PERFORMANCE COMPARISON OF PI AND FUZZY LOGIC CONTROLLER OF A HEAT RECOVERY STEAM GENERATOR

by

ABDULLAH SOBRI BIN NIK MU'TASIM

A project dissertation submitted to the Electrical & Electronics Programme

in partial fulfilment of the requirements

for the Degree

Bachelor of Engineering (Hons)

(Electrical & Electronics Engineering)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2011

CERTIFICATION OF APPROVAL

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Approved 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.

Abdullah Sobri bin Nik Mu'tasim

ABSTRACT

Recently, energy consumption is getting increased rapidly. However, the sources of energy nowadays are limited and the demand is getting increased in the course of time. Heat recovery steam generator or HRSG is one of the big equipment that is productively being used these days to recover the heat and to produce it into steam that can be used in many applications. However, it is known that HRSG is a complex system and using conventional controller to control the system has brought a lot of drawbacks. Providentially, the requirements for fast and flexible responses along with the increasing complexities of modern plant process control applications has motivated new enhancements and works in the invention of various control techniques in many process plant and Fuzzy logic is known as one of the technique available. This project aims to develop a control strategy using a fuzzy logic controller to be used as a pressure controller to control the input of the Heat recovery steam generator (HRSG) model which is the exhaust gas from a connected gas turbine as per the steam demand and also as an alternative to the existing conventional PI controller. The model of the heat recovery steam generator and the designed Fuzzy logic controller is entirely developed by using the MATLAB/Simulink software. The PID and Fuzzy Logic toolbox available in the MATLAB Product Family is used to its full advantage in order to perform the necessary simulations for the designed controllers. Mamdani approach is chosen in order to develop the Fuzzy Inference System (FIS). The effectiveness, feasibility and the performance of the designed fuzzy logic controller is studied through simulation and the results are compared with the existing conventional PI controller. The simulation results shows that a fuzzy logic controller developed in this study yields a better performance compared to a PI controller in terms of settling time, overshoot, final value, rising time and integral of absolute error.

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LIST OF ABBREVATIONS AND SYMBOLS

FLC	Fuzzy Logic Controller
HRSG	Heat Recovery Steam Generator
PID	Proportional, Integral, Derivative
PI	Proportional, Integral
MFs	Membership Functions
COG	Centre of gravity
BOA	Bisector of Area
NVB	Negative Very Big
NB	Negative Big
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big
PVB	Positive Very Big
W_i	Inflow of mass flow rate of steam
W_o	Outflow of mass flow rate of steam
ρ	Density of steam in vessel
V_s	Volume of steam in vessel
p_v	Function of steam pressure
Csh	Pressure drop
T_v	HRSG drum time constant
T_u	Super heater time constant
T_m	Steam generation system time constant
Blspm	Gas Turbine exhaust
Pr	Pressure Controller set point
xmd	Steam demand
xme	Output of steam generation

xp	Saturated steam
W_v	Virtual steam production
F	Firing intensity
$e_{(k)}$	Error
$ce_{(k)}$	Change of error
K_e	Scaling factor for error
K_{ce}	Scaling factor for change of error
K_u	Scaling factor for output
UD	Universe of discourse
Δu	Fuzzy logic control output
MV	Manipulated Variable
PV	Process variable
Kp	Proportional gain
Ti	Integral gain
p.u	Per unit
Tr	Rising time
Ts	Settling time
IAE	Integral of absolute error
Mp	Maximum Overshoot

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Recently, energy consumption is getting increased rapidly. Basic human needs can only be met through industrial growth, which depends on the capability of energy supply. However, the sources of energy nowadays are limited and the demand is getting increased in the course of time. The increase in number of population during the last few decades have placed great burden on the electrical utility industry and process plants resulting in the need for additional capacity in the areas of power and steam generation throughout the world [2].

Steam is used in nearly every industry, and it is well known that steam generators and heat recovery boilers are of prime importance to power and process plants [2]. Waste heat recovery has become very important to the efficient use of energy in the industrial process as the need for energy recovery from low to medium sources is vital.

Heat recovery steam generator or HRSG is one of the big equipment that is productively being used these days to recover the large amount of heat that is produced from the exhaust of a gas turbine and turning the heat into saturated steam that can be used in many applications. Consequently, a HRSG must be designed to operate efficiently and safely while responding rapidly to demand changes particularly in the demand of steam.

More on, having seen that the complexities of HRSG system increasing day by days and the need for fast and accurate responses has risen up a question on whether is it still possible to use the conventional control methods to control this complex system. Thus, in order to solve the question an implementation of intelligent control techniques that is capable of reducing operating costs while providing greater flexibility in plant management and control is needed so that engineers can observed the differences that it can give compared to the conventional one. Here, Fuzzy Logic technique is one such intelligent technique that is believed can be easily implemented to control a complex system.

1.2 Problem Statement

Heat recovery steam generator (HRSG) system is a complex industrial process with highly nonlinear characteristics and has to operate under many uncertainties [2]. In order to fully utilize the functioning of a Heat Recovery Steam Generator (HRSG) system, a reliable control of super-heated steam pressure is necessary to ensure high efficiency and quick load meeting capability. Previously, the use of conventional Proportional Integral (PI) controller does not provide adequate control performance with the consideration of nonlinearities [1] thus making it often difficult to achieve the required target.

More on, the increasing complexities of modern industrial processes and the requirement of fast and flexible responses have limited the capability of the conventional PI controller. In these days with the advancement in technology and industrial processes, based on [3] it is believed that Fuzzy logic as one of such advanced control technique, in which knowledge based design rules can easily be implemented to control a complex system can be used to overcome the inconsistency produced by the conventional controller.

1.3 Objectives

There are several objectives that have been listed to be achieved throughout this project which are as follows:

- To investigate the process variable that effect on controlling of the Heat Recovery Steam Generator (HRSG) model.
- To design and implement a fuzzy logic controller (FLC) as a pressure controller for the simplified HRSG model.
- To study the effectiveness of the designed fuzzy logic controller (FLC) by simulation via MATLAB environment.
- To compare the performance of fuzzy logic controller (FLC) with the conventional Proportional Integral (PI) controller.

1.4 Scope of Study

The scope of this project is mainly focus on designing a PI and Fuzzy logic Controller using the PID and Fuzzy Logic toolbox that are available in the MATLAB Simulink software. Both of these designs will then be integrated into the reduced order model of a Heat recovery steam generator system which is also build using the MATLAB Simulink environment. The integrated HRSG model with both of the respective controllers will then be simulated and tested. The output of the simulation will be analyzed in details.

1.5 Significance of the research

As been mentioned before, HRSG system is a complex system with nonlinear characteristic consists of many uncertainties. Thus, it is hoped that the successfulness of this finding for the right method to control the HRSG system particularly in controlling the steam pressure could provide a significant impact in terms of the development of advanced controllers for plant process applications, especially in terms of the Fuzzy Logic Control approach.

CHAPTER 2

LITERATURE REVIEW

2.1 Heat Recovery Steam Generator (HRSG) System

A heat recovery steam generator or HRSG is an energy recovery heat exchanger that recovers heat from a hot gas stream. It produces steam that can be used in a process or used to drive a steam turbine. Heat recovery steam generators (HRSGs) are widely used in process and power plants, refineries and in several cogeneration/combined cycle systems. They are usually designed for a set of gas and steam conditions but often operate under different parameters due to plant constraints, steam demand, different ambient conditions (which affect the gas flow and exhaust gas temperature in a gas turbine plant), etc. [5]. As a result, the gas and steam temperature profiles in the HRSG, steam production and the steam temperature differ from the design conditions, affecting the entire plant performance and economics. HRSG performance has a large impact on the overall performance of a combined-cycle power plant [7].

Figure 1: Modular of a HRSG system

Figure 2 below shows a schematic diagram of a HRSG system. The HRSG generates steam utilizing the energy in the exhaust from the gas turbine [6]. Heat recovery steam generator consists of four fundamental parts which are drum, super heater, evaporator and economizer. Generally, the input of the heat recovery steam generator is coupled to a gas turbine exhaust and the output is connected to the steam turbine which is connected to its electric generator. The large amount of waste heat energy that is produced from the gas turbine exhaust or the supplementary fuel is used to generate steam in the evaporator. As the generated steam reaches the point at the top position of the drum, the generated steam will flow through the super heater and will be further heated to be converted into saturated steam. Hence, the produced saturated steam will be used to drive a steam turbine to produce electricity.

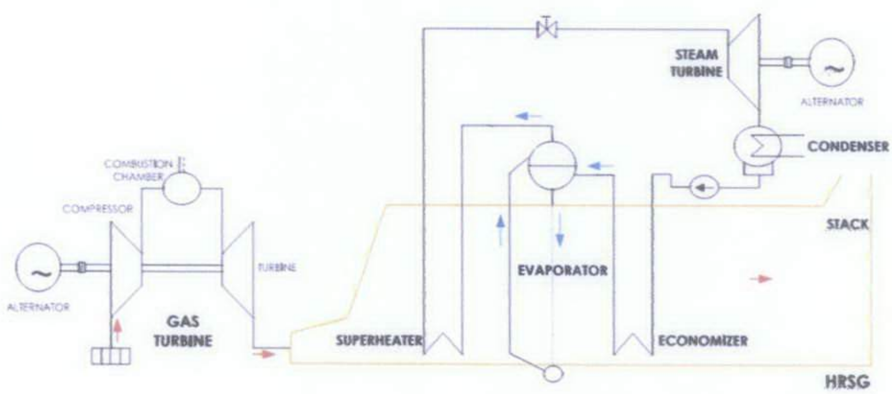

Figure 2: Schematic diagram of HRSG system

2.2 Mathematical Model of Heat Recovery Steam Generator (HRSG)

The mathematical model of the HRSG for the purpose of studying the steam pressure control used throughout the research is fully obtained and referred to [4]. Low order or reduced order model is used for the HRSG for control system tuning and analysis. Basically, the steam pressure in any vessel depends on thermodynamics principle and energy mass balance of rate of flow of steam at the inlet and outlet like as shown below:

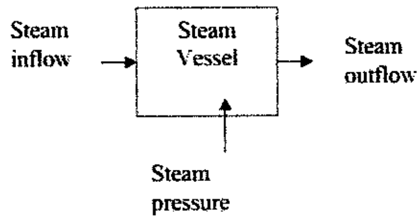

Figure 3: Steam Vessel

Inflow = Outflow = Rate of change of stored energy mass

$$W_i - W_o = \frac{d}{dt}(\rho . V_s) \qquad (1)$$

The above equation shows the energy mass balance of rate equation. W_i and W_o is the mass flow rate of steam in and out respectively and ρ is the density of steam in vessel. V_s is the volume of the steam vessel. Density (ρ) is a function of steam pressure (p_v) assumed uniform in the vessel [4].

