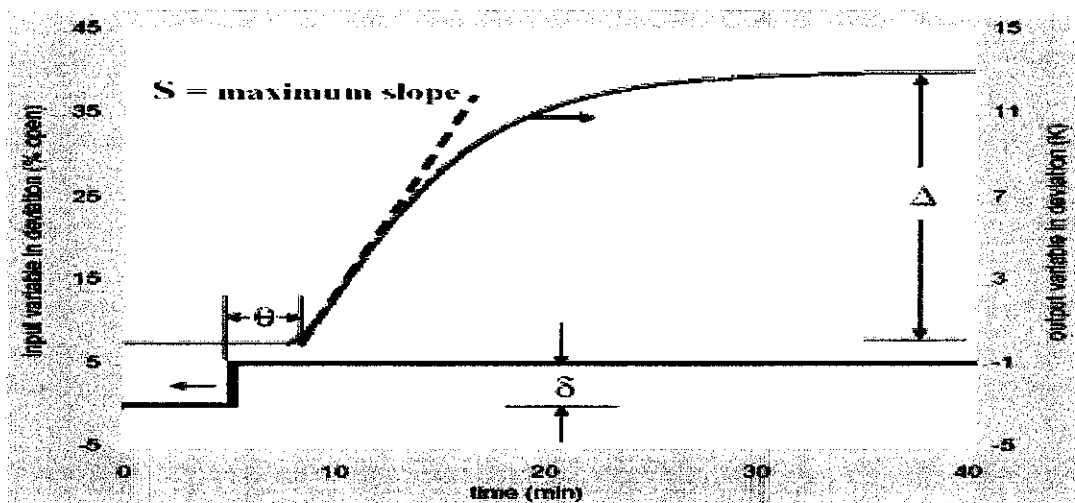


Figure 9 Empirical modelling – Method I

Method II uses the graphical calculation shown in **Figure 9**. The values determined from the graph are the magnitude are the magnitude of the input change, the

magnitude of the steady state change in the output, and the times at which the output reaches 28 and 63 percent of its final value. This two values are selected to determine the unknown parameters, θ and τ . The typical times are selected where the transient response is changing rapidly so that the model parameters can be accurately determined in spite of measurement noise. The expressions are

$$Y(\theta + \tau) = \Delta (1 - e^{-1}) = 0.632 \Delta$$

$$Y(\theta + \tau/3) = \Delta (1 - e^{-1/3}) = 0.283 \Delta$$

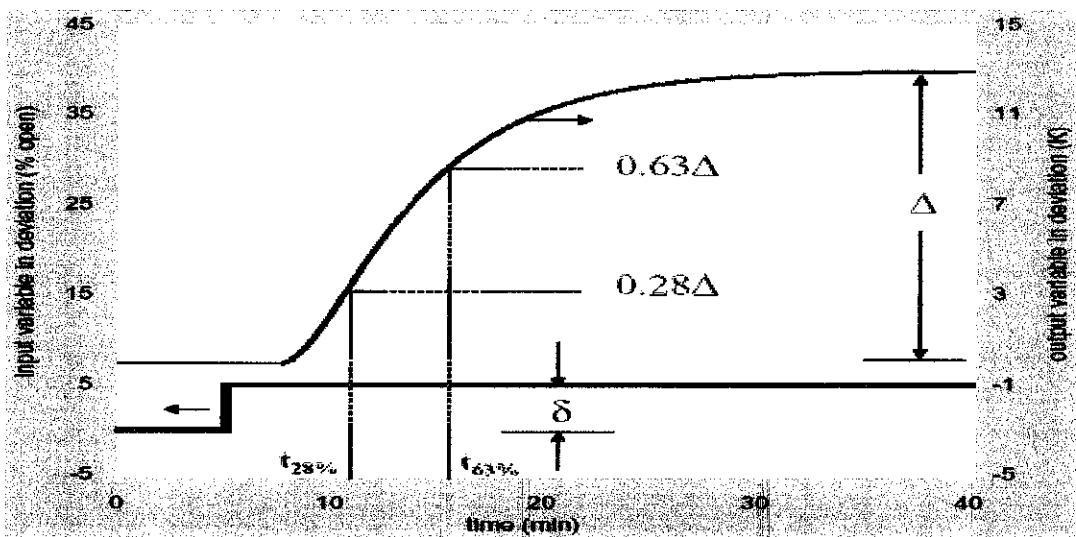


Figure 10 Empirical modelling – Method II

Thus, the values of time at which the output reaches 28.3 and 63.2 percent of its final value are used to calculate the model parameters.

$$t_{28\%} = \theta + \tau/3$$

$$t_{63\%} = \theta + \tau$$

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

$$\theta = t_{63\%} - \tau$$

Where:

$$K_p \text{ (gain)} = \Delta/\delta$$

$$\delta = \text{input change}$$

$$\Delta = \text{magnitude of the steady state change in the output}$$

$$\tau = \Delta/S$$

S = maximum slope

θ = intercept of maximum slope with initial value

3.5 Conventional PID Controllers (*Ciancone Coerrelation and Ziegler-Nichols*)

Two tuning methods have been evaluated prior to the tuning procedure. The methods, namely *Ciancone Coerrelation and Ziegler-Nichols*, have different control objectives.

The *Ziegler-Nichols* Tuning Method aims to have an underdamped initial CV dynamics with 4:1 decay ratio. It does not concern about the MV performance and the controller designed using this method is less robust compared to the controller designed using the *Ciancone* method. However, it guarantees the system to be maintained in the safe margin of stability. In common industry practice, the desired control performance is usually set to have one goal, which is usually to achieve the CV performance of at least 4:1 decay ratio.

Ziegler-Nichols closed loop with Bode plot:

- i. The amplitude ratio and the phase angle in a form of Bode plot is plotted for $G_{OL}(s)$. At this step, the controller is a proportional only algorithm with the gain K_c set to 1.
- ii. The critical frequency and the amplitude ration at the critical frequency are determined. The value of the gain for the proportional only controller that would result in the feedback system being in the stability margin is calculated.

$$\text{Ultimate Gain: } K_u = \frac{1}{|G_p(j\omega)|}$$

$$\text{Ultimate Period: } P_u = 2\pi / \omega_c$$

- iii. The tuning algorithms, k_c , τ_I and τ_D are calculated based on the Ziegler-Nichols Tuning method.

The *Ziegler-Nichols* with Bode Plot tuning method involves calculating the initial tuning parameters which shown in **Table 1** below:

Controller Type	k_c	τ_I	τ_D
P	0.5 K_u	-	-
PI	0.45 K_u	0.83 P_u	-
PID	0.6 K_u	0.5 P_u	0.125 P_u

Table 1 Initial tuning parameter for Ziegler-Nichols with Bode Plot tuning method

The *Ciancone* Tuning Method aims to have the initial CV dynamics with minimum IAE and the initial MV dynamics within the defined boundary line. The controller designed using this method is also robust, where it is able to perform good control over noisy CV with $\pm 25\%$ error in the model parameters. However, it does not guarantee the system to be maintained in the safe margin of stability. The *Ciancone* method involves calculating the fraction dead time, $[\theta/(\theta + \tau)]$, and obtaining the respective tuning constants by referring to the standard *Ciancone* Tuning Correlations Chart as shown in **Appendix I**.

Ciancone Correlation tuning procedure:

- i. The dynamic model is determined using empirical modeling to have the value of k_p , θ and τ .
- ii. The fraction dead time, $\theta / (\theta + \tau)$ is calculated
- iii. The appropriate correlation is determined whether disturbance or set point.
- iv. The dimensionless tuning values is determined from the graphs for the $k_c k_p$, $\tau_I / (\theta + \tau)$, and $\tau_D / (\theta + \tau)$
- v. The tuning algorithms, k_c , τ_I and τ_D are calculated.

3.6 Basic IMC Design Procedure

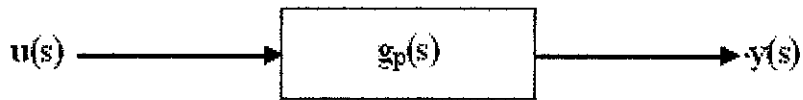


Figure 11 Basic ideal process model

The assumption is made that the model is perfect, so that the relationship between the output, y and the set point, r is given by equation:

$$y(s) = g_p(s) u(s)$$

1. The process model is factored into invertible and non-invertible elements. The factorization is performed so that the resulting controller will be stable.
2. The idealized IMC controller is formed. The ideal internal model controller is the inverse of the invertible portion of the process model.
3. Filter is added to make the controller proper. A transfer function is proper if the order of the denominator polynomial is at least as high as the numerator polynomial.
4. The filter tuning is adjusted to vary the speed of response of the closed loop system.

3.7 IMC-Based PID Feedback Design for Processes with time delay

1. The first order Pade approximation is used for dead time.

$$e^{-\theta s} \approx (-0.5\theta s + 1) / (0.5\theta s + 1)$$

2. The noninvertible element is factored out.

$$\tilde{g}_p(s) = k_p / (\tau_p s + 1)(0.5\theta s + 1)$$

$$\tilde{g}_{p+}(s) = -0.5\theta s + 1$$

3. The idealized controller is formed.

$$\tilde{q}(s) = (\tau_p s + 1)(0.5\theta s + 1) / k_p$$

4. The filter is added.

$$q(s) = \tilde{q}(s) f(s) = [(\tau_p s + 1)(0.5\theta s + 1) / k_p] [1 / (\lambda s + 1)]$$

5. PID equivalent is determined.

$$g_c(s) = q(s) / (1 - \tilde{g}_p(s)q(s)) = \tilde{q}(s)f(s) / (1 - \tilde{g}_p(s)\tilde{q}(s)f(s))$$

$$g_c(s) = \tilde{q}(s)f(s) / (1 - \tilde{g}_{p+}(s)f(s)) = [1/k_p][(\tau_p s + 1)(0.5\theta s + 1) / (0.5\theta s + 1)]$$

6. Multiplied equation by $[\tau_p + 0.5] / [\theta / (\tau_p + 0.5)]$ to find PID parameter.

$$k_c = (\tau_p + 0.5\theta) / k_p (\lambda + 0.5\theta)$$

$$\tau_i = \tau_p + 0.5\theta$$

$$\tau_D = \tau_p \theta / 2 \tau_p + \theta$$

3.8 Performance test, fine tuning and observation

Following the tuning of both conventional PID controller and IMC, performance tests are then conducted in order to observe the initial behavior of the controllers designed previously. A series of performance tests need to be done subsequently. *All tests are done in simulation using the MATLAB Simulink.* The configuration of the simulation blocks used to test the feedback control performance and the IMC control performance are included in **Appendix F** and **Appendix G**, respectively.

In the entire control performance test, the tuning parameters obtained using the

preferred tuning methods are testified whether they can perform acceptable feedback control on the temperature. *The required specification is a CV performance with at least 4:1 decay ratio and $\pm 2\%$ allowable band.*

The feedback controller design will then require an additional procedure - fine tune. Fine tune is necessary to improve the feedback control performance by means of adjusting the tuning parameters accordingly. An effective method of fine tuning is by trial-and-error. A rough guideline for fine tuning is to multiply the tuning parameter by 0.75 if it is to be decreased, and to multiply with 1.3 if it is to be increased. The guideline ensures that the magnitude of change of the respective tuning parameter is not large enough to skip the best possible value.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Identify the Process Reaction Curve

The dynamic response data of the system is shown in the **Appendix C**. Diagnostic evaluation is done towards the process reaction curve, and it is found that the output variable responded to the change by returning to the initial value with a small, negligible difference. The result for the diagnostic evaluation on the process model data is shown below. From this result, the accuracy of the process model data is conclusively verified.

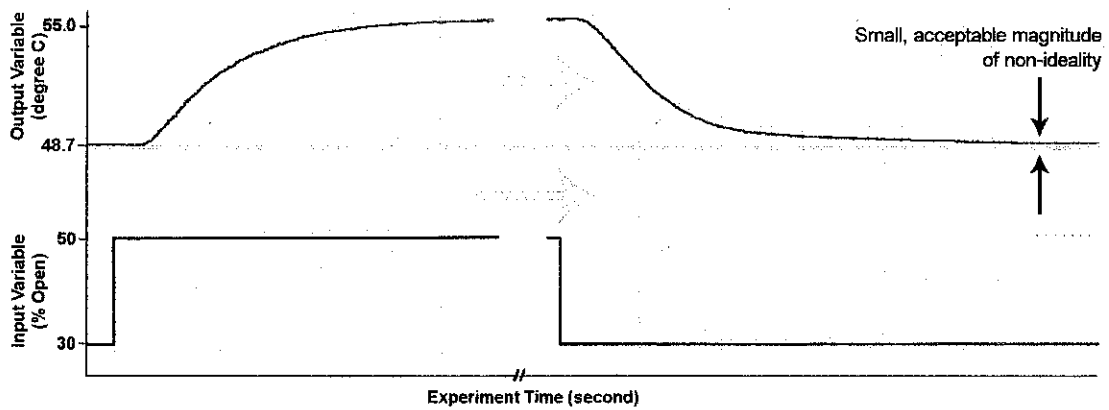


Figure 12 Diagnosis evaluation for process model

The reaction curve represents a first-order-with-dead-time model and has the following characteristics:

	K_p	τ	θ	Estimated Error
Method I	0.235	2.91	1.3	1.68%
Method II	0.235	2.25	0.22	2.22%

The IAE of Method I is calculated less than the IAE of Method II. The result of the reaction curve is not affected by the noise. Therefore, the slope of the reaction curve can be clearly determined.