Equation 1 can be written in the form of transfer function through Laplace transformation and referring the variables to their nominal values with subscript 'u' whereby T_{sv} is under the units of seconds like as shown below:

$$(W_{iu} - W_{ou}) = [(1/\, T_{sv}.\, s)\, p_v\,] \qquad (2)$$

In the HRSG storage behavior model as shown in figure 4, the drum, super heater and the connected piping are represented by the above type of transfer function. T_u represents the time constant of the drum and T_v represents the time constant of super heater. The steam flow through super heater is related to the pressure drop across it as indicated by the parameter *Csh* [4].

The block diagram showing the HRSG model is shown as below.

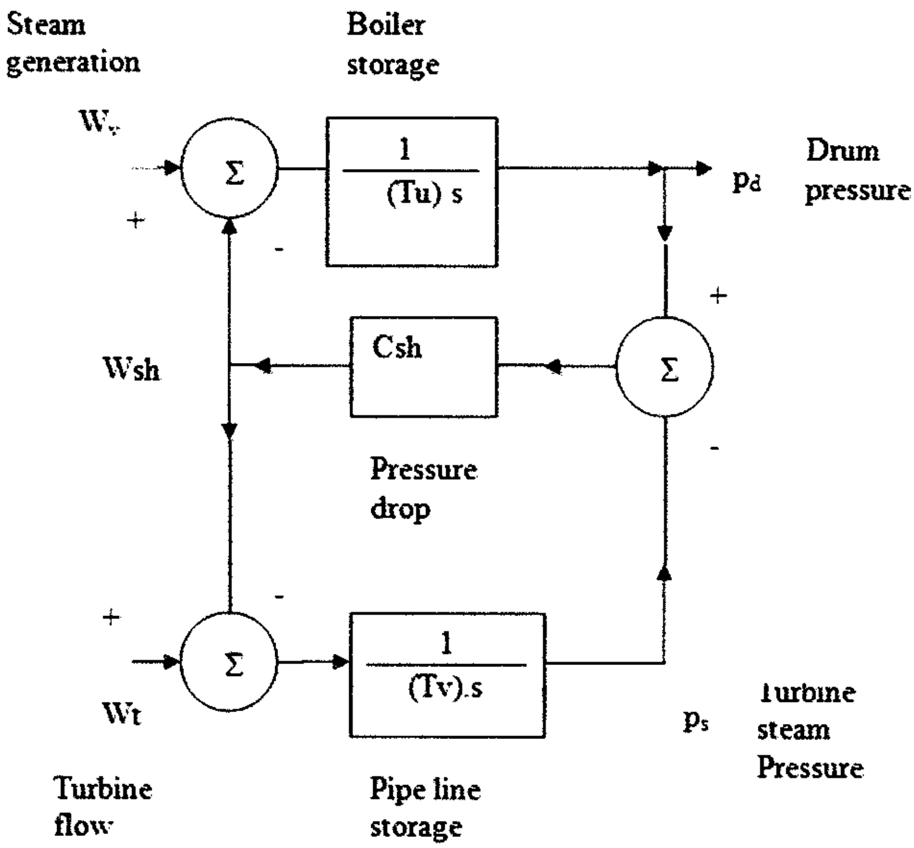

Figure 4: HRSG Storage behavior model

2.2.1 Firing system and Thermal Inertia

The steam generation in the HRSG is subjected to a time constant which depends upon the firing system time lag and the 'thermal inertia'. Thermal inertia may be defined as the time constant associated with the virtual steam production (W_v) in the boiler when the firing intensity (F) is changed by the firing system. The firing system time constant and the thermal inertia time can be represented by the transfer functions as shown in Figure 5. The firing system has a transport lag term ($e^{-Td\ s}$) which represents the dead time associated with coal mills [4].

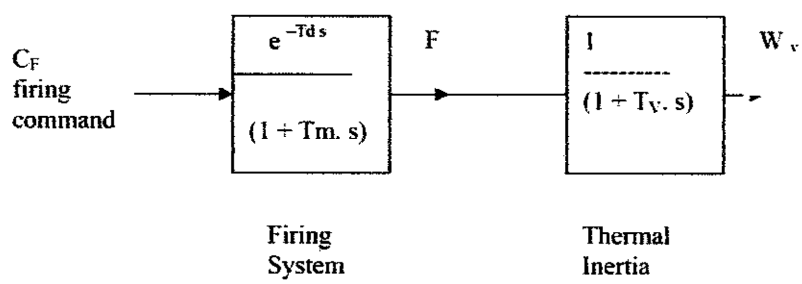

Figure 5: Firing system and thermal inertial model

The firing command is given by the pressure controller or combustion controller which is of proportional – integral- derivative (PID) type. Combining the above blocks completes the mathematical model of the HRSG for the simulation of pressure control loop like as shown in Figure 6.

The model of HRSG developed is as shown below:

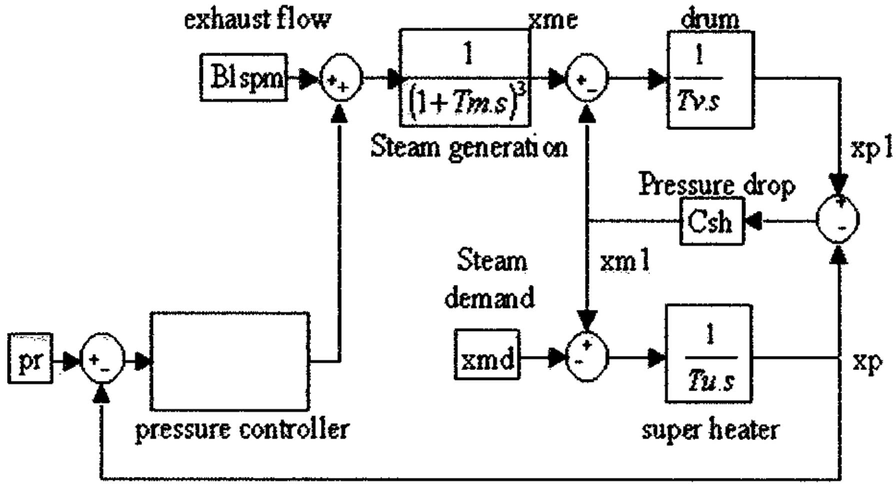

Figure 6: HRSG mathematical model

In Figure 6, *Blspm* is the set point for steam generation (or power output) and *pr* is the pressure set point. All the variables are in non-dimensional form. Steam demanded by the turbine is shown as *xmd*. The unit delay term ($e^{-Td\ s}$) has been replaced by cascaded first order block [$1/(1 + \text{Tm s})^3$] for convenience in simulation process. The description of parameters for the above HRSG model can be referred in the appendices section in table I.1.

2.3 Conventional Approach

Conventional Proportional, Integral and Derivative feedback control is a simple, design based on the deviation, or error, between a set point and the value of a process variable. The output variable is usually a final element such as a control valve or variable speed drive. The corrective action will be taken based from the signal of which is calculated from the magnitude of the error (proportional mode), the persistence of the error (integral mode) and the rate-of-change of the error (derivative mode) [8].

The PID controller calculation (algorithm) involves three separate parameters; the proportional, the integral and derivative mode. The proportional mode determines the reaction to the current error, the integral value determines the reaction based on the sum of recent errors, and the derivative value determines the reaction based on the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the input supply of a heating element. By tuning the three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements.

The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. PI controllers are particularly common, since derivative action is very sensitive to measurement noise, and the absence of an integral value may prevent the system from reaching its target value due to the control action.

2.4 Fuzzy Logic Control

2.4.1 Fuzzy Logic concept

A fuzzy system consists of fuzzification module, fuzzy rule base, fuzzy inference engine and defuzzification module. Generally, the fuzzification module converts real world value or variable into the fuzzy expert system or fuzzy sets. The inference engine uses the results of the fuzzification module and accesses the fuzzy rules in the fuzzy rule base to determine directly the outputs from the knowledge base and online data by minimum and maximum operation. The final output of the fuzzy expert system is provided by the defuzzification module. With defuzification module, the aggregated fuzzy set can be converted into a crisp value which is known as defuzzification. A typical fuzzy logic system is shown in figure 7.