Method II is preferably used for the signal with high frequencies of noise where there is difficult to identify the slope value. Both calculation of Method I and Method II are attached in the **Appendix D** and **Appendix E**, respectively. The plant model transfer function using the variable calculated from Method I:

$$\frac{Y(s)}{X(s)} = \frac{K_p e^{-0s}}{\tau s + 1}$$

$$= \frac{0.235 e^{-1.3s}}{2.91s + 1}$$

The block diagram that represents the process model is shown in **Figure 13** below. An observation on the process model is that it has a relatively large dead time (1.3 minutes). However, this value is reasonable since the process being modeled is temperature, which has slow dynamic characteristic:

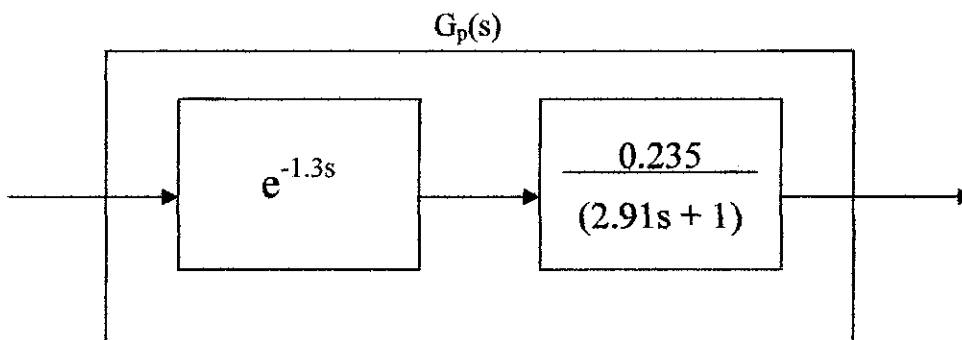


Figure 13 Process model block diagram

In order to verify the accuracy of the data used for modeling the process, diagnostic evaluation is performed by means of checking the process response for any non-

ideality such as unmeasured disturbance or a sticky valve that did not move as expected. Diagnostic evaluation is done by returning the input variable back to the initial value.

Naturally, the output variable will not return to exactly the same value due to the nonideality. **[Figure 12]** However, if the difference between the output variable before and after the valve is returned to the initial position is too large (i.e more than 50% of the change in output variable recorded during the experiment), then the empirical model is most likely corrupted by disturbance. The experiment should then be repeated.

4.2 PID controller design (Ciancone correlation tuning method).

$$G_p(s) = \frac{0.235 e^{-1.3s}}{2.91s + 1}$$

The result and calculation of the initial tuning using the Ciancone Correlation tuning method is shown in the table next page. The Ciancone Correlation Chart is shown in **Appendix I**.

No.	Criteria	Measurement
From plant model		
1	Process gain, K_p	0.235
2	Process dead time, θ (minutes)	1.3
3	Process time constant, τ (minutes)	2.91
4	Fraction dead time, $\theta / (\theta + \tau)$	0.413
From Ciancone correlation table (refer Appendix K)		
5	$K_c K_p$	0.8
6	$\tau_I / (\theta + \tau)$	0.75
7	$\tau_D / (\theta + \tau)$	0.06
Calculated value (only for PID controller)		
8	Process Gain, K_c	3.4
9	Integral Time, τ_I	3.158
10	Derivative Time, τ_D	0.235

Table 2 Initial tuning algorithm for Ciancone correlation tuning method

The dynamic response of the initial tuning is shows in **Figure 14** and **Figure 15** below:

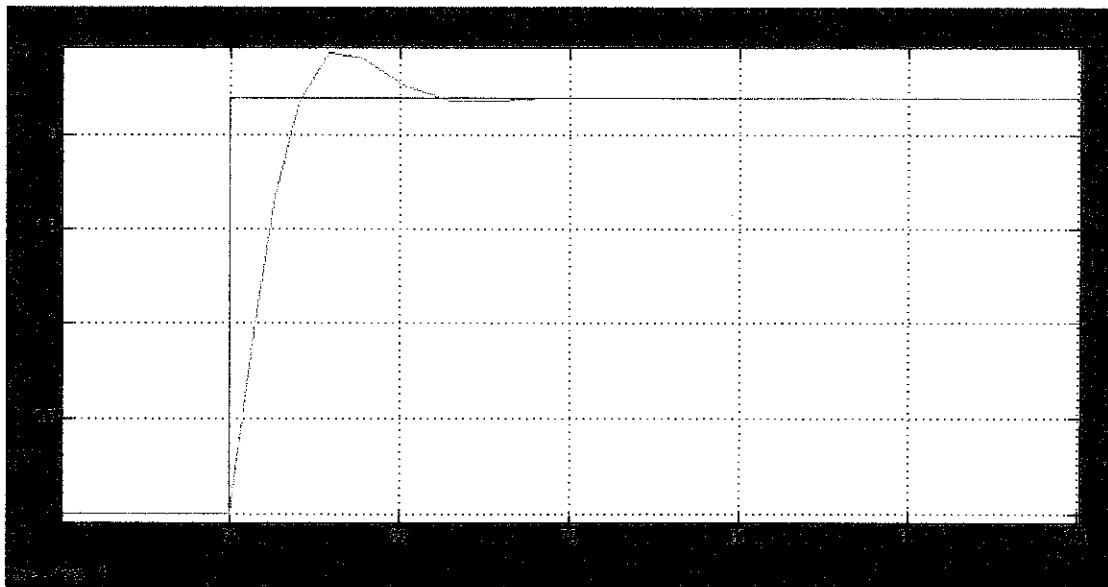


Figure 14 CV dynamic response for Ciancone tuning method

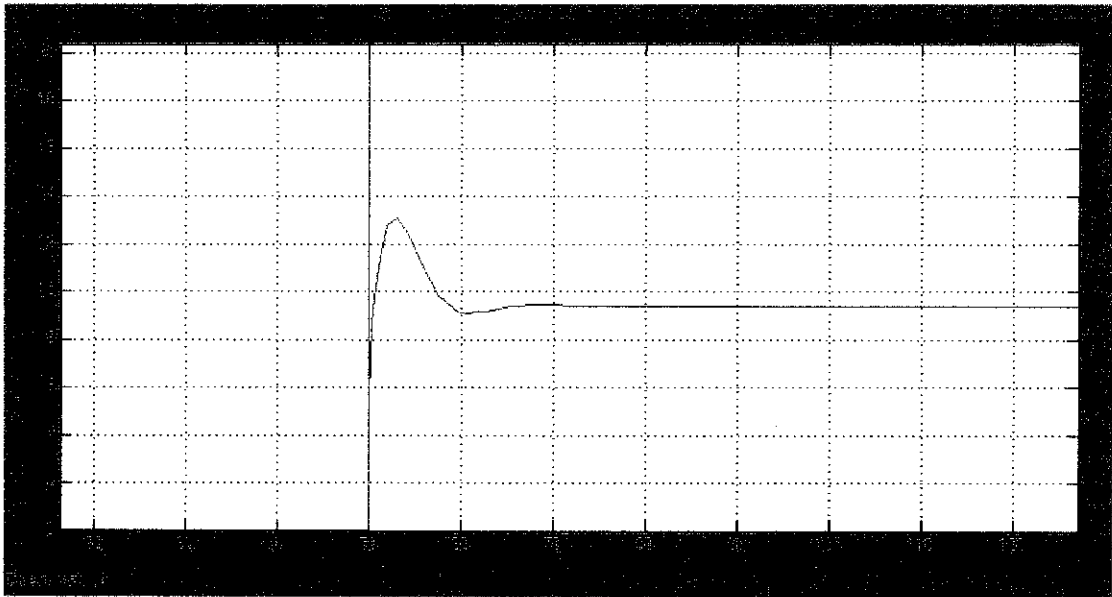


Figure 15 MV dynamic response for Ciancone tuning method

From the CV dynamic response curve, it shows that the system reached zero offset with 9% OS, fast rise time-2 minutes, while the settling time is 20 minutes. The %OS of MV is 36% which is quite low in a real plant process.

4.3 PID controller design (Ziegler-Nichols closed loop method with Bode plot)

Figure 16 below shows the value of the ultimate period and controller gain to be used in the Ziegler – Nichols technique. Refer to Appendix H for the calculation method.

No.	Criteria	Absolute Value
1	Magnitude, K_u	17.85
2	Frequency, P_u	4.52
3	Process Gain, K_c	10.5
4	Integral Time Constant, τ_I	2.26
5	Derivative Time Constant, τ_D	0.565

Table 3 Initial tuning algorithm for Ziegler Nichol tuning method

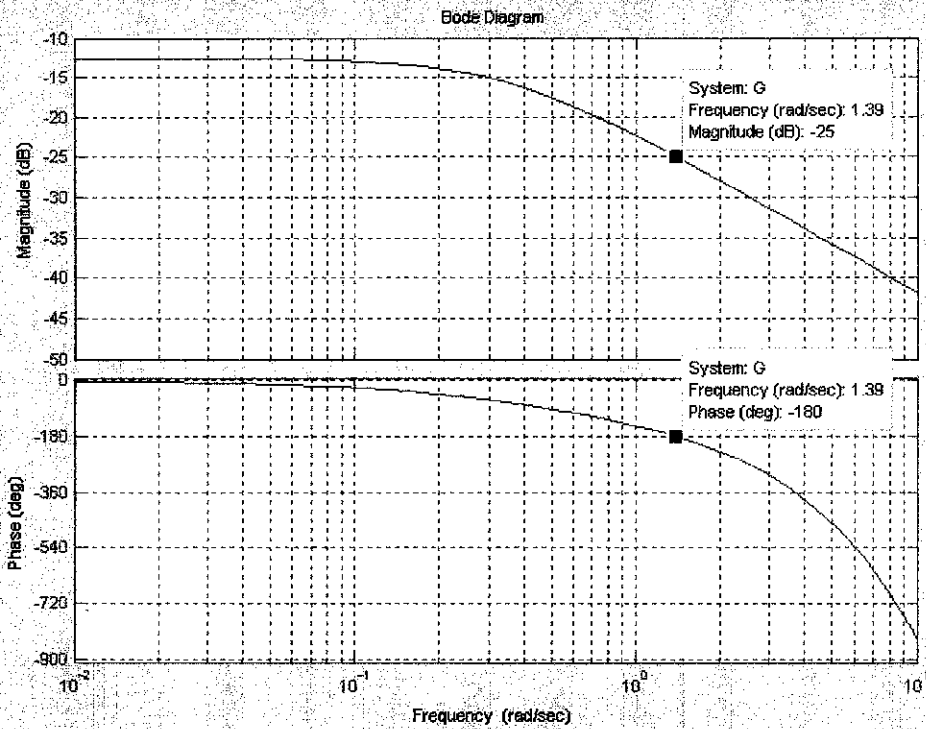


Figure 16 Bode plot to find the ultimate gain and period

Figure 17 and Figure 18 below show the result of the initial tuning for Ziegler Nichols tuning method. The system reached zero at same time with the Ciancone correlation which is 20 minutes. The different is only with the rise time and %OS. There is no over shoot and the rise time is 1.5 minutes. It is designed as an overdamp system by using Ziegler Nichols tuning method.

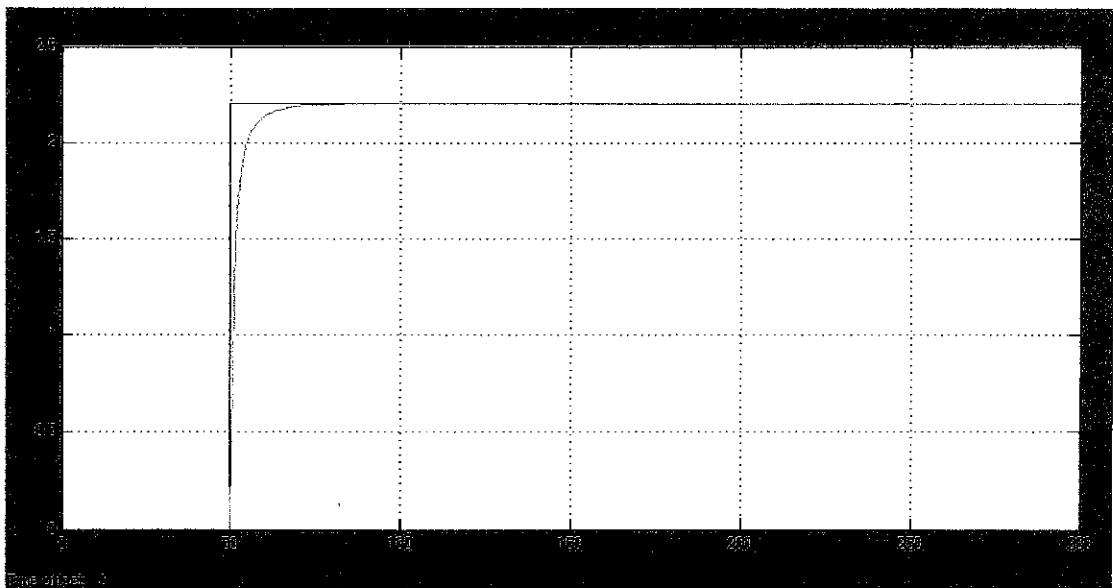


Figure 17 CV dynamic response for Ziegler Nichols tuning method

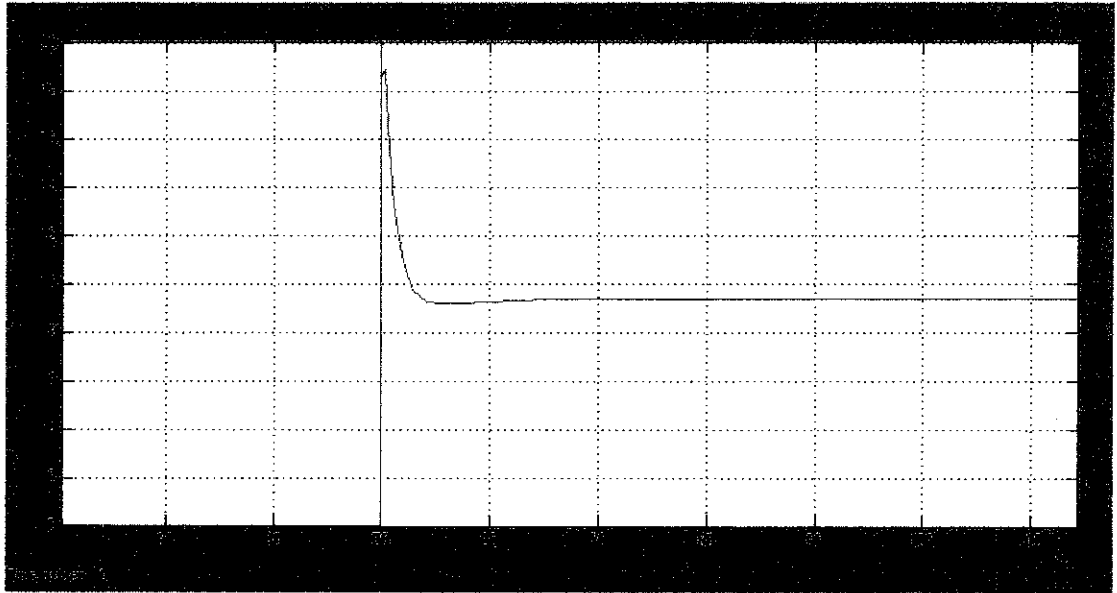


Figure 18 MV dynamic response for Ziegler Nichols tuning method

4.4 Comparison Analysis of the Conventional PID Controllers.

The analysis of the process control and manipulated variables has been done through the previous **Section 4.2 and 4.3**. Table below summarized the observation of both conventional PID controller tuning methods:

	Ciancone Correlation	Ziegler-Nichols
CV percentage overshoot	10% OS	0
MV percentage overshoot	36.8% OS	110% OS
CV decay ration	0	0
Rise Time	1.5 minutes	2 minutes
Settling Time	20 minutes	20 minutes

Table 4 Comparison result for initial tuning of both PID controllers tuning method

For Ciancone the fine tune system actually has 10% of overshoot in CV, an instant overshoot to 36.8% in MV. The decay ratio is approximately zero which means that there is no second overshoot occurred. On the dynamics of the response, it takes 1.5 minutes to reach 63% of the final value and 20 minutes of settling times. Meanwhile,

the Ziegler Nichols method developed an overdamp system which is without overshoot. With the same value of settling time, it created a very large overshoot for the MV which is 110%. The dynamics is fast that the rise time is approximately 1.5 minutes. The Ciancone tuning method result is complied with the control requirement.

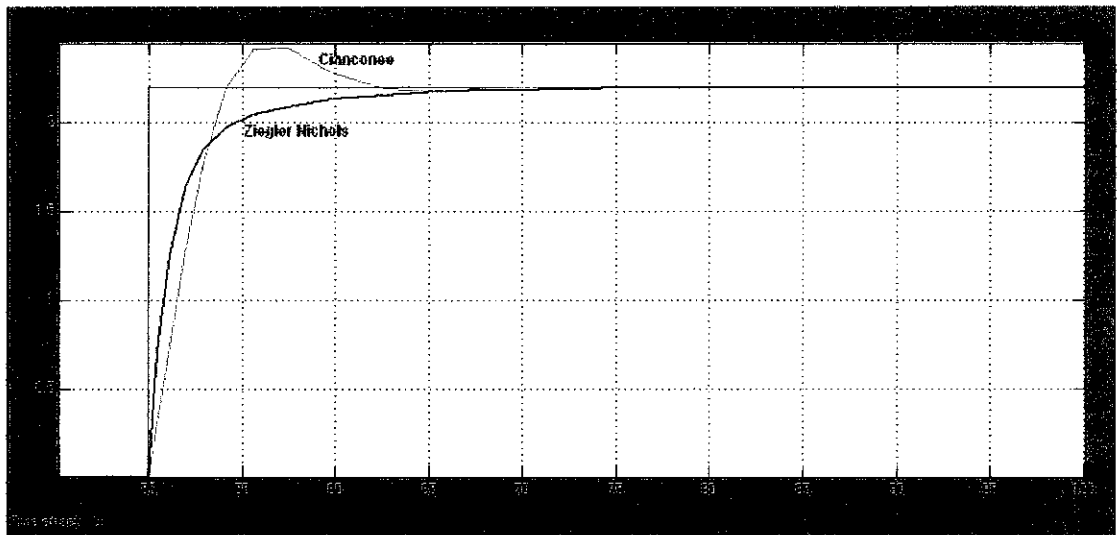


Figure 19 Comparison result of CV performance for initial tuning

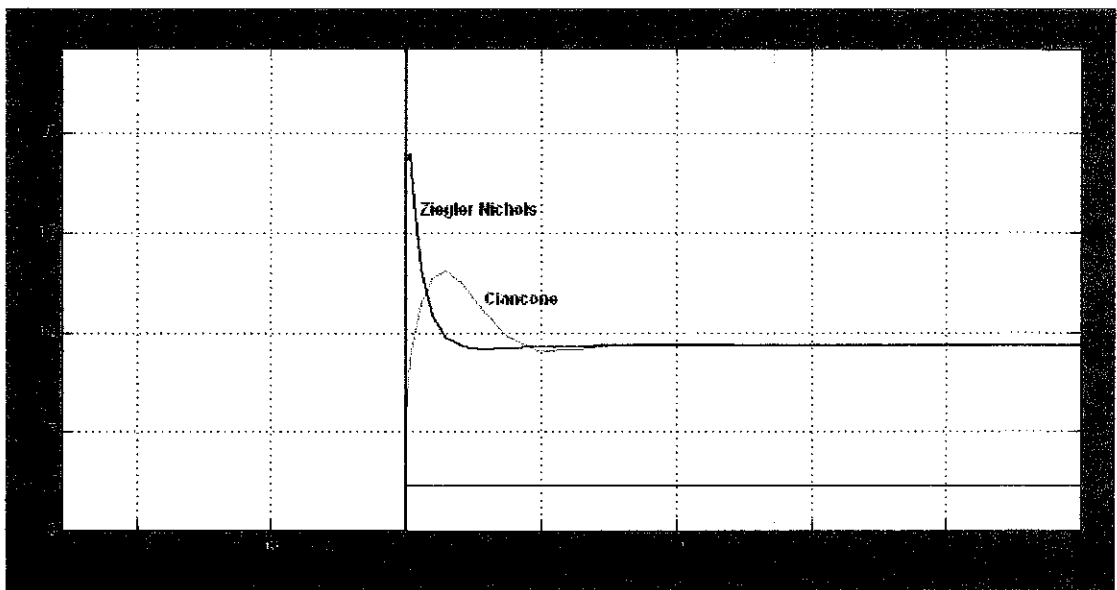


Figure 20 Comparison result of MV performance for initial tuning

4.5 Ideal IMC Design with Delay-Free for Stable Process

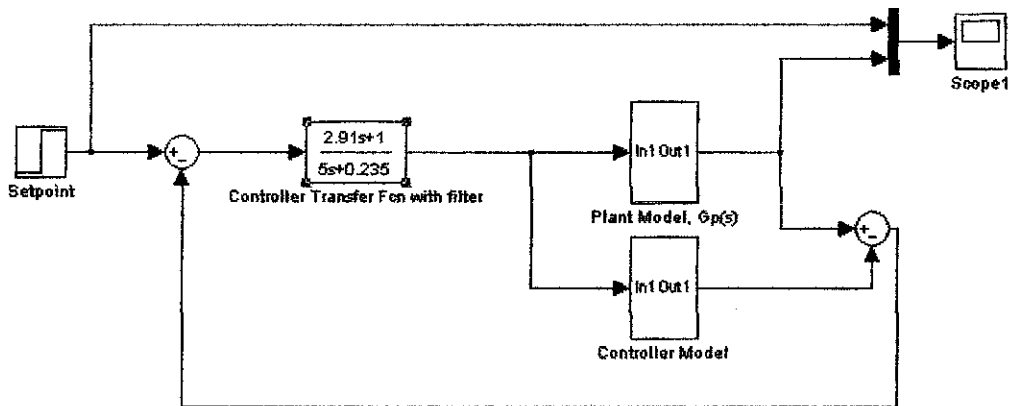


Figure 21 Ideal Internal Model Controller

FODT model:

$$\tilde{g}_p(s) = 0.235 e^{-0.22s} / 2.25s + 1$$

Process model is factored into invertible and non-invertible elements:

$$\tilde{g}_p(s) = \tilde{g}_{p+}(s) \tilde{g}_{p-}(s) = (e^{-0.22s}) (0.235 / 2.25s + 1)$$

The idealized IMC controller

$$\tilde{q}(s) = \tilde{g}_{p-}^{-1}(s) = 2.25s + 1 / 0.235$$

Add filter to make the controller proper, $n = 1$ (FODT):

$$f(s) = 1 / (\lambda s + 1)^1$$

$$\tilde{q}(s) = \tilde{q}(s) f(s) = \tilde{g}_{p-}^{-1}(s) f(s)$$

Finally λ is adjusted for response speed and robustness. From the graph below shows that by increasing the value of λ , the system become slower. But then the system still reached zero offset.

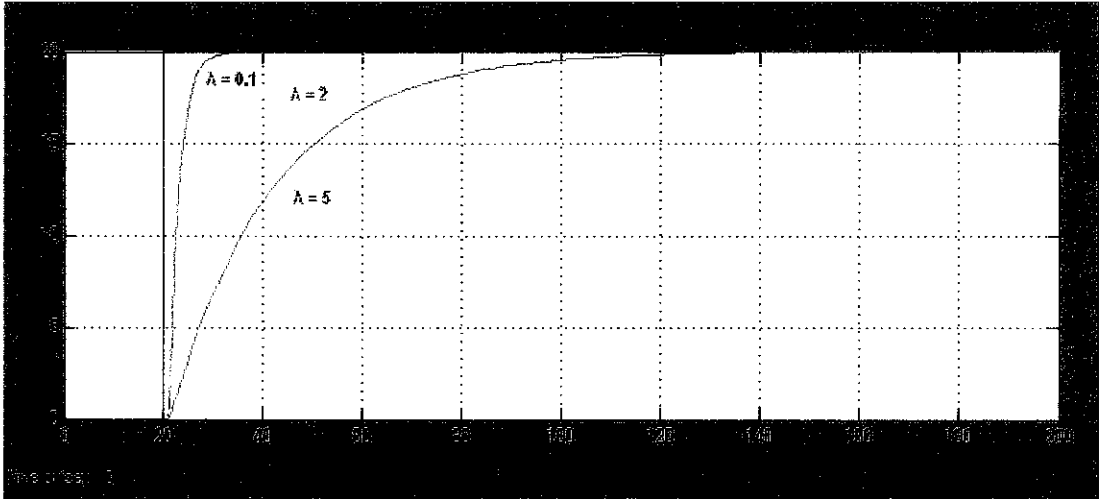


Figure 22 Process response by adjusting the λ

4.6 IMC – Based PID Design for First Order with Dead Time

After the basic model of IMC is completed, the model is then compared with the conventional PID feedback model. The equivalent result is shown in **Appendix K**.

$$k_p = 0.235$$

$$\theta = 1.3$$

$$\tau_p = 2.91$$

$$k_c = (\tau_p + 0.5\theta) / [k_p (\lambda + 0.5\theta)]$$

$$\tau_I = \tau_p + 0.5\theta$$

$$\tau_D = \tau_p \theta / [2 \tau_p + \theta]$$

4.7 IMC Control Performance Test and Fine Tuning

For the IMC, the tuning technique is simpler where only the λ need to be varies to achieve control objectives. **Table 5** below shows the value of k_c that affected by the occurrence of the λ . The results of the comparison are shown in **Appendix L**.

Fine-tune will improve the settling time and the rise time with desirable overshoots.

More importantly, fine-tune will ensure that the control performance will achieve the predetermined goal; a CV performance with at least 4:1 decay ratio, a maximum overshoot of 25% and $\pm 2\%$ steady-state band. The red dotted line present the best tune for IMC.

	TEST 1 $\lambda = 0.1$	TEST 2 $\lambda = 1$	TEST 3 $\lambda = 2$	TEST 4 $\lambda = 5$	TEST 5 $\lambda = 10$
k_c	20.20	9.18	5.72	2.68	1.42
τ_I	3.56	3.56	3.56	3.56	3.56
τ_D	0.53	0.53	0.53	0.53	0.53
Observation					
%OS	0	0.9	6.82	18.2	56.2
Rise Time (min)	0.7	1.3	1.8	2.1	2.3
Settling Time (min)	50	13	13	22	25.5

Table 5 Test result with different value of λ

Figure 23 and Figure 24 show the fine tuning result for the IMC. The result achieved when the value of λ is set to 1. This is the best performance of the system with smallest %OS which is only 0.9% OS, 1.3 minutes rise time and also 13 minutes settling time.