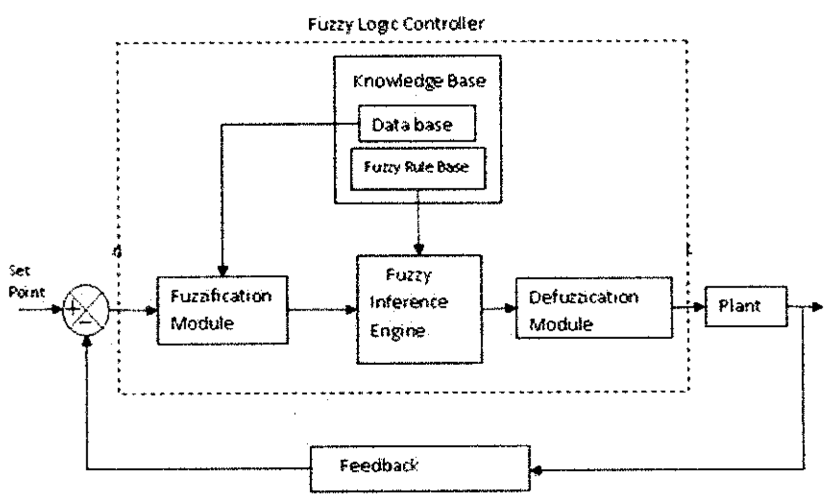

Figure 7: Fuzzy logic system

2.4.2 Fuzzy Sets

Set theory forms the foundations of arithmetic, logic and indeed the major part of mathematics and formal reasoning. We tend to move naturally from the classification of everyday language to mathematical formulation of a set [9].

2.4.3 Membership function

The membership function of a fuzzy set is a graphical representation of the magnitude of participation of each input [10]. It is a generalization of the indicator function in classical sets. Membership functions represent the degree of truth as an extension of valuation. Degrees of truth are often confused with probabilities, although they are conceptually distinct, because fuzzy truth represents membership in vaguely defined sets, not likelihood of some event or condition [11].

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. There are different membership functions that are associated with each input and output response. Figure 8 shows different types of membership functions that can be used to create a fuzzy logic controller.

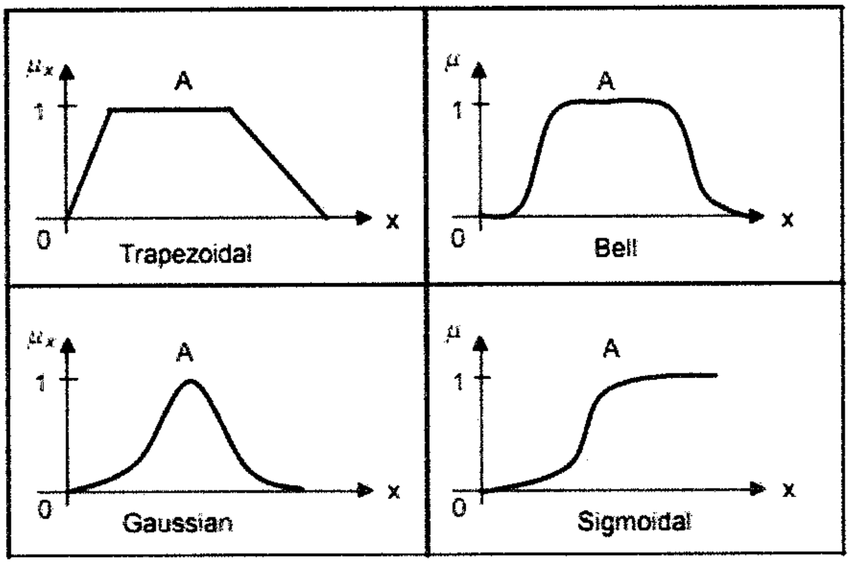

Figure 8: Types of Membership Functions

2.4.4 Rule Base

The fuzzy rule base consists of a collection of fuzzy rules. Fuzzy rules can be developed by two different methods. One method is to derive IF-THEN rules based on the knowledge. Another method is to select a few data as input-output pairs to determine IF-THEN rules. When fuzzy logic rules are obtained from input/output data, data pairs can become the canters of appropriate fuzzy regions, which correspond to appropriate fuzzy variables.

2.4.5 Defuzzification

Defuzzification is the process of producing a quantifiable result in fuzzy logic. It is the process in which the fuzzy quantities are defined over the output membership functions that are mapped into a non-fuzzy value. Typically, a fuzzy system will have a number of rules that transform a number of variables into a "fuzzy" result, that is, the result is described in terms of membership in fuzzy sets. There are many different methods to achieve the defuzzification process such as which Centre of Gravity (COG), Bisector of Area (BOA) and Mean of Maxima.

CHAPTER 3

METHODOLOGY

3.1 Project Workflow

The project workflow is as shown below:

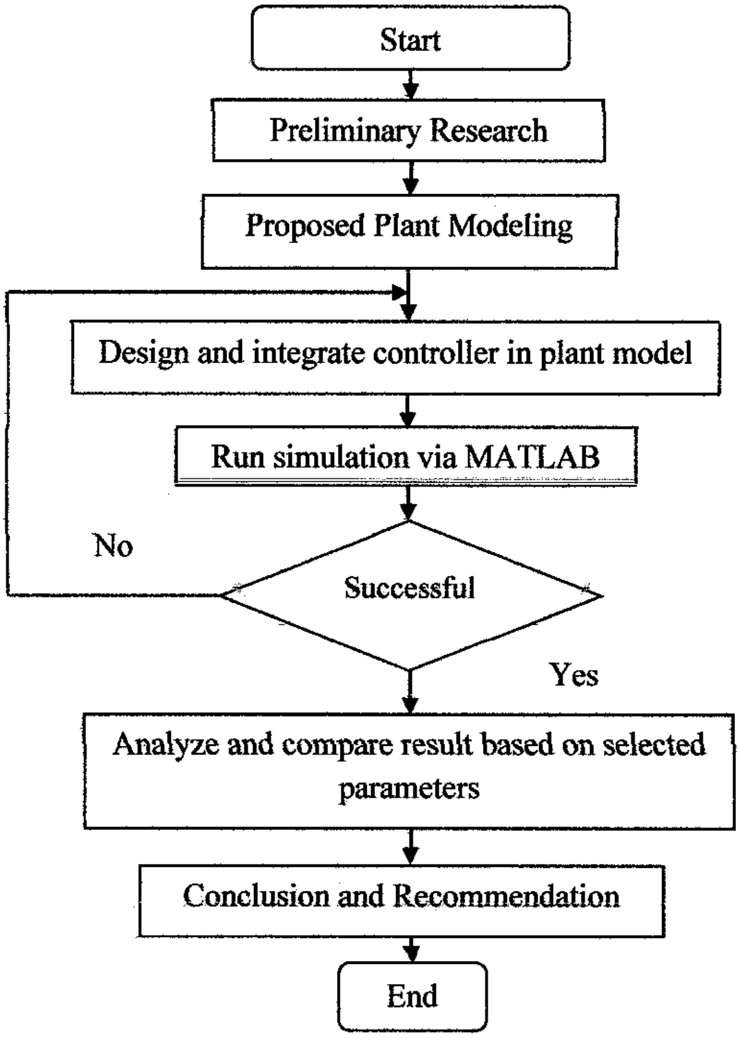

Figure 9: Project Activities Flow Chart

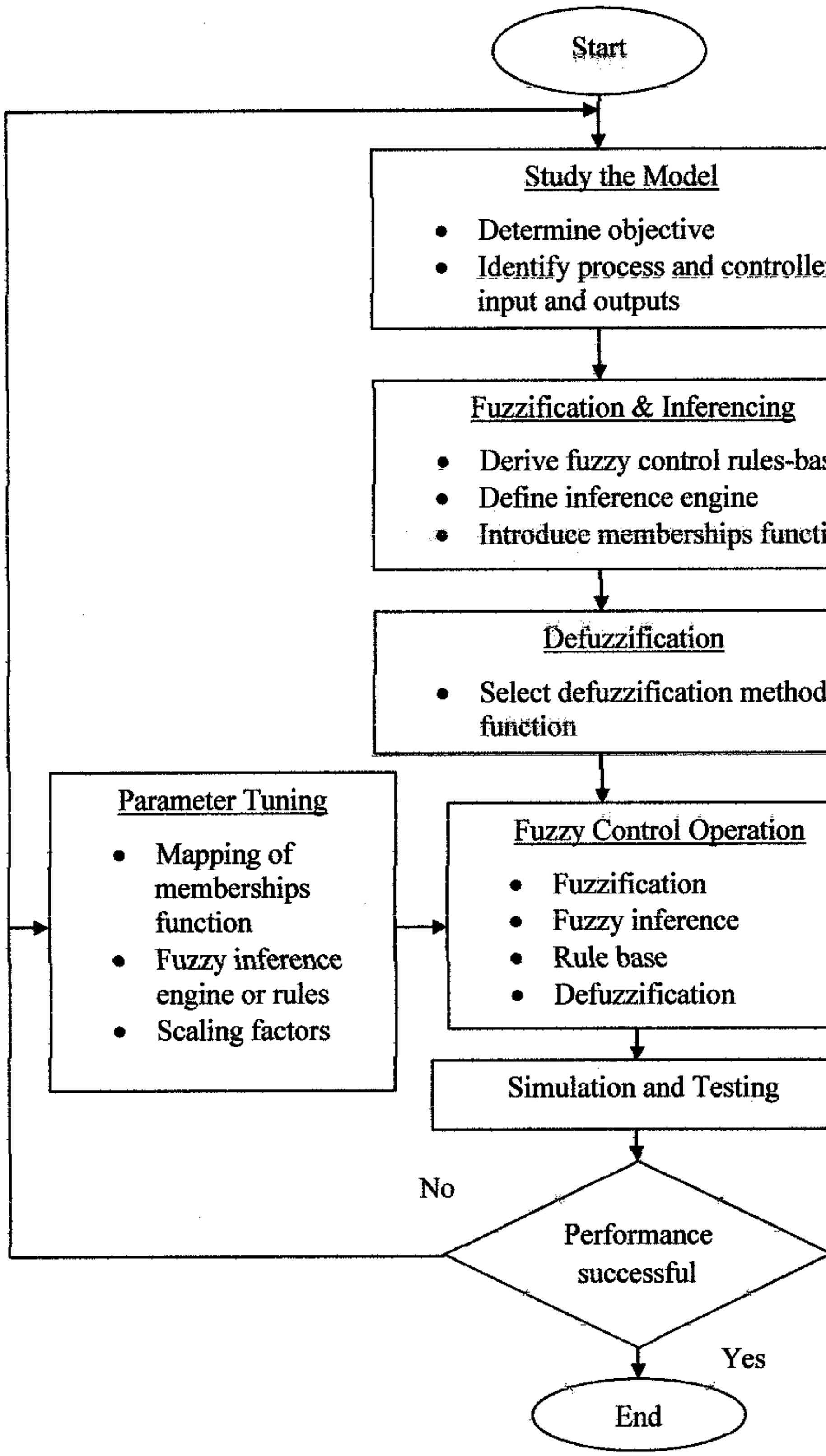

Figure 10: FLC design methodology

3.2 Gantt Chart

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

3.3 Tools Required

Throughout this project, MATLAB SIMULINK environment is used as the medium to design and implement the modeling and simulation of HRSG model. The designing of Fuzzy logic controller was completed by using the Fuzzy Logic Toolbox which is available in MATLAB software.