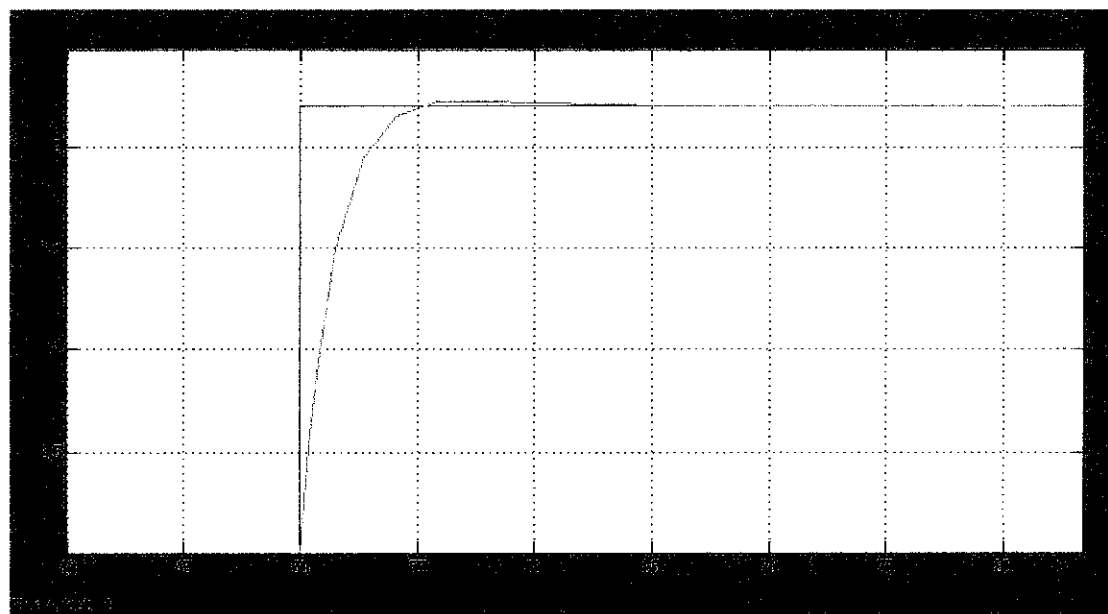


Figure 23 Control variable after fine tuning

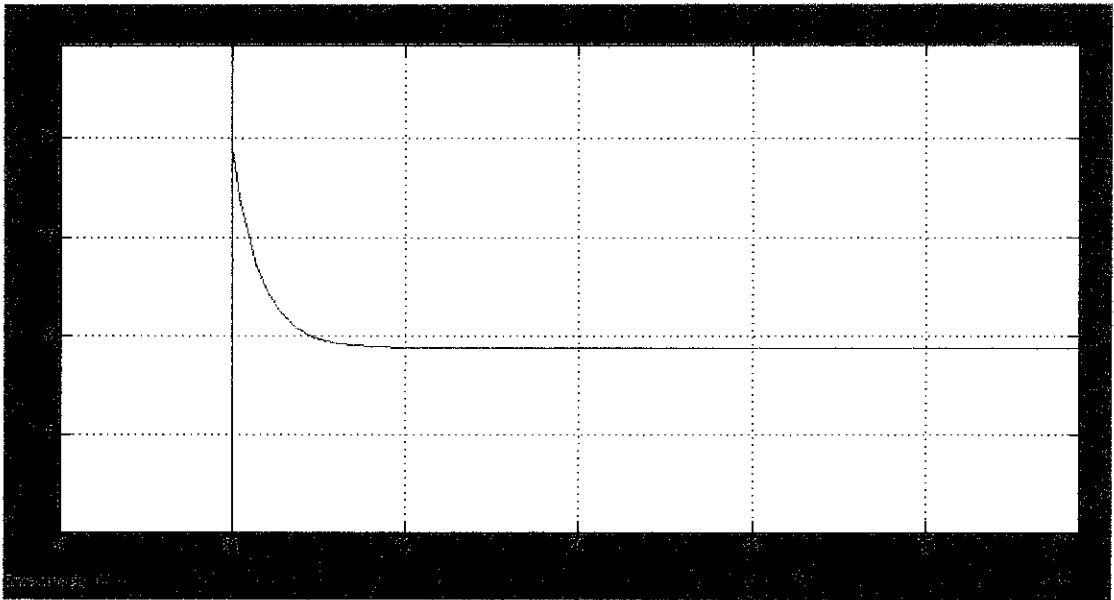


Figure 24 Manipulated variable after fine tuning

4.8 Fine Tuned Conventional PID Controllers to match up with the IMC.

The PID Feedback control performance test uses the tuning parameters obtained previously, which is then followed by fine tune if necessary. This procedure is done in the simulation using MATLAB Simulink. *The calculated tuning parameters obtained provide close estimation on the optimum control performance.* Both conventional PID controllers are fine tuned to match with the IMC performance.

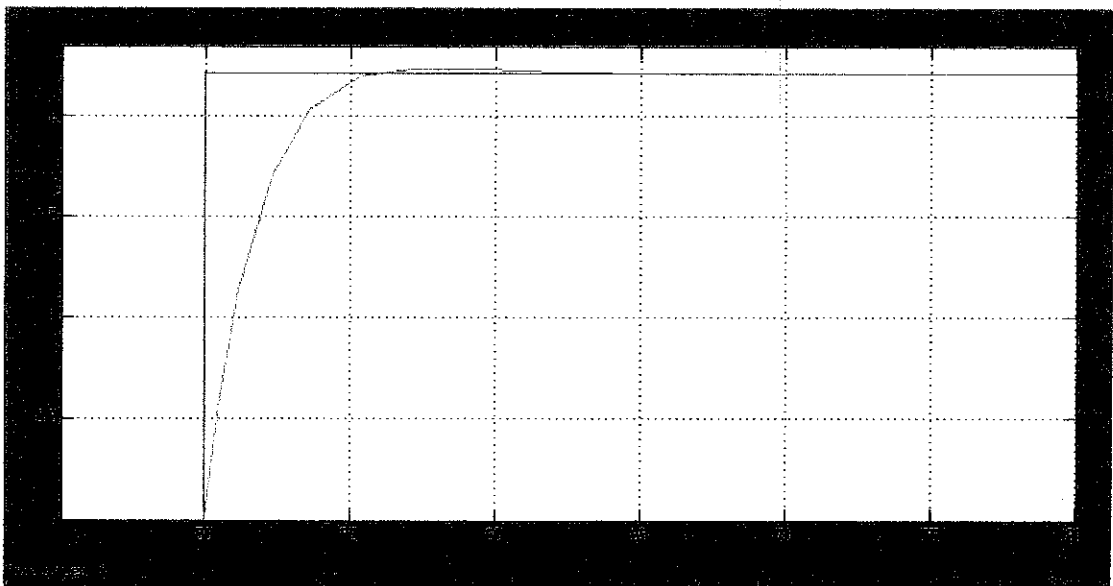


Figure 25 CV dynamic response of Ciancone tuning method after fine tuned

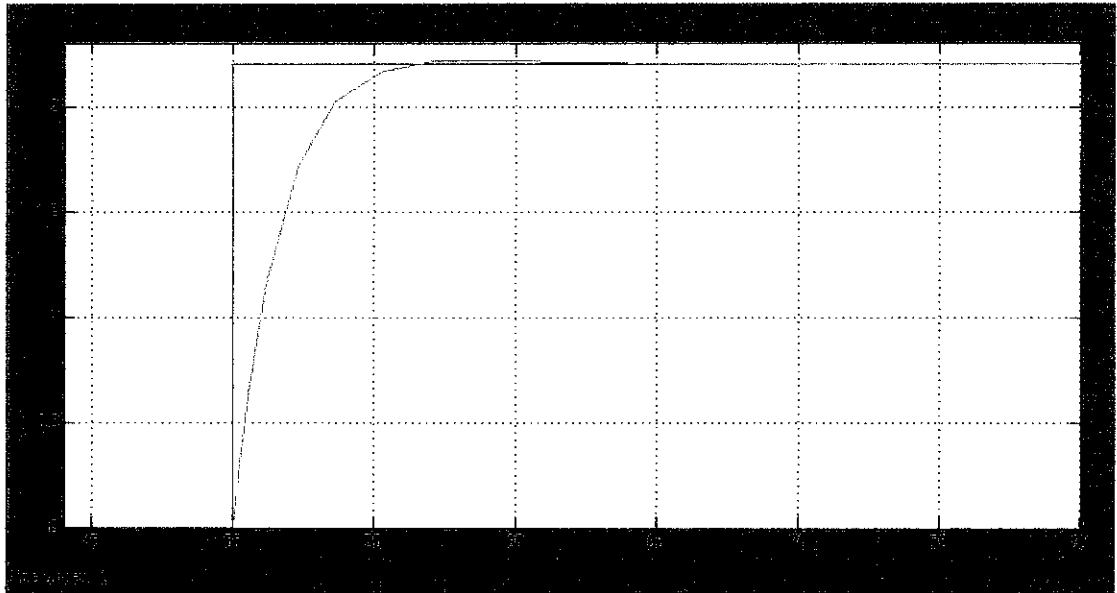


Figure 26 CV dynamic response of Ziegler Nichols tuning method after fine tuned

For the Ciancone tuning method, the goal is met when the Proportional term is increased to 7.47 and the Integral term is decreased to 3 seconds while Derivative term is increased with 0.516 for more aggressive performance. The desired result is shown in **Figure 25** above.

For the Ziegler Nichols tuning method, the goal is met when the Proportional term is decreased to 7.875 and the Integral term is increased to 2.938 seconds while Derivative term is maintain with 0.565 for more aggressive performance. The desired result is shown in **Figure 26** above.

Figure 27 and **Figure 28** below shows the CV and MV dynamic response comparison after fine-tuned control performance for the feedback controller, with respect to 2.2^oC set point change:

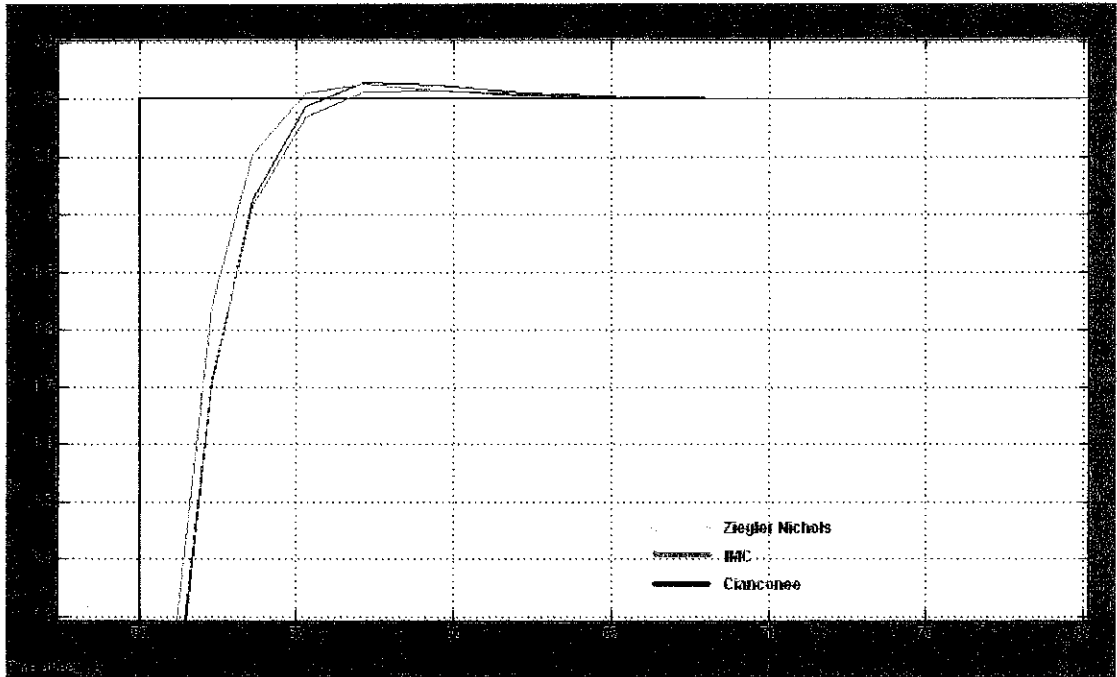


Figure 27 CV result after fine tuned of all methods

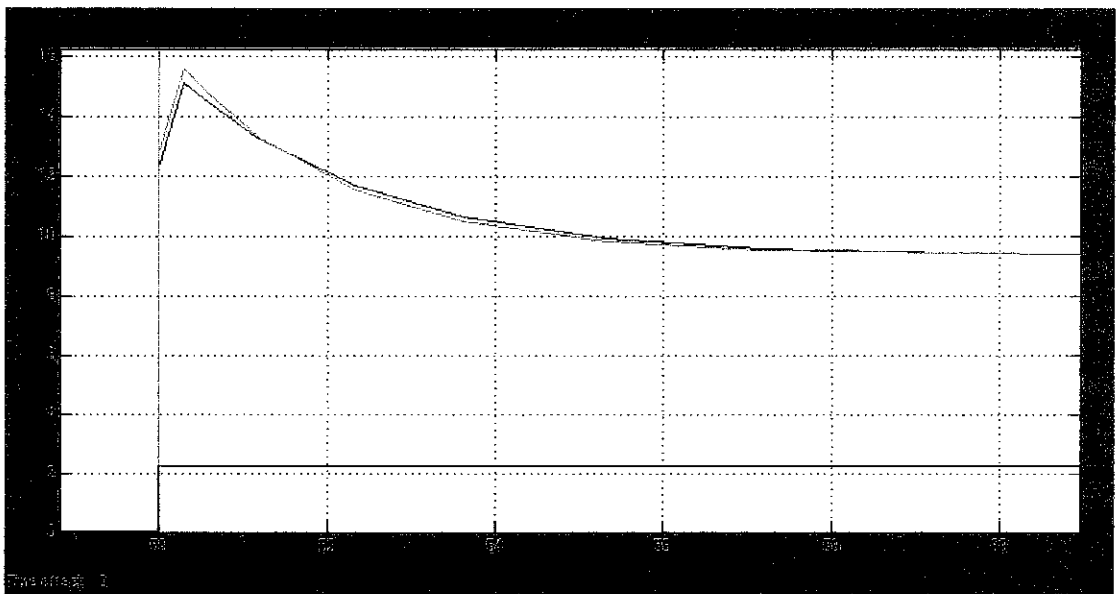


Figure 28 MV result after fine tuned of all methods

Table 6 next page summarize the result after fine tuned for both conventional PID controller, using Ciancone Correlation and Ziegler Nichols tuning method.

	Ciancone Correlation		Ziegler Nichols	
	Initial	Fined-Tuned	Initial	Fined-Tuned
<i>Decay Ratio</i>	0	0	0	0
<i>CV Overshoot</i>	10%	0.45%	0	1.36%
<i>MV Overshoot</i>	36.8%	57.89%	110%	63.15%
<i>Rise Time, T_r</i>	1.5 minutes	2 minute	2 minutes	2 minute
<i>Peak Time, T_p</i>	7.5 minutes	7 minutes	0	7 minutes
<i>Settling Time, T_s</i>	20 minutes	15 minutes	20 minutes	15 minutes

Table 6 Dynamic Responses for Initial and Fine-Tuned Feedback Control

	Ciancone Correlation		Ziegler Nichols	
	Initial	Fined-Tuned	Initial	Fined-Tuned
Process Gain, k_c	3.4	7.47	10.5	7.875
Integral Time, τ_I	3.158	3.158	2.26	3.819
Derivative Time, τ_D	0.235	0.516	0.565	0.565

Table 7 Tuning parameters value for initial and fine tuning

4.9 Analysis and Comparison

From the result, it is shows that it is very easy to tune the IMC controller based PID compared with the conventional PID controllers. Only one variable, λ is tune to have suitable process control for the IMC base PID controller. By reducing the value of λ , the response of the system becomes faster.

From two experiments for conventional PID controller tuning which have been done, both method can be fine tuned to have better performance of the system. For the conventional PID controller, the tuning parameters cannot be optimized independently. The difficulties occurred when to determine the suitable value of all the tuning parameters k_c , τ_I and τ_D . Compare with the IMC, only the λ , is tuned to have a better performance of the system. **Table 7** summarizes the parameters changes after fine-tune of the conventional PID controllers.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The results and outcome of the project must be judged based on diagnostics and knowledge of the process behavior based on some fundamental models. The project is expected to challenge the author to familiar with some types of modeling technique and the process of the real plant operation. At the end of the project, the student will be able to outline the benefits of using Internal Model Controller to control applications and to suggest the suitability of real-life implementation with strong reason and background information.

The modeling technique used throughout the project is Empirical modeling technique. All the tasks including design and simulation during the project period is done using the MATLAB Simulink version 6.5.

The comparative study between controller, IMC and conventional PI controller has been done. The most advantage of the IMC is more on tuning parameter where it is only required to tune only one tuning parameter, λ . By using the conventional PID controller, the controller gain, k_c , τ_I and τ_D have to be tuned in order to have better performance.

CHAPTER 6

RECOMMENDATIONS

The project can be extended to cover more aspects of case study. Further analysis can be done if the project timeline is extended and the project scope is broadened:

6.1 System Identification and Modeling Techniques Improvement.

The knowledge should be continually updated. It is very important to have an accurate plant transfer function, because the transfer function will be used throughout the design process. The knowledge about the basic controller such as PID controller has to be improved in order to implement other controller such as Internal Model Controller to a certain system.

6.2 Hardware Implementation.

If the designed of IMC can be physically developed and installed to the control system of the heat exchanger pilot plant, comparison analysis can be performed in the real environment. It is important to have more accurate result because in design process most of the cases are assumed to be ideal.

6.3 More Comparison Against Other Types of Tuning Methods.

There still a lot more tuning method can be used and each every method has their own objectives to be achieved. By comparing more controllers, the performance analysis of the controller will be more accurate.

REFERENCES

Some references used throughout the project period:

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6. "Internal Model Control Based on Locally Linear Model Tree (LOLIMOT) Model with Application to a PH Neutralization Process", by Jalili-Kharaajoo, M.; Rahmati, A.; Rashidi, F.
7. "Internal Model Control: Robust Digital Controller Synthesis for Multivariable Open-Loop Stable or Unstable Systems" by Zafiriou M. Morari
8. "Internal Model Control Using Neural Networks" by Isabelle Rivals and Léon Personnaz.

APPENDICES

APPENDIX A:

P&ID of heat exchanger loop control

APPENDIX B:

Setup procedure of the loop control

APPENDIX C:

Process dynamic of TT634

APPENDIX D:

Method I - Plant Model Calculation

APPENDIX E:

Method II - Plant Model Calculation

APPENDIX F:

Feedback control performance configuration

APPENDIX G:

IMC control performance configuration

APPENDIX H:

Tuning Algorithms Calculation using Bode Plot Method

APPENDIX I:

Ciancone Correlation Table

APPENDIX J:

Dynamic response data

APPENDIX K:

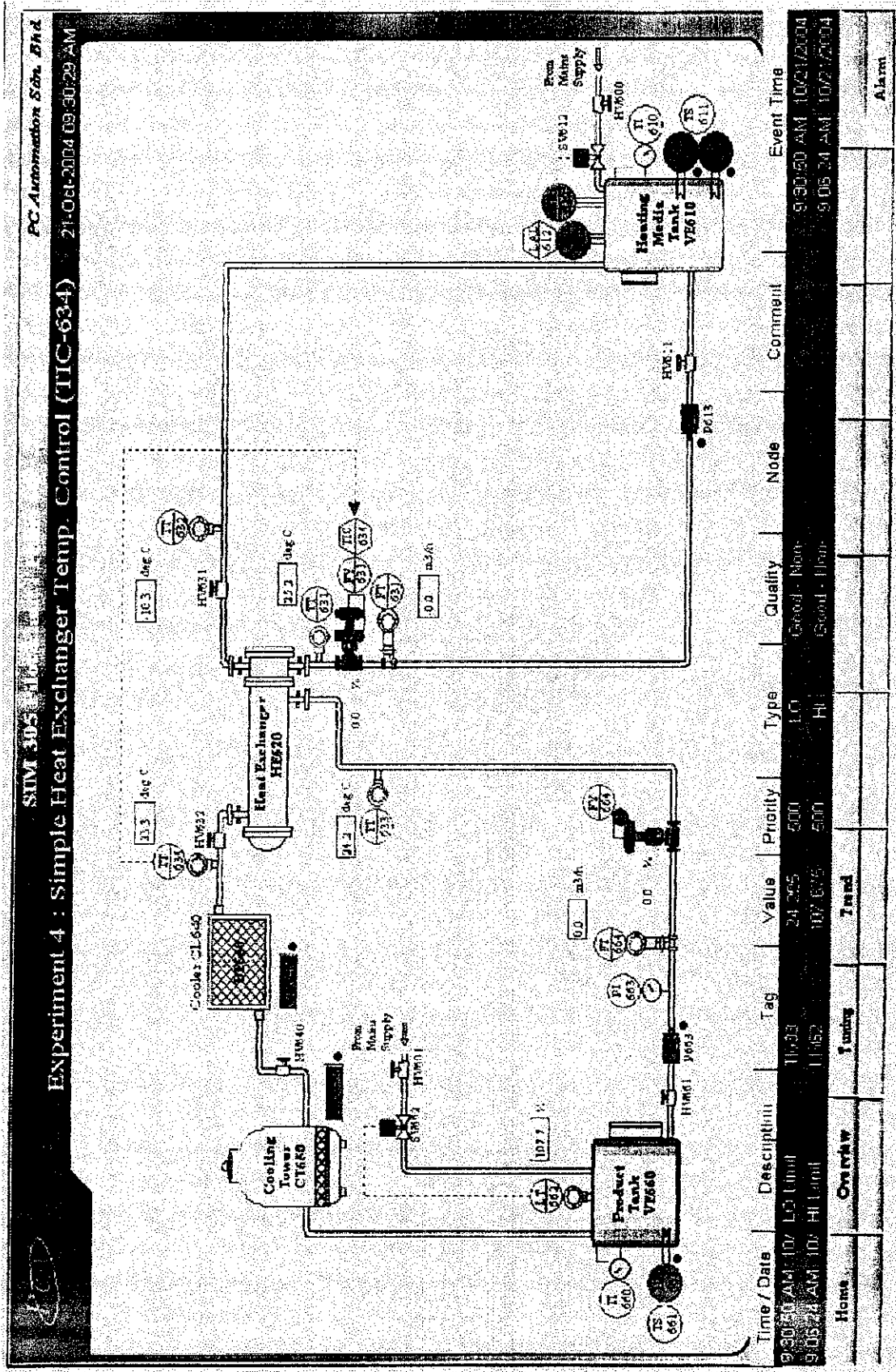
Equivalent diagram of IMC and PID controller

APPENDIX L:

Result of IMC tuning

APPENDIX A

P&ID OF HEAT EXCHANGER LOOP CONTROL



APPENDIX B

SETUP PROCEDURE OF THE LOOP CONTROL

This experiment is to divided into Four (4) sections:

- Section A: is for the student to **Identify the Process**,
- Section B: is for the student to perform **Open Loop Controller Tuning**,
- Section C: is for the student to perform **Closed Loop Controller Tuning**, and
- Section D: is for the student to carry out **Performance Test** for the Control Loop.

PREPARATION:

<i>STEP</i>	<i>ACTION</i>	<i>REMARKS</i>
1	Ensure that all Utility Services are ready (ie. Switch on Power Supply to Control Panel and Switch on Air Supply System to the Pilot Plant).	
2	Open hand valve HV300 and HV320. Fill The Vessel VE 610 and VE660 with water until it reach the high level.	
3	Ensure that the DCS is Ready (ie. It is communicating properly with the control Panel)	
4	When the computer start up, go in the Home page and then perform the login experiment operation .	"Experiment 4 : Simple Heat Exchanger Temperature Control (TIC-634)" will appear after user perform the login Experiment operation.
5	Switch on heater HE611A ,HE611B ,CL640 and CT650.	
6	Open the Control Valve FY 664 Manually (30% open)	
7	Open the Control Valve FY 631 Manually (40% open)	
8	Open or Close hand valves at the Pilot Plant as follows: -Open Hand Valve HV611, HV600, HV631, HV632, HV640 and HV661 , Close others	Hand Valves to be Open/Closed Fully
9	Start the pump P663 and P613.	
10	Stop the pump P663 and P613 when temperature of water in VE610 reach 60 degree celcius.	

Experiment 4– Simple Heat Exchanger Temperature Control (TIC634)

SECTION : Process Identification

4.A1 Start Experiment

<i>STEP</i>	<i>ACTION</i>	<i>REMARK</i>
1	Open control valve FY664 to 25% manually .	
3	Start Pump P663, P613 Start CT350, CL340.	Set the "RUN / STOP " Button to "RUN"
4	At the TIC634 Controller faceplate manually open control Valve FY 634 to 40 %	
5	Observe the Temperature Curve (TT-634) from the trend window and wait until it has stabilized	
6	At the PID Controller Faceplate (TIC-634) , make a step change of between 10 % to the control valve manually	MV=50 %
7	Observe the Temperature Curve (TT-634) from the Trend Window and wait until it has Stabilized to a new constant value , then Freeze the trend window	
8	Print out the PV Trend curve.	Print in color
9	Stop Pump P663 and P613 Stop the CT650 and CL640	Set the "RUN / STOP " Button to "STOP"

4.A 2 Result Analysis

1	Compare the Temperature curve with a set of expected process Reaction Curves provided in Appendix A of this manual.	
2	Identify the process response with the corresponding Reaction Curve	
3	Make several measurement as per the Reaction Curve chart.	Refer Appendix A1
4	Sketch a Block Diagram to represent the process and Describe the Characteristics of this Process.	Dead time, Capacity/Rate of Rise, Time Constant, Noise, etc
5	Suggest the suitable Control Modes for a PID Feedback Control Loop for regulating of the process.	eg. P, I, D settings

Experiment 4- Simple Heat Exchanger Temperature Control (TIC-634)

SECTION 4B: Open Loop Tuning Method

4B1 Tabulation and Analysis of Result

<i>STEP</i>	<i>ACTION</i>	<i>REMARKS</i>
1	Using the printed graph obtained from Section above (Process Analysis) above, measure and tabulate the relevant values as required. Refer to Appendix B, Table B-1 as example.	Note dB_n and dM are change from the 1 st stable output to the 2 nd .
2	Base on the equations for Open Loop Tuning, calculate the required controller tuning parameters. Refer to Appendix C, Table C-1 .	
3	At the TIC 634 controller faceplate, key in the calculated controller tuning parameters	
4	You are now ready to test the performance of the Control Loop. Proceed to Section D to continue.	

Experiment 4– Simple Heat Exchanger Temperature Control (TIC- 634)

SECTION 4C: Closed Loop Tuning Method

4C.1 Start Experiment

STEP	ACTION	REMARKS
1	Open control valve FY664 to 25% manually .	
2	At the TIC -634 controller Faceplate Set the Controller Gain to 32, the Integral time to 9999, and the Derivative time to 0	
3	Set the Controller to Manual mode ,	
4	Start Pump P663 and P613 Start the CT650 and CL640	Set the "RUN / STOP " Button to "START"
5	Slowly Open the Control Valve FY-631 to bring the Process Value (PV) to almost equal to the Set Point.	Adjust through MV
6	Observe the Process Value (TT634) 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 Process Value (PV) of TT631 and FY631 to stabilise	
9	Make a Small Step Change to the Set point of the TT634 (ie. increase the set point by 10%)	
10	Observe the Process Value (TT634) from the Trend Window. If the PV response is not oscillatory, double the controller gain value until it becomes oscillatory.	
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 the PV is decreasing increase the controller gain by 1.5 times. Aim to obtain an oscillatory response with almost constant amplitude.	
12	When Constant Amplitude Oscillation is achieved, allow up to 3 or more oscillation cycles to be recorded and Freeze the trend window	
13	Print out the PV response curve	Print in color
14	Stop Pump P663 and P613 Stop the CT650 and CL640	Set the "RUN / STOP " Button to "STOP"

Experiment 4 – Simple Heat Exchanger Temperature Control (TIC 634)

4C.2 Results Analysis:

1	Using the printed graph obtained from Section above, measure and tabulate the relevant values as required. Refer to Appendix B, Table B-2 as example.	
2	Base on the equations for Closed Loop Tuning, calculate the required controller tuning parameters. Refer to Appendix C, Table C-2 .	
3	At the TIC634 controller faceplate, key in the calculated controller tuning parameters.	
4	You are now ready to test the performance of the Control Loop. Proceed to Section D to continue.	