3.4 Fuzzy Logic Controller Design

Fuzzy logic control is based on heuristic knowledge and linguistic description. FLC uses fuzzy sets and fuzzy inference to derive control laws in which no precise model of the plant exists and most of the priori information is available only in qualitative form. Since FLC does not require accurate mathematical models of a system, the effects from inaccurate parameters and models are reduced. FLC design approach is shown in figure 10.

The fuzzy controller design can be performed by defining four things. Firstly, the fuzzy input and output variables and their membership functions are determine and selected with respect to the model of the system. Secondly is by establishing the rule base or sets. Then the inference engine rule linking the input and output variables is expressed. The final part of designing the FLC is the defuzzification part of the output parameter. In this project, FLC is used as a steam pressure controller in order to control the HRSG system with respect to the changes in steam demand.

Figure 11 shows the typical block diagram of a HRSG coupled with FLC. As shown in figure 11, the inputs to the fuzzy controller are the error $e_{(k)}$ between the *pressure controller set point (pr) and superheater steam pressure (xp) and the change of* error $ce_{(k)}$. The output of the controller is the pressure. K_e, K_{ce} and K_u are the scaling factors that are used to tune the FLC to obtain the desired response.

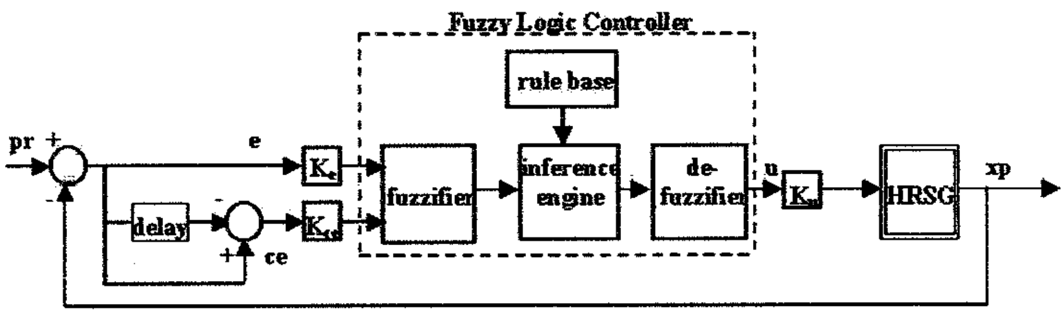

Figure 11: Block diagram of Fuzzy logic Controller integrated with HRSG model

3.4.1 Fuzzification

The first block inside the fuzzy logic controller is fuzzification. The fuzzification block converts each piece of real world variables or data into fuzzy sets. In order to select the number of fuzzy sets and their parameters, the universe of discourse has to be decided. The inputs and output can be described as follows:

$$E = e_{(k)} = y_{ref} - y_{(k)}$$

$$CE = ce_{(k)} = y_{(k)} - y_{(k-1)}$$

$$KU = u_{(k)} - u_{(k-1)}$$

The universe of discourse can be described as the range over which the selected variable can vary. In this project, the universe of discourse is taken as [-1 1] for both the inputs and output of the FLC.

3.4.2 Defining Fuzzy Membership Functions

Based on the literature review, in order to perform fuzzy computation both inputs and output must be converted from numerical or "crisp" value into linguistic forms. Fuzzy membership functions are used as a tool to convert crisp values into linguistic terms. The number of membership functions used in the fuzzification plays a very vital part in the final performance of a FLC system and the choice of membership functions has sturdy impact on the control effect.

Basically, a fuzzy membership function can contain several fuzzy sets depending on how many linguistic terms that are used. Each fuzzy set represents one linguistic term. Selecting types of membership functions requires the use of expert knowledge and experience. In this project, the membership functions used to design the FLC are shown in the following figures:

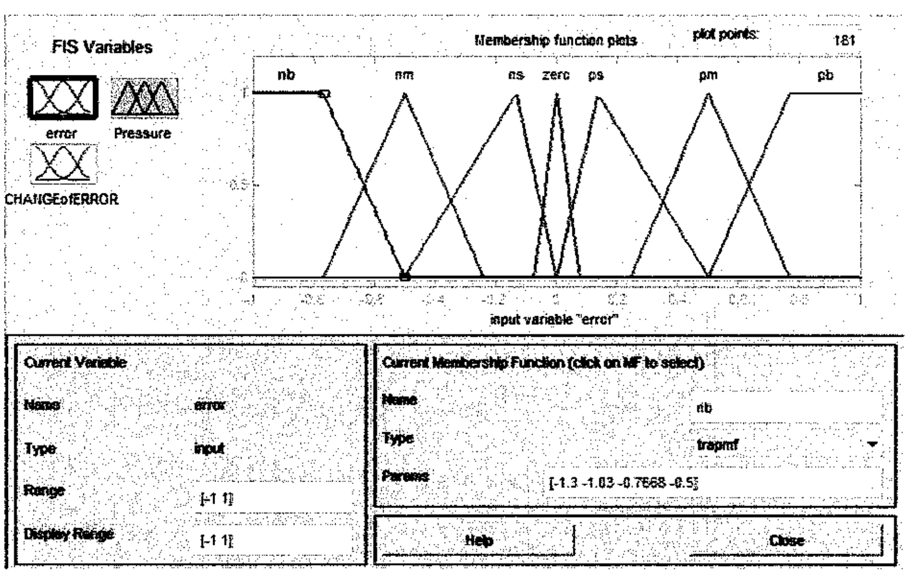

Figure 12: First input (error) of 7 membership function

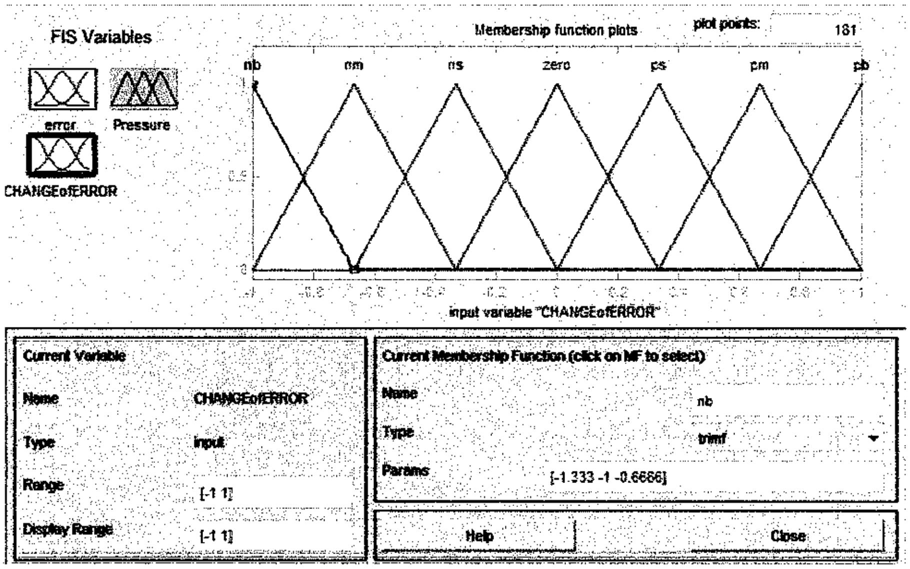

Figure 13: Second input (change of error) of 7 membership function

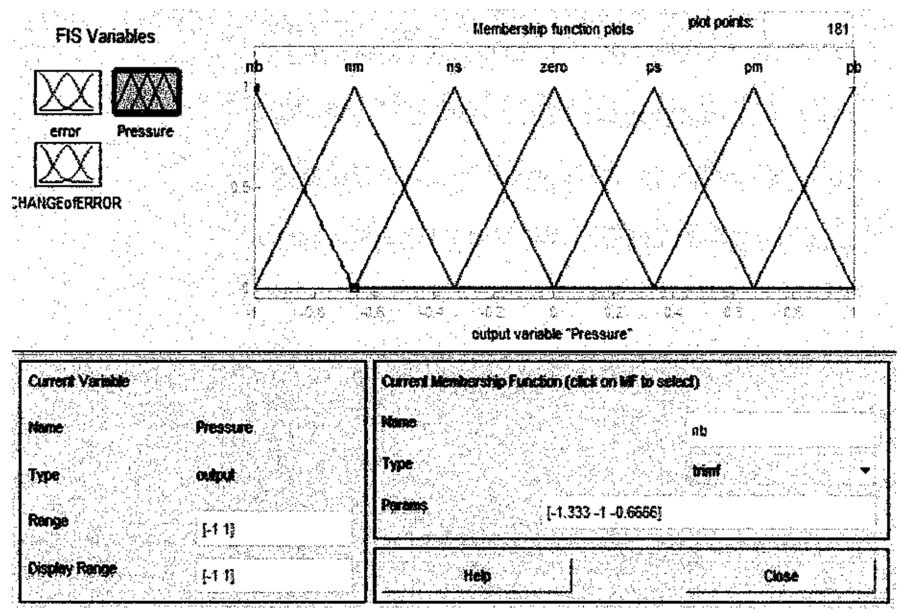

Figure 14: Output of 7 membership function

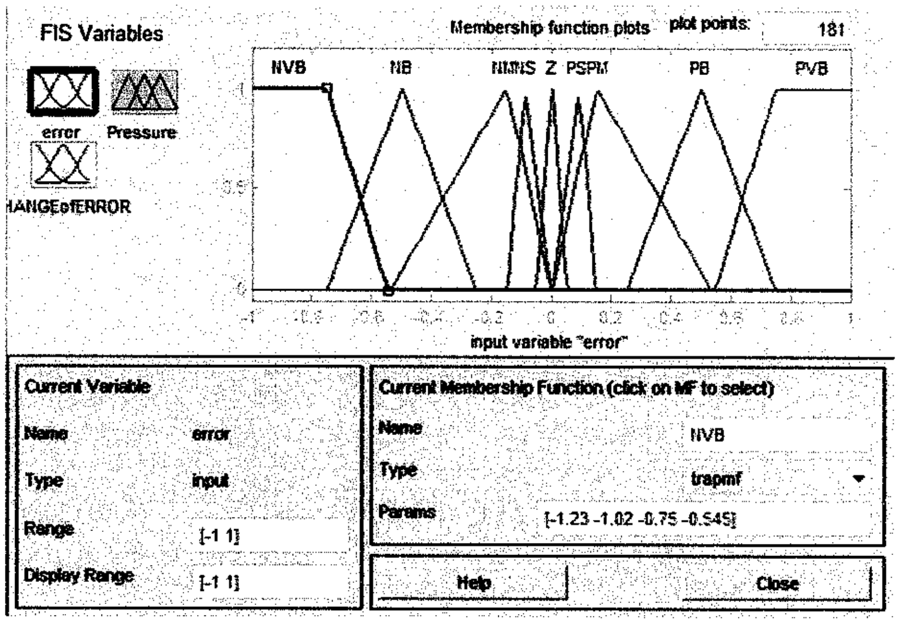

Figure 15: First input (error) of 9 membership function

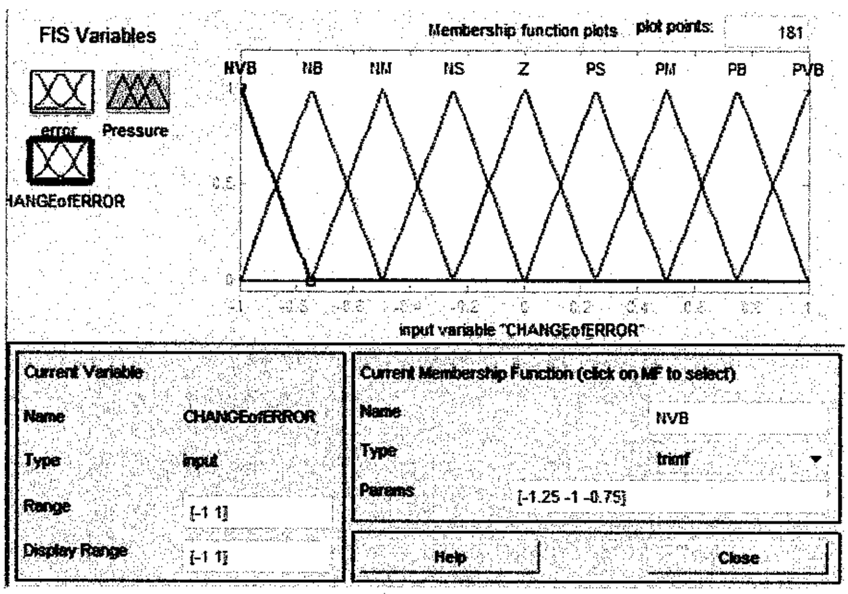

Figure 16: Second input (change of error) of 9 membership function

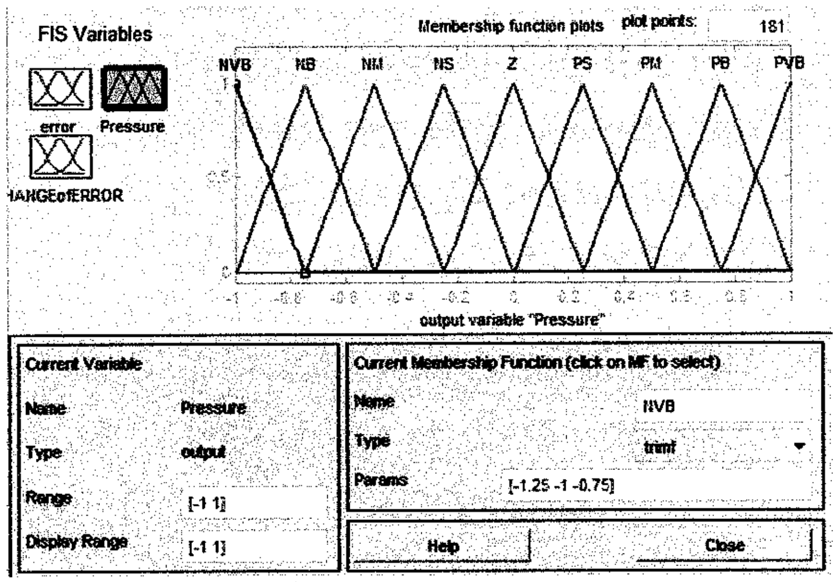

Figure 17: Output of 9 membership function

In this project, the membership functions NB and PB that is shown in figure 12 and membership function NVB and PVB illustrated in figure 15 was set to be in the form of trapezoidal functions while the other are triangular functions in order to have a fast response control on large errors. The range of Z set is made to be small and the peaks of NS and PS are to be as close to Z set in order to reduce the steady state error.

3.4.3 Defining Fuzzy Rule Base

The linguistic variables are used to derive the number of rules in the rule base. As shown in table 1 and table 2 below, 49 rules are used for fuzzy with 7 membership function and 81 rules are used for fuzzy with 9 membership function to control the HRSG model. The rule is developed using basic engineering sense of knowledge. For example, *IF* e is NB and ce is Z *THEN* u is NB.

Table 1: Rule Base with 7 membership function

Error

Change of error	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NS	PS	PS	PS
NM	NB	NB	NB	NS	PS	PS	PS
NS	NB	NB	NM	NS	PS	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NM	NS	PS	PM	PB	PB
PM	NS	NS	NS	PS	PB	PB	PB
PB	NS	NS	NS	PS	PB	PB	PB

Table 2: Rule Base with 9 membership function

Error

Change of error	**NVB**	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**	**PVB**
NVB	NVB	NVB	NVB	NVB	NS	PS	PS	PS	PS
NB	NVB	NB	NB	NB	NS	PS	PS	PS	PS
NM	NVB	NB	NB	NB	NS	PS	PS	PS	PS
NS	NB	NB	NB	NM	NS	PS	PS	PM	PM
Z	NB	NB	NM	NS	Z	PS	PM	PB	PB
PS	NM	NM	NM	NS	PS	PM	PB	PB	PB
PM	NS	NS	NS	NS	PS	PB	PB	PB	PVB
PB	NS	NS	NS	NS	PS	PB	PB	PB	PVB
PVB	NB	NM	NS	NS	PS	PB	PB	PB	PVB

3.4.4 Inference Engine

The basic function of inference engine is to process the overall value of the output from the fuzzy logic controller or formulating of the mapping from a given input to an output based on the effects of each rule from the rule base. Basically the process of inference engine involves all the membership function and *IF – THEN* rules.

3.4.5 Defuzzification

In this project, based on the literature review the method used to perform defuzzification is the center of gravity (COG). Defuzzification is very important in designing a fuzzy logic controller as it involves the process of the fuzzy quantities to be defined over the output membership functions that are mapped into a non-fuzzy value. Hence, the fuzzy logic control output, Δu is determined based on the following equation.

$$\Delta u = \frac{\sum_{i=1}^{81} \mu i \; \mu i}{\sum_{i=1}^{i=81} \mu i} \qquad (3)$$

CHAPTER 4

RESULT & DISCUSSION

This chapter presents the result of the output response of the proposed model with respect to the response of controllers which had been taken for analysis, using simulation process. As discussed in previous chapter the simplified heat recovery steam generator (HRSG) simulation block diagram model [4] is implemented under MATLAB SIMULINK environment using two different controller which is PI controller, and Fuzzy Logic controller respectively. Basically, the result and discussion of the project is divided into three parts; whereby the first part is the result obtained using the PI controller and the second part is the result obtained using the fuzzy logic controller with different memberships function. The last part will emphasize on the performance comparison of both controllers.

4.1 Design of Proportional Integral Controller

In the first part of the project, a PI Controller is developed to act as a pressure controller for the HRSG. The PI controller shown in figure 18 is simulated based on the equation 4.

$$MV(t) = \mathrm{Kp}\ \mathrm{E(t)} + \mathrm{Ki} \int E(t) \tag{4}$$

Based on the literature review and on trial and error method, the PI controller parameters were determined. There were five simulations conducted to determine the best PI controller parameters.

Table 3: PI controller data Simulation

Simulation	K_p	T_i	Settling time (sec)		Maximum Overshoot (p.u)
			2%	5%	
Sim1	2.68	0.0045	471.9	220.9	0.185
Sim2	2.69	0.0045	475.2	222	0.186
Sim3	2.69	0.0048	476.8	224.28	0.188
Sim4	2.089	0.0045	605	317.55	0.137
Sim5	2.098	0.0045	600	315	0.138

Table 3 show the parameter of the five simulations along with the settling time and maximum overshoot. These five experiments were conducted based on the case of sudden increase in steam demand of 0.5 p.u. The settling parameters chosen and used in this project are as follows, $K_p = 2.68$, $T_i = 0.0045$s.

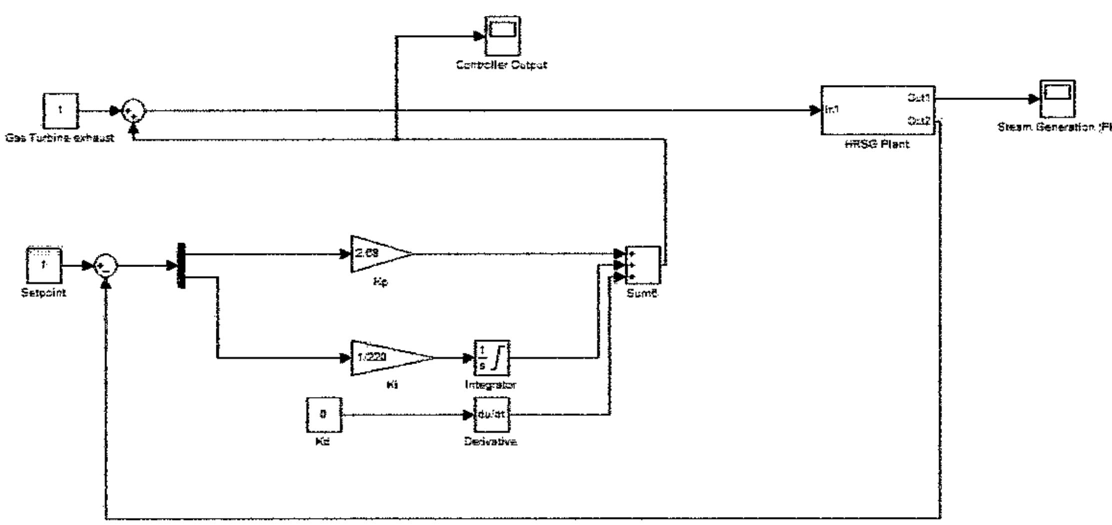

Figure 18: SIMULINK representation of PI controller

4.2 Simulation Result of PI Controller

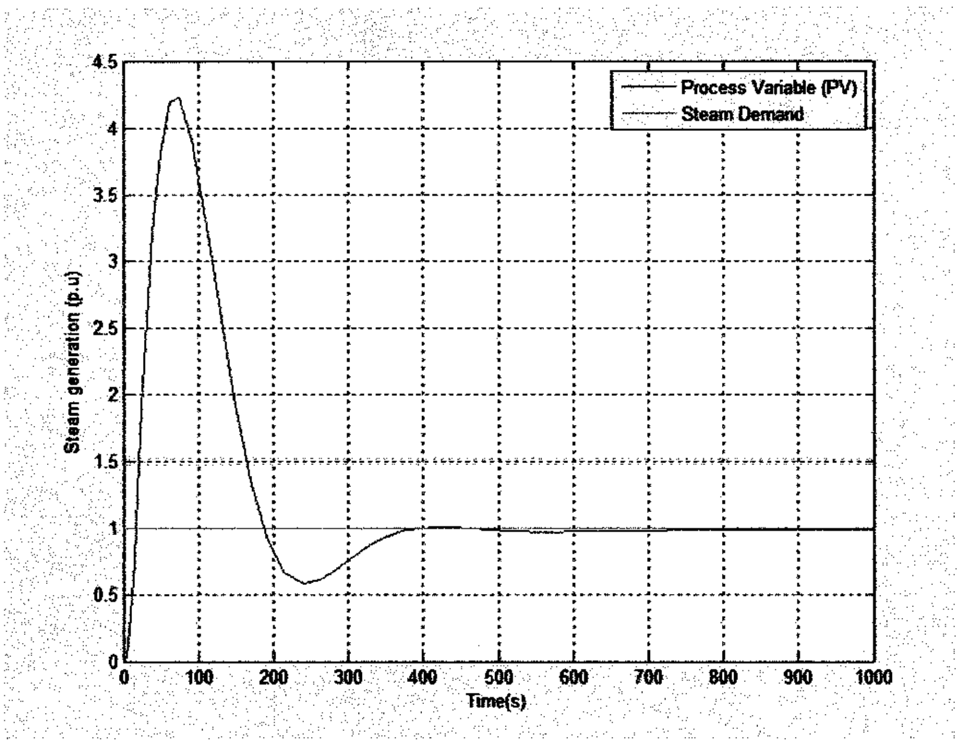

Figure 19: The output response of HRSG with PI controller

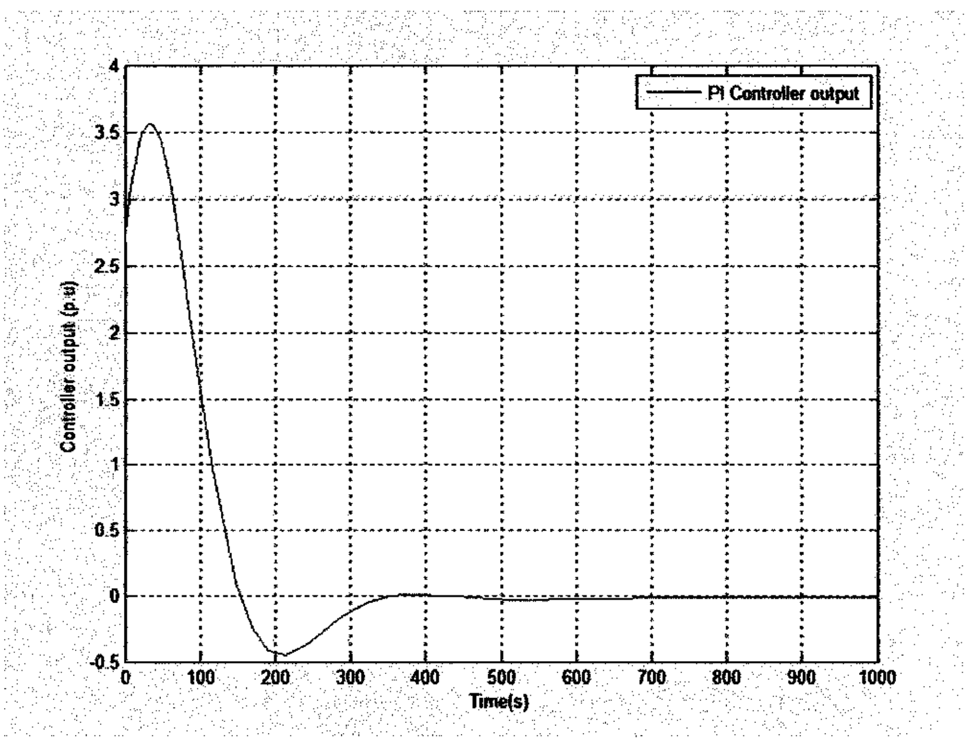

Figure 20: The controller output response of PI controller

Figure 19 shows the output response of steam generation in HRSG system with PI controller with respect to steam demand at its initial value which is at 1.0 p.u. When the steam demand remains at 1.0 p.u, the steam pressure in the Super heater *(refer to figure 6)* remains the same which in result will not affect or actuates the pressure controller. It is observed that the PI controller output remain at 0 p.u at the time of 350s until 1000s which means no actuations of pressure controller occurred as shown in figure 20. Consequently, the pressure controller will maintain the exhaust input to the steam generation system to meet the steam demand which is 1.0 p.u.

In order to investigate and compare the performance of the designed PI and Fuzzy Logic controller, two cases is considered for the simulation study of the simplified HRSG model which is firstly by applying a sudden increase and decrease in steam demand by 0.5 p.u. The second case emphasize on the set point tracking experiment in order to evaluate the robustness of the controllers.