Experiment 4– Simple Heat Exchanger Temperature Control (TIC 634)

SECTION 4D: Control Loop Performance Test

4D.1 Start Experiment:

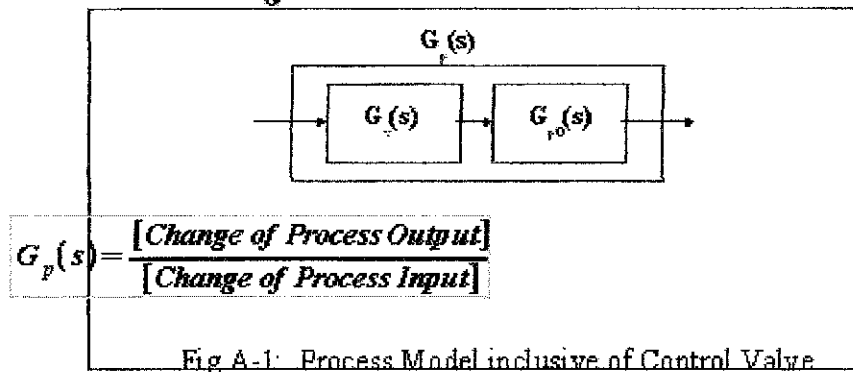
<i>STEP</i>	<i>ACTION</i>	<i>REMARKS</i>
1	Open control valve FY664 to 25% manually .	
2	At the TIC-634 controller Faceplate , set its P,I,D parameters obtained from the previous experiment .	
3	Adjust the Set Point (SP) of TIC334 to 45	
4	Start the pump P613 and P663 .Start the CT650, and CL650 via the computer	Set the "RUN / STOP " Button to "RUN"
5	Adjust the controller output (MV) until its process value (PV) is close to its set point (SP)	
6	Set the Controller to "Auto Mode"	
7	Observe its PV curve (TT-634) from the Trend Window and wait until it is reasonable stable..	
8	Increase the controller Set point (SP) by making a step change of increment of 5.	
9	Observe its PV curve (TT-634) from the trend window and look for some typical response characteristics.	
10	Capture the important process responses and print out the Trend curve	Print in color
11	Stop the pump P613 and P663 .Start the CT650 and CL650 via the computer	Set the "RUN / STOP " Button to "STOP"

4D.2 Tabulate and Analyze Results:

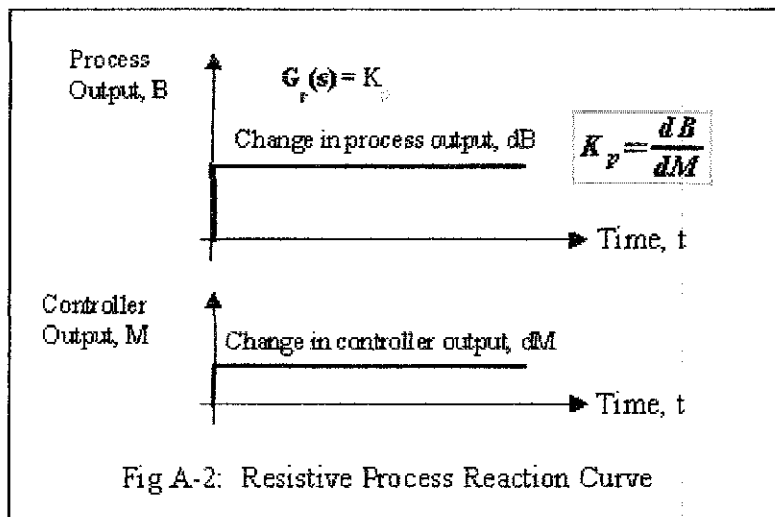
1	Using the printed graph obtained from Section 4D.1 above, measure and tabulate the relevant values as required. Refer to Appendix B, Table B-3 as example.	
2	Describe the Characteristics of the Process response.	
3	Discuss the functions of each controller tuning parameters, P, I and D.	
4	Suggest any improvements to the process control loop and its total error.	

APPENDIX A

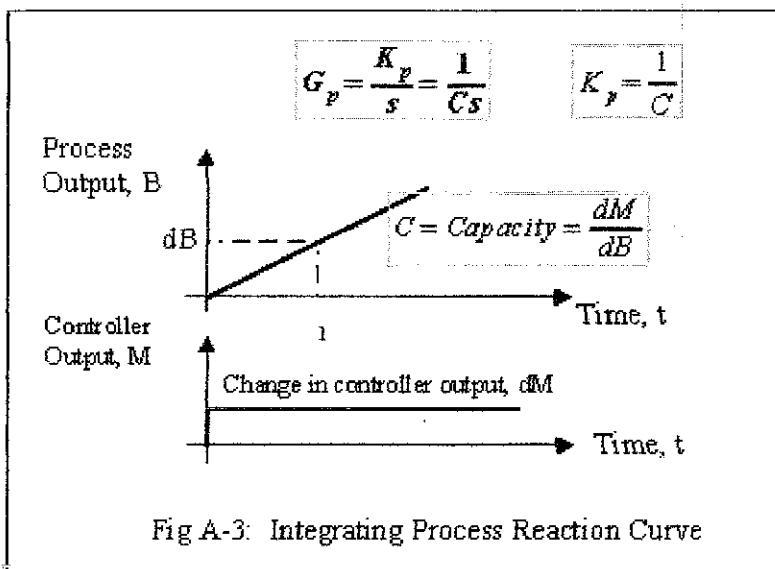
Process Block Diagram



Process Reaction Curve 1

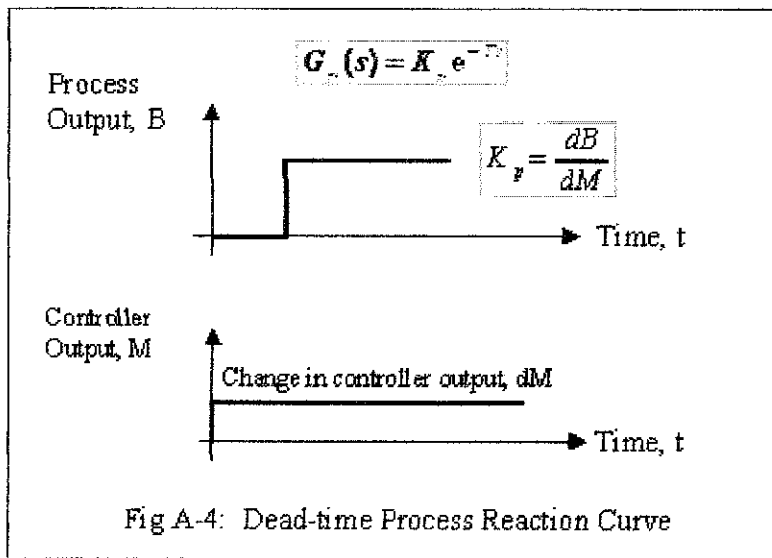


Process Reaction Curve 2

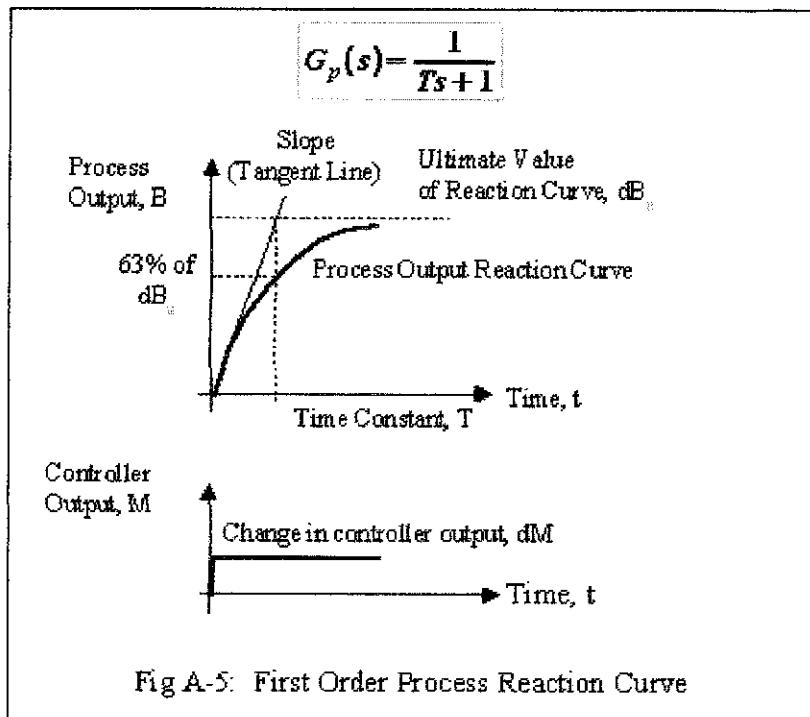


APPENDIX A

Process Reaction Curve 3

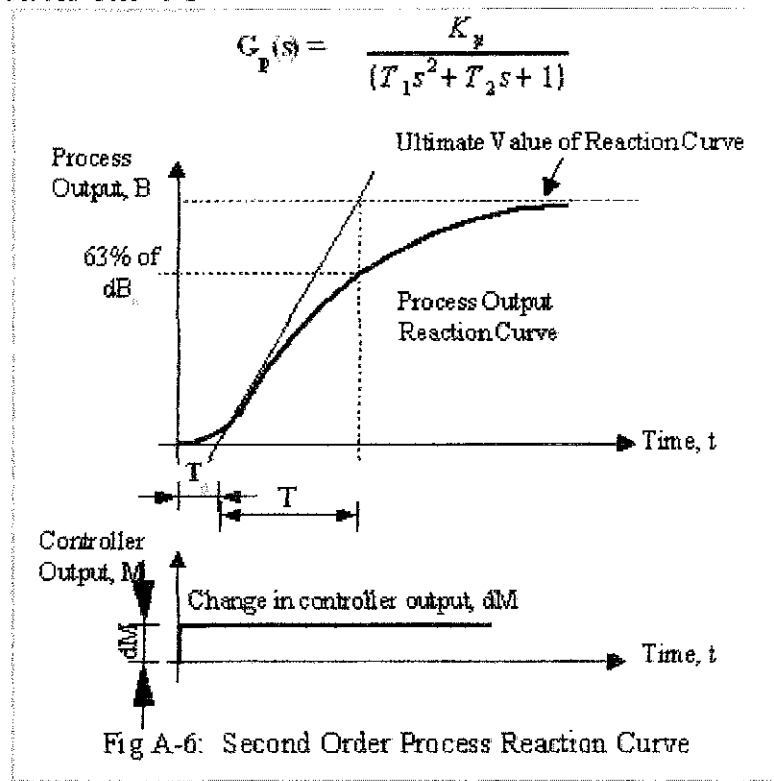


Process Reaction Curve 4

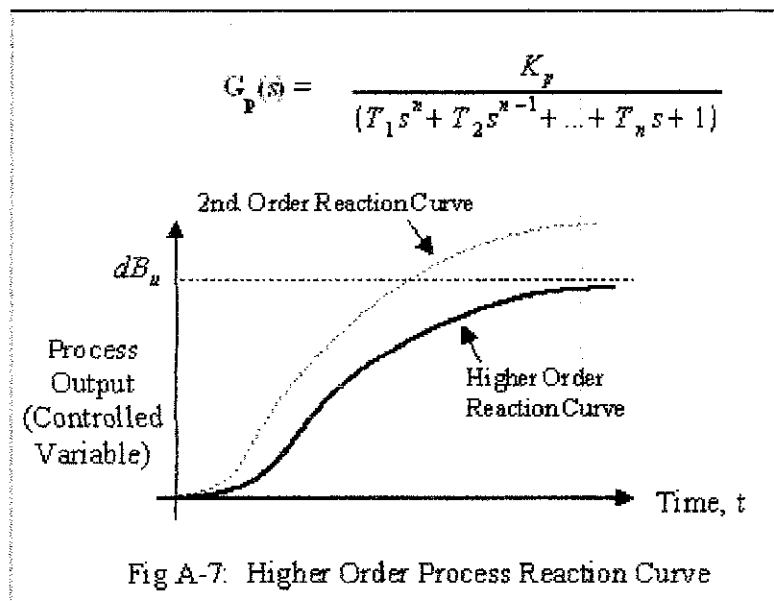


APPENDIX A

Process Reaction Curve 5



Process Reaction Curve 6



APPENDIX B: Tabulation of Results

Table B.1: Results for Open Loop Tuning

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

APPENDIX B: Tabulation of Results

Table B.2: Results for Closed Loop Tuning

<i>Measurement</i>	<i>Test 1</i>	<i>Test 2</i>	<i>Test 3</i>	<i>Average</i>
K _c Ultimate Controller Gain				
Time for 3 Oscillation periods, or more				
CALCULATIONS:				
Ultimate Time T _u (Time for one Oscillation period)				
Tuning Parameters:	<i>Test 1</i>	<i>Test 2</i>	<i>Test 3</i>	<i>Average</i>
K _c (Gain)				
Integral Time, T _i (minutes/repeat)				
Derivative Time, T _D (minutes/repeat)				

APPENDIX C

SECTION C1: Calculation of Open Loop Tuning Parameters

Cohen & Coon Rules

The Cohen & Coon tuning rule assumes that the S-shaped Process Reaction curve can be approximated by a process model consisting of a First order lag and a Dead Time.

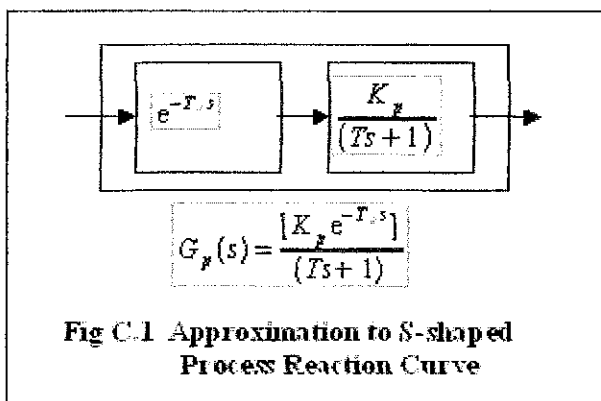


Table C.1. Open Loop Tuning – Controller Parameter Calculations

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

SECTION C2: Calculation of Closed Loop Tuning Parameters

Ziegler-Nichols Rules

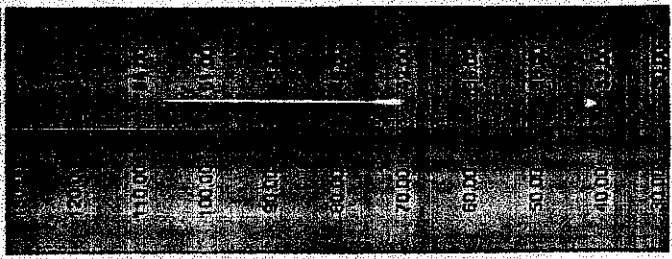
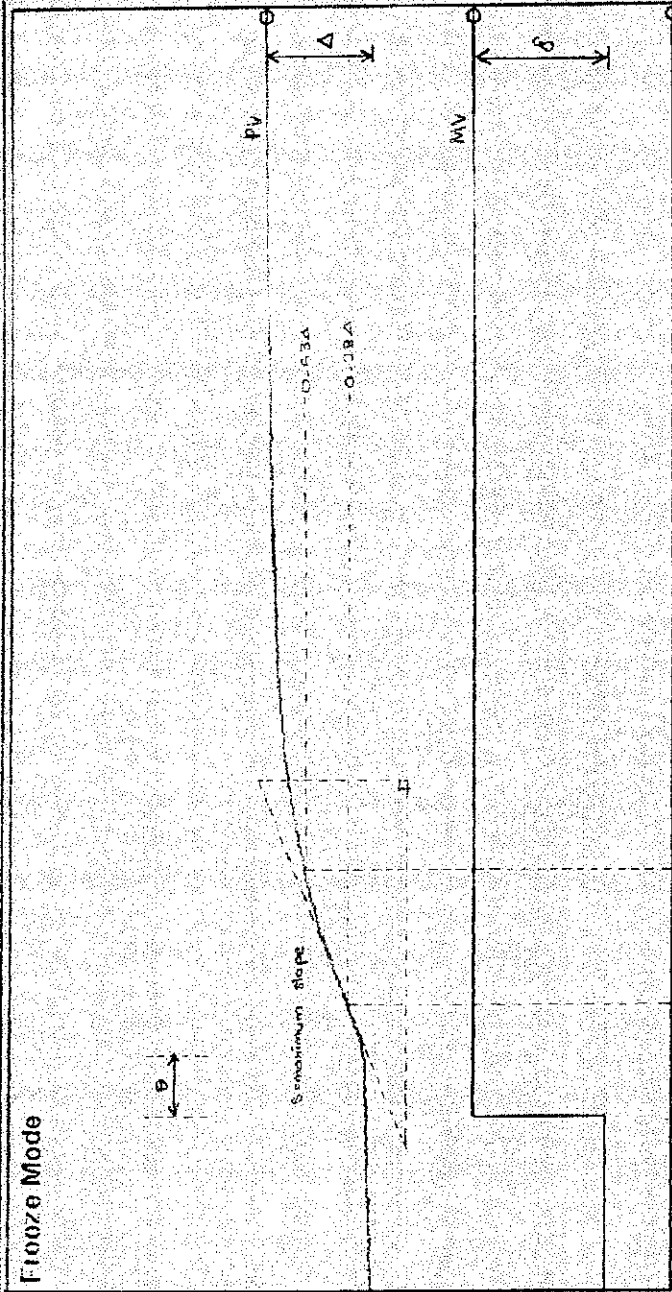
Table C.2. Closed Loop Tuning – Controller Parameter Calculations

<i>Control Modes</i>	<i>K_c</i>
P only	$K_c = 0.5K_u$
P+I	$K_c = 0.45K_u$
	$T_I = T_u/1.2$
P+I+D	$K_c = 0.6K_u$
	$T_I = T_u/2$
	$T_D = T_u/8$

APPENDIX C

PROCESS DYNAMIC OF TT634

SIM 305 Pilot Plant
 PC Automation Sdn. Bhd.
 Experiment 4 - Heat Exchanger Temperature Control - Tuning TIC-634
 14-Sep-2004 04:24:17 PM



Time	PV	MV
4:08:14 PM	60.00	0.00
9/14/2004		
4:09:44 PM	60.00	0.00
9/14/2004		
4:11:14 PM	60.00	0.00
9/14/2004		
4:12:44 PM	60.00	0.00
9/14/2004		
4:14:14 PM	60.00	0.00
9/14/2004		
4:15:44 PM	60.00	0.00
9/14/2004		
4:17:14 PM	60.00	0.00
9/14/2004		
4:18:44 PM	60.00	0.00
9/14/2004		
4:20:14 PM	60.00	0.00
9/14/2004		

Description	Value	Time	Date
TIC634 MV	60.00	4:21:38 PM	9/14/2004
TIC634 PV	48.30	4:21:38 PM	9/14/2004
TIC634 SP	0.00	4:21:38 PM	9/14/2004

Home	Overhaul	Trend	Alarm
Back	Tune TIC634		

APPENDIX D
METHOD I - PLANT MODEL CALCULATION

Method 1

$$\delta = 20 \% = 0.2$$

$$\Delta = 4.7^{\circ}\text{C}$$

$$K_p = \Delta / \delta = 0.235$$

$$S = 7 / 4.33 = 1.615$$

$$\tau = \Delta / S = 2.91$$

$$\theta = 1.3$$

The model transfer function:

$$\begin{aligned} \frac{Y(s)}{X(s)} &= \frac{K_p e^{-\theta s}}{\tau s + 1} \\ &= \frac{0.235 e^{-1.3s}}{2.91s + 1} \end{aligned}$$

APPENDIX E
METHOD II - PLANT MODEL CALCULATION

Method II

$$\partial = 20 \%$$

$$\Delta = 4.7 \text{ }^\circ\text{C}$$

$$K_p = \Delta / \partial = 0.235$$

$$0.63\Delta = 46.5 \text{ }^\circ\text{C} \quad t_{63\%} = 2.475$$

$$0.28\Delta = 44.8 \text{ }^\circ\text{C} \quad t_{28\%} = 0.975$$

$$\tau = 1.5(t_{63\%} - t_{28\%}) = 2.25$$

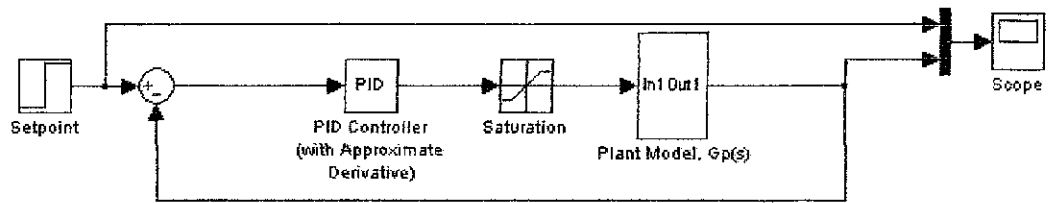
$$\theta = t_{63\%} - \tau = 0.225$$

The model transfer function:

$$\begin{aligned} \frac{Y(s)}{X(s)} &= \frac{K_p e^{-\theta s}}{\tau s + 1} \\ &= \frac{0.235 e^{-0.225s}}{2.25s + 1} \end{aligned}$$

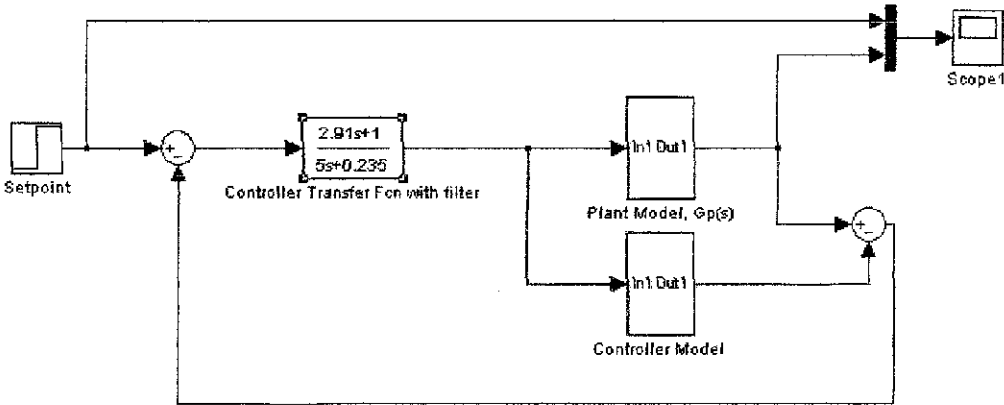
APPENDIX F

FEEDBACK CONTROL PERFORMANCE CONFIGURATION



FEEDBACK MODEL

APPENDIX G
IMC CONTROL PERFORMANCE CONFIGURATION



IMC MODEL

APPENDIX H

TUNING ALGORITHM CALCULATION USING BODE PLOT METHOD

Generated Bode Plot using MATLAB:

```
>> s = tf('s');  
>> G = [0.235/(2.91*s+1)];  
>> G.inputdelay=1.3;  
>> bode(G)  
Grid
```

Bode Plot Calculation:

$$\begin{aligned}20 \log_{10} X &= -25\text{dB} \\ X &= \log_{10}^{-1} (-25/20) \\ &= 0.056\end{aligned}$$

Based on Ziegler Nyquist Stability Criterion:

$$\begin{aligned}\text{Ultimate Gain: } Ku &= \frac{1}{|G_p(j\omega)|} \\ &= 1/2.44 \\ &= 0.41 \\ \text{Ultimate Period: } Pu &= \frac{2\pi}{\omega_c} \\ &= 29.78\end{aligned}$$

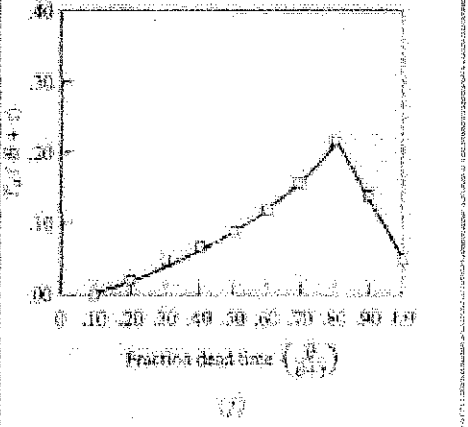
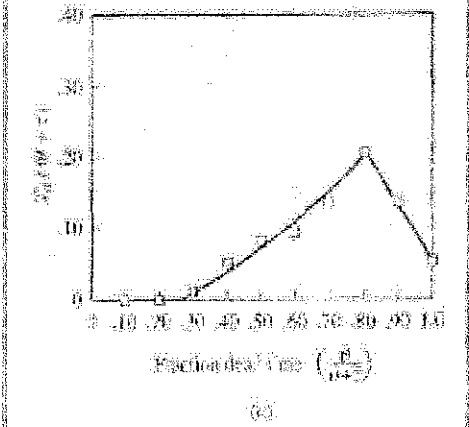
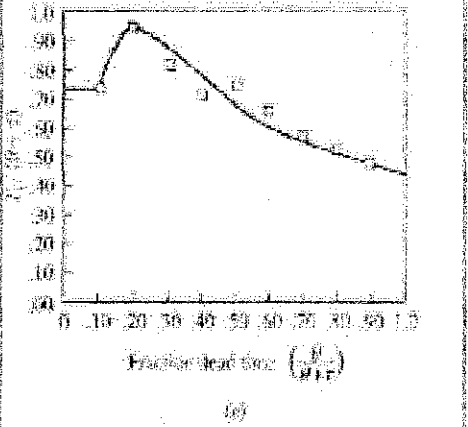
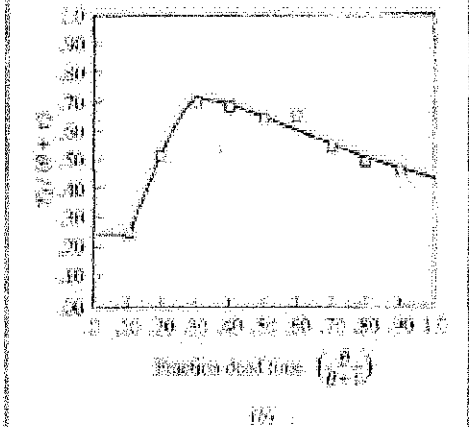
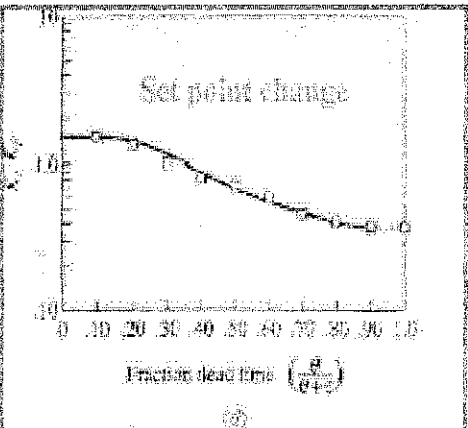
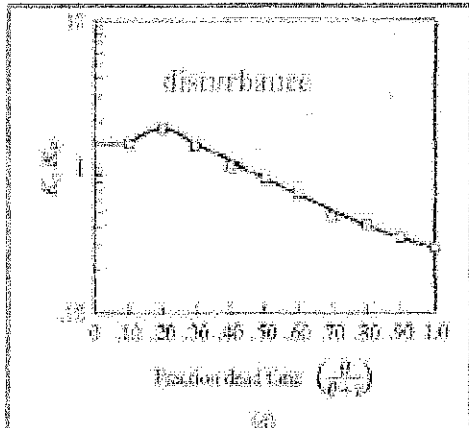
$$\begin{aligned} \text{Process Gain, } K_c &= K_u / 1.7 \\ &= 0.24 \end{aligned}$$

$$\begin{aligned} \text{Integral Time Constant, } \tau_I &= P_u / 2 \\ &= 4.9 \end{aligned}$$

$$\begin{aligned} \text{Derivative Time Constant, } \tau_D &= P_u / 8 \\ &= 3.73 \end{aligned}$$