4.2.1 Sudden increase in steam demand by 0.5 p.u

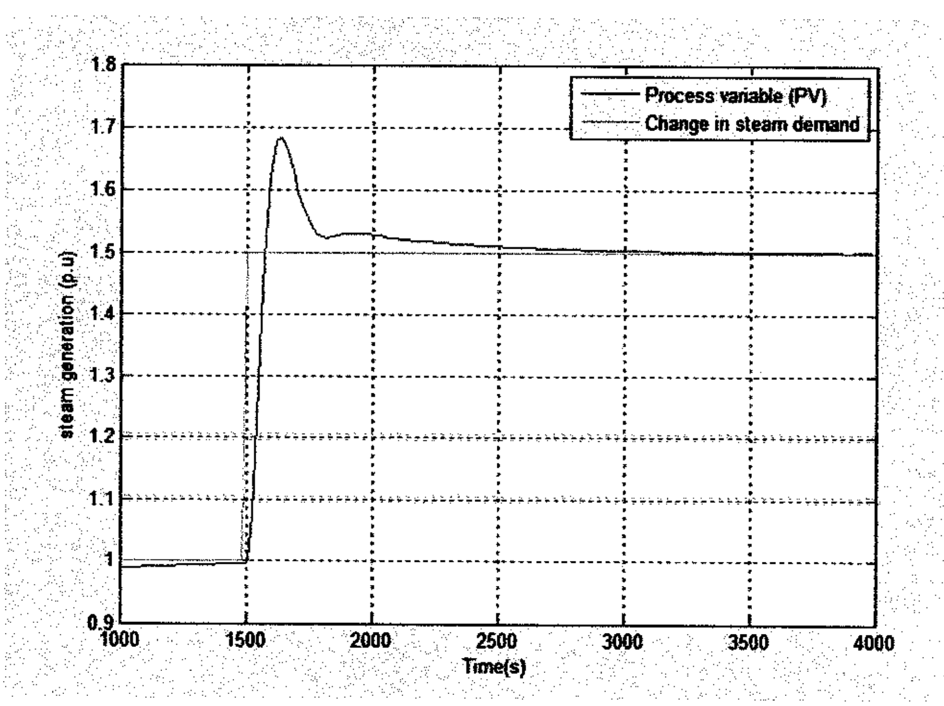

Figure 21: The output response of HRSG with PI controller

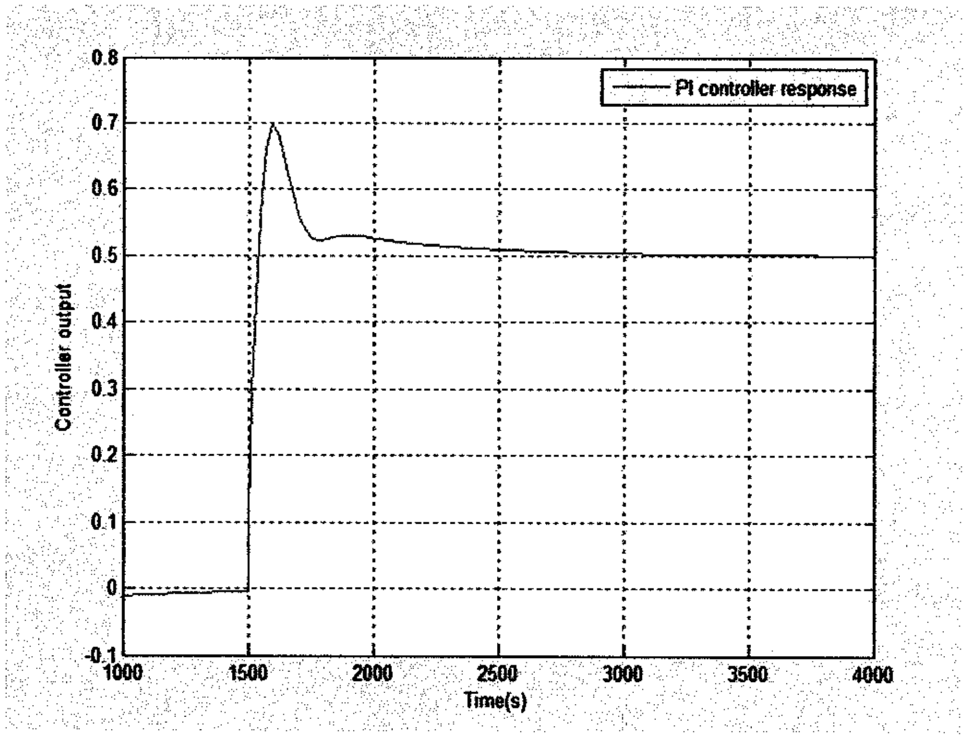

Figure 22: The controller output response of PI controller

Figure 21 shows the effect of sudden increase in steam demand by 0.5 p.u on the HRSG response. We can observe that the steam demand was initially at 1.0 p.u. After the sudden increase of 0.5 p.u, the steam demand is increased to 1.5 p.u. When the steam demand suddenly increases, the steam pressure inside the super heater falls immediately. This in turn will actuate the PI pressure controller which can be observed in figure 22 whereby the PI controller output response changes from 0 p.u to 0.5 p.u. Thus, the PI pressure controller will immediately correspond *(refer figure 6)* by increasing the amount of exhaust input (gas or fuel) to the steam generation system in order to achieve the desired steam demand.

4.2.2 Sudden decrease in steam demand by 0.5 p.u

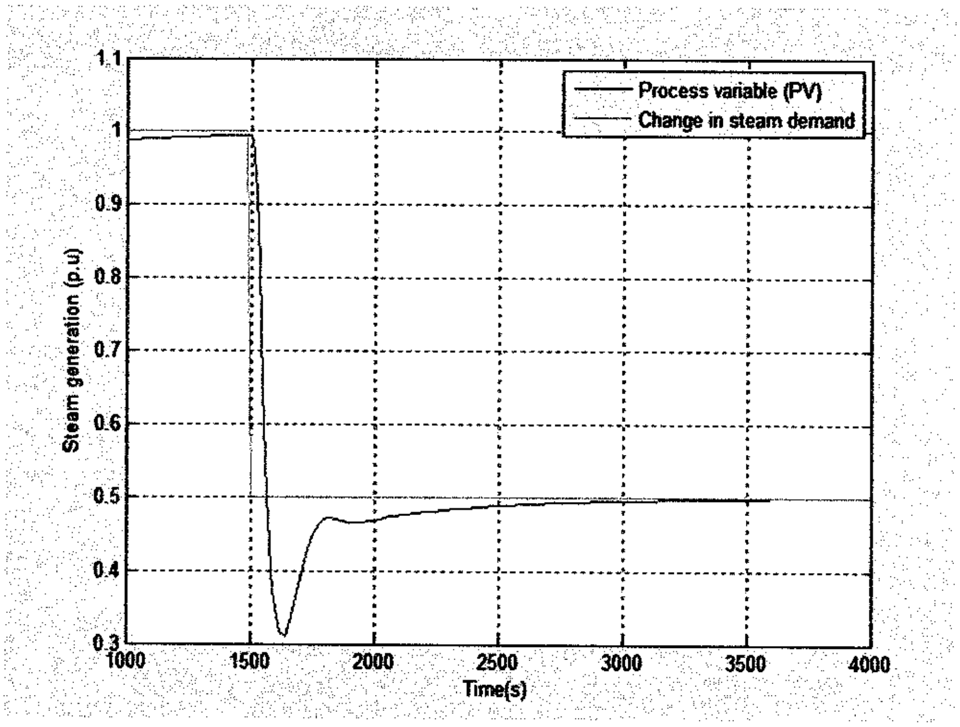

Figure 23: The output response of HRSG with PI controller

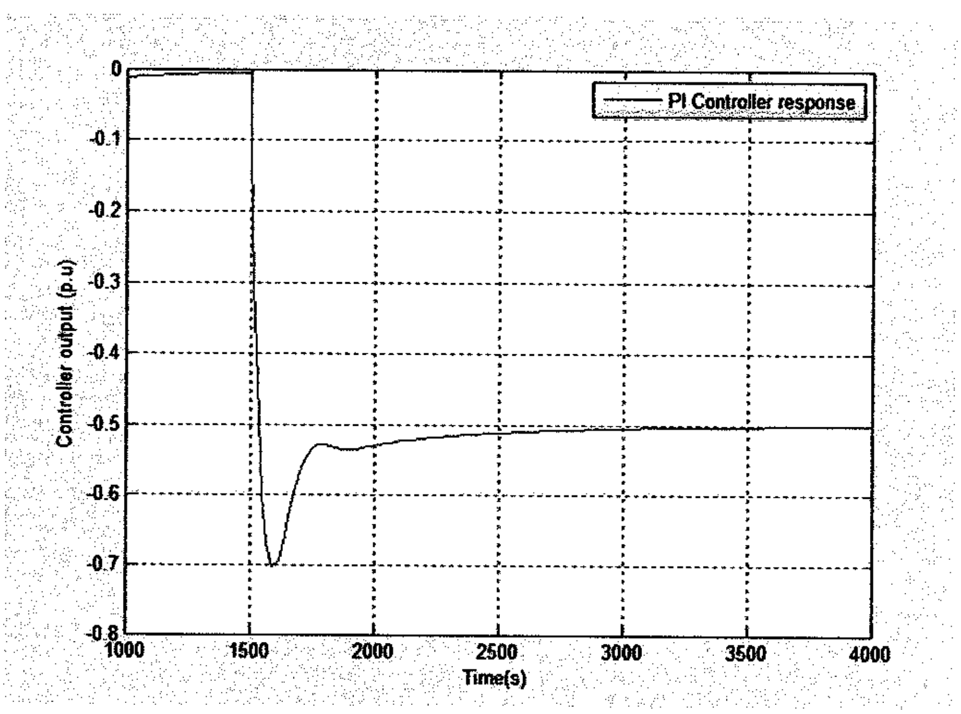

Figure 24: The controller output response of PI controller

Figure 23 displays the output response of the HRSG system with regard to the effect of sudden decrease in steam demand by 0.5 p.u. Based on figure 23, after the sudden decrease of 0.5 p.u, it can be observed that the steam demand is decreasing from 1.0 p.u to 0.5 p.u. Based on the literature review, whenever the steam demand suddenly falls, the steam pressure inside the super heater increases immediately, which as a result will actuate the pressure controller to respond to the changes occurred. Thus, the pressure controller (PI controller) will immediately correspond *(refer figure 6)* by decreasing the amount of exhaust input (gas or fuel) going into the steam generation system in order to achieve the desired steam demand.