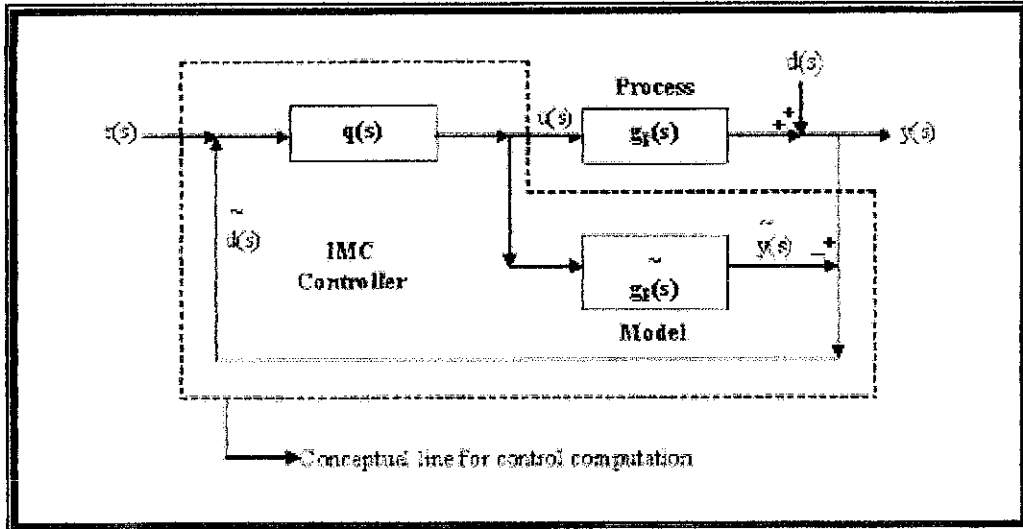
APPENDIX I

CIANCONE CORRELATION TABLE

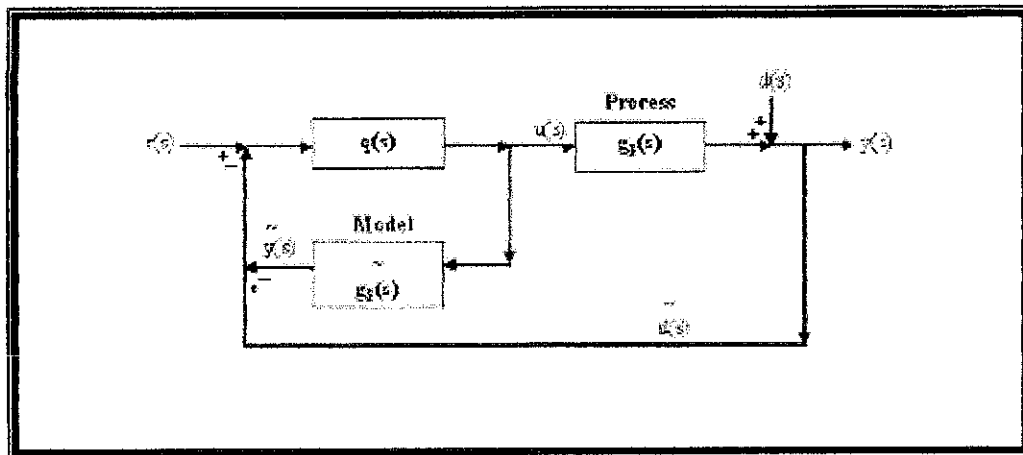


APPENDIX K

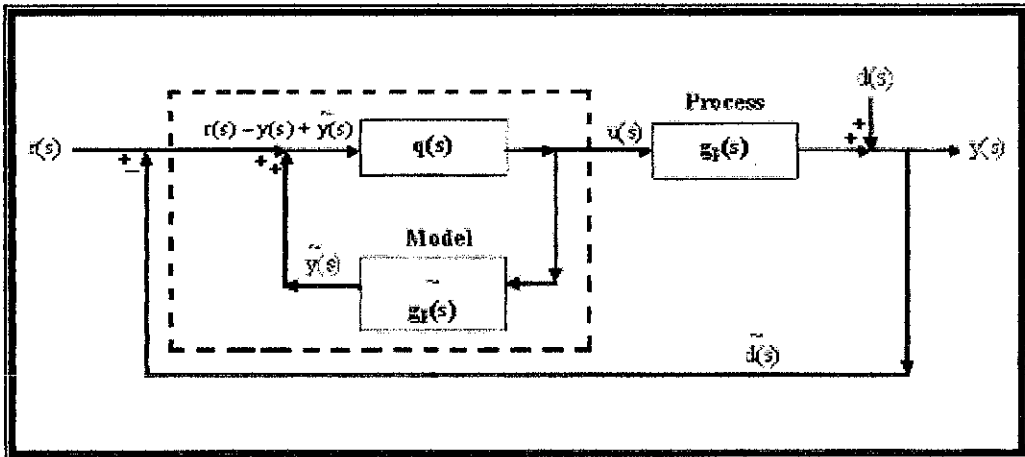
EQUIVALENT DIAGRAM OF IMC AND PID CONTROLLER



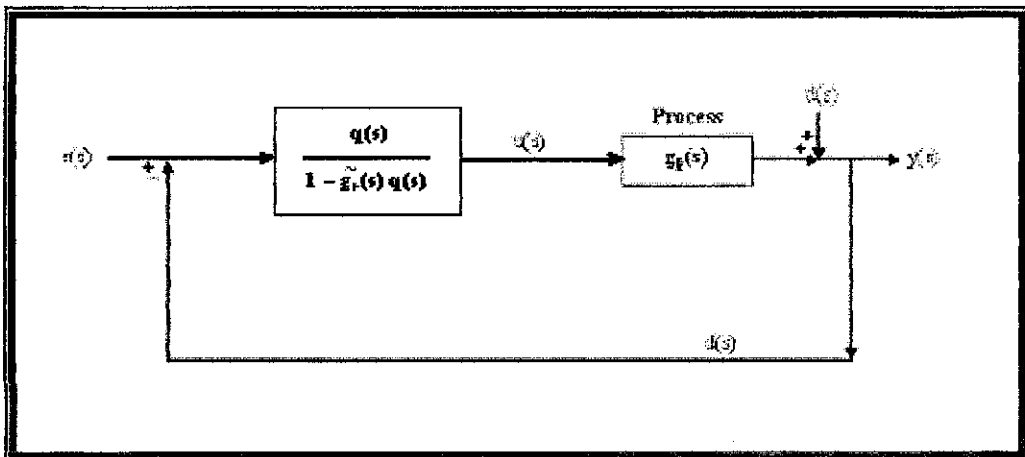
BASIC IMC MODEL



NEW ARRANGEMENT OF IMC MODEL



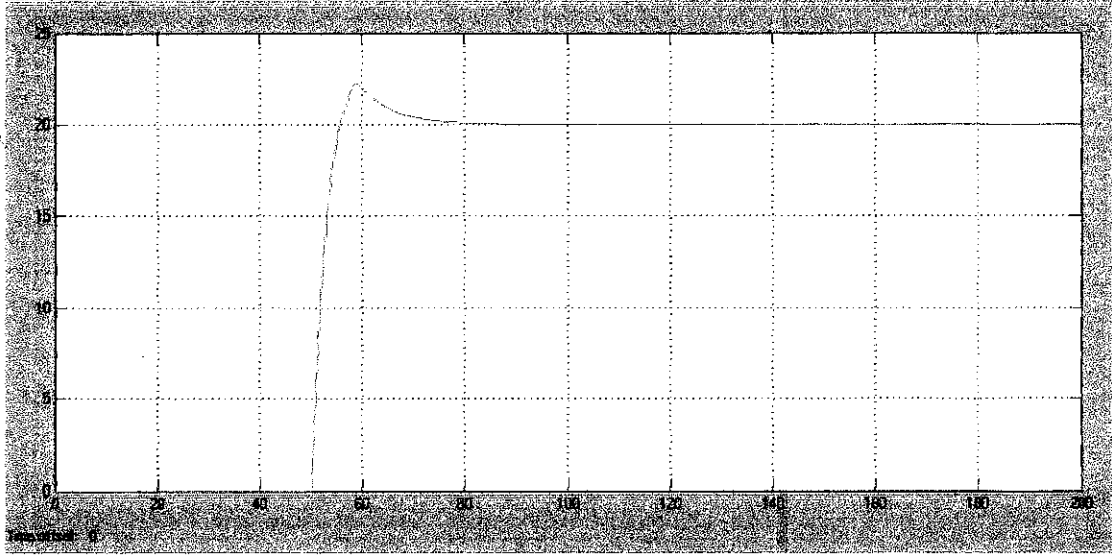
BLOCK DIAGRAM (LOOP SPLITTED) TO GIVE BETTER OVERVIEW



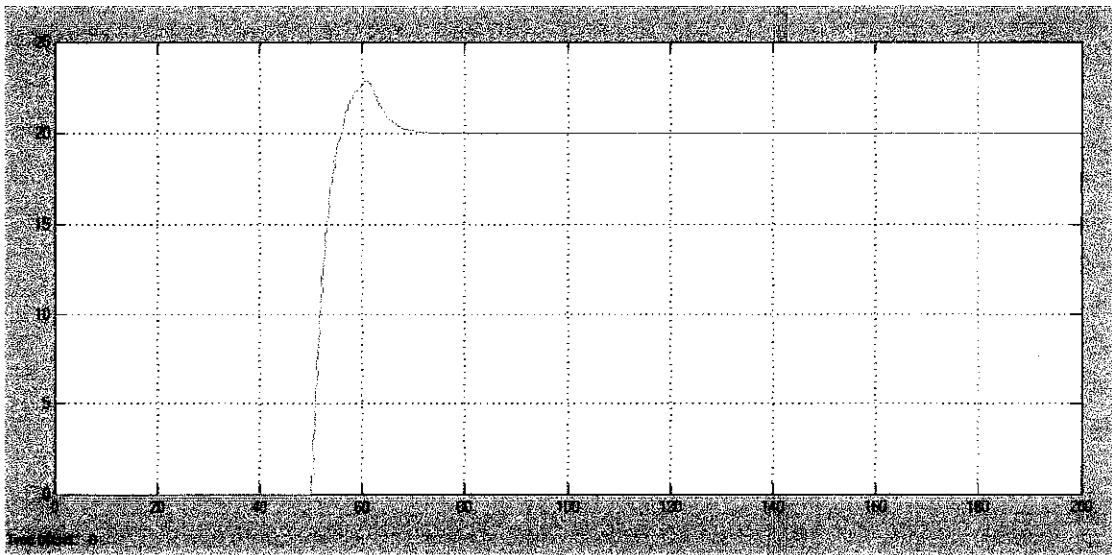
SIMPLEST BLOCK DIAGRAM REDUCTION

APPENDIX L
RESULT OF IMC TUNING

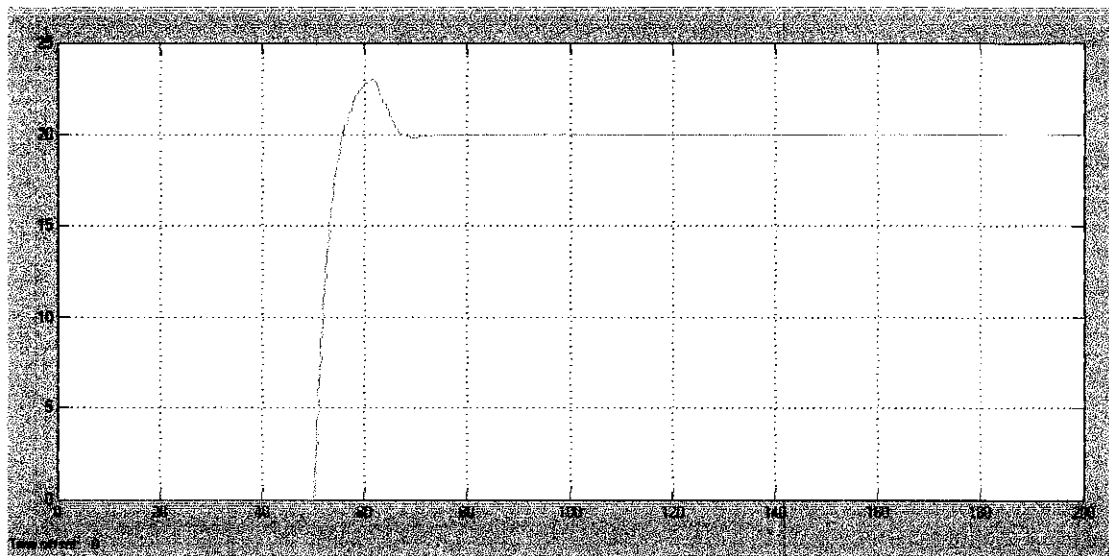
$\lambda = 0.1$



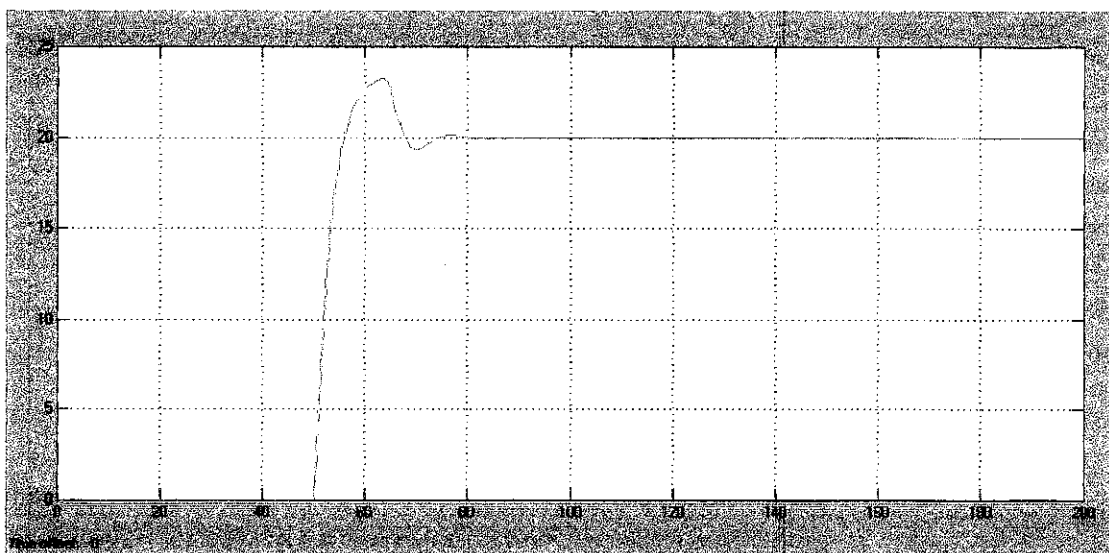
$\lambda = 1$



$$\lambda = 2$$



$$\lambda = 5$$



$$\lambda = 10$$