4.2.3 Set point tracking

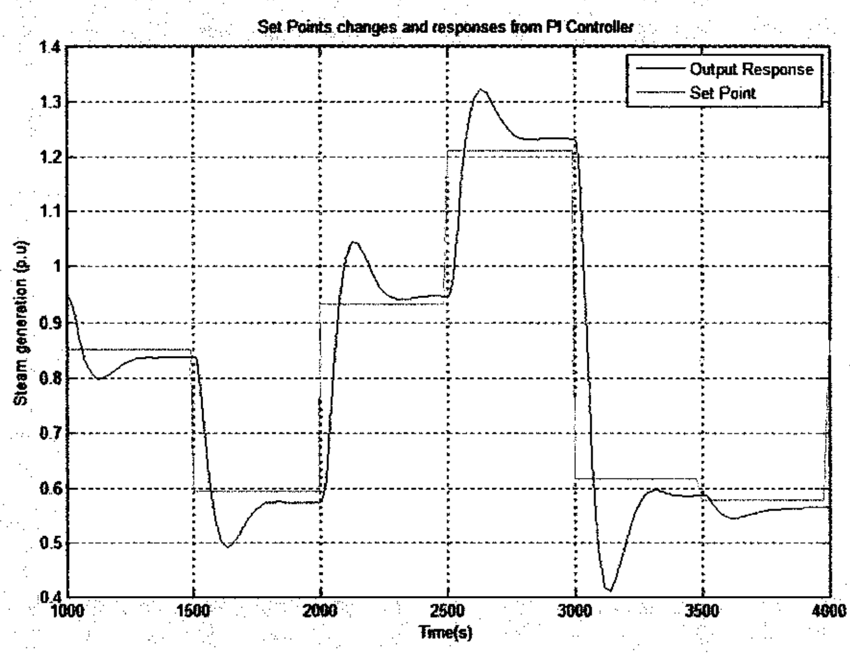

Figure 25: PI controller performance for set point tracking

Figure 25 show the performance of the PI controller with respect to set-point changes. This experiment involves a few step changes in the set point of steam demand respectively. As shown in figure 25 above, the overall performance of PI controller is not very encouraging and satisfying. For example, at the time of 1500s to 2500s it can be observed that the output response of the steam generation with the use of PI controller does not precisely manage to settle at the desired set point after changes from another set point. There is an offset error of approximately 0.02 to 0.03. In addition, the PI controller is observed to not able to adapt quickly whenever there is a sudden change in the set point.

4.2.4 Discussion on PI controller performance

Based on figure 21 and figure 23, though the steam demand is achieved, the use of conventional PI controller still does not yield adequate control performance. As can be observed, when there is a sudden increase or decrease in steam demand, the output response of the HRSG system or steam generation (p.u) requires some time to settle down. In addition, there is also an approximately 12.36% of overshoot. The analysis of the rise time (Tr) shows that 72.4s of time is needed for the response to reach 90% of the final value and 471.9s to reach the steady state. Therefore, it is believed that because of the nonlinearity and complexity of the reaction process the PI controller is unable to provide satisfactory control performance as required.

4.3 Simulation Result of Fuzzy Logic Controller

4.3.1 Sudden increase in steam demand by 0.5 p.u

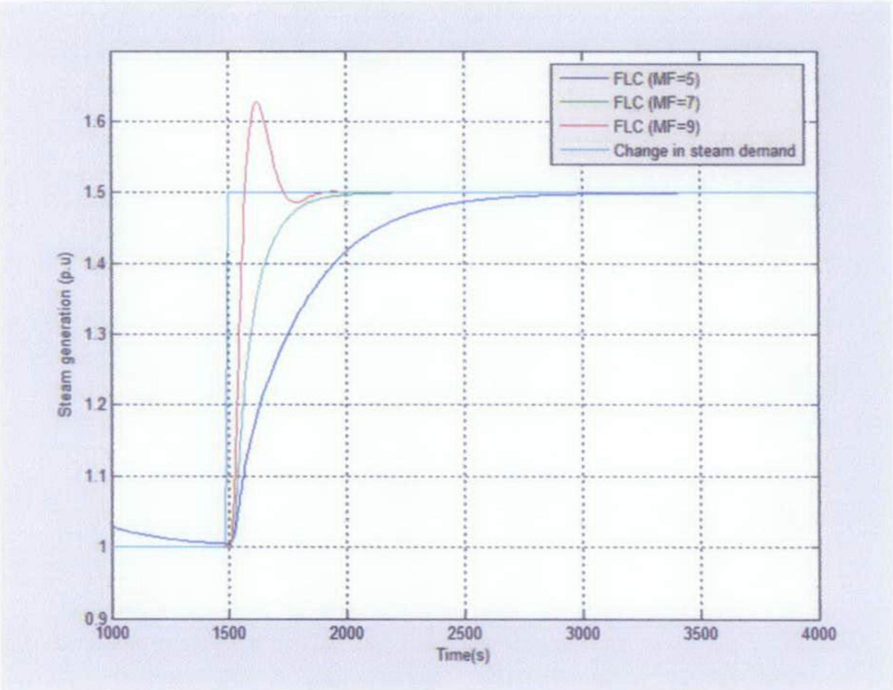

Figure 26: The output response of HRSG with Fuzzy logic Controllers

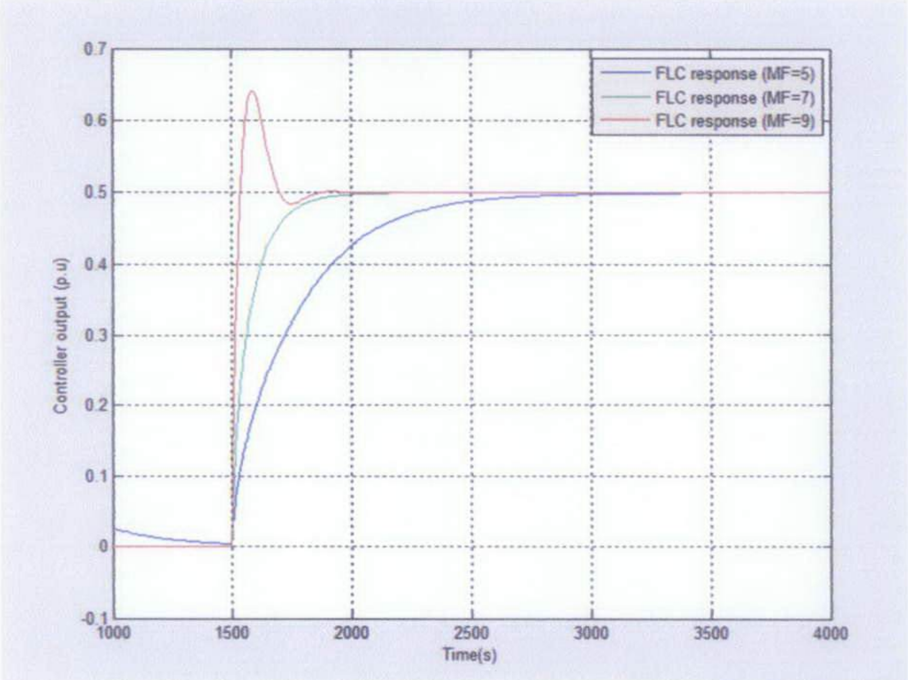

Figure 27: The Fuzzy logic controllers output response

4.3.2 Set point tracking

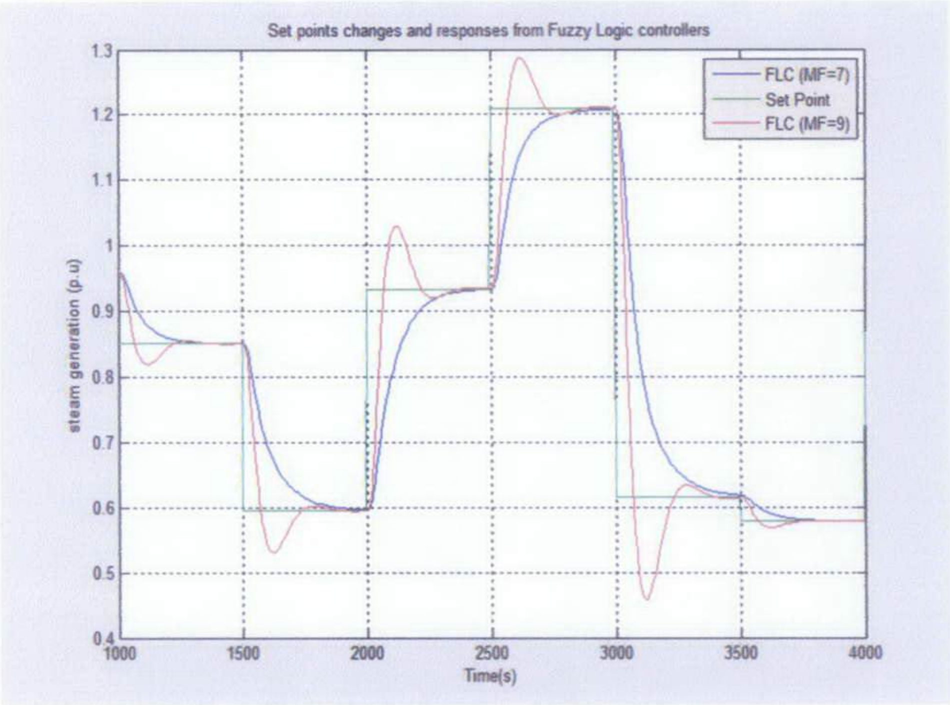

Figure 28: Fuzzy Logic controller performance based on set point changes

4.3.3 Discussion on Fuzzy Logic controller performance

The performance of Fuzzy logic controller with different membership functions were tested on two different experiments. First, the controllers is tested with sudden rising in steam demand by 0.5 p.u and followed by the set point tracking experiments to test the robustness of the fuzzy logic controller. Based on the result from the testing, the overall performance of the fuzzy logic controller with different membership functions is very promising. For example, in figure 26 it can be observed that all of the fuzzy logic controllers managed to settle down to the desired set point of steam demand. Though there is some slight oscillation and an overshoot of approximately 8.52% response from fuzzy logic controller with 9 membership function, the settling time is faster which is 189.5s compared to the other two fuzzy logic controllers respectively.

Figure 28 show the performance of the fuzzy logic controller with 7 and 9 membership functions with respect to set-point changes. This experiment involves a few step changes in the set point of steam demand respectively. This experiment was performed to test the robustness of the fuzzy logic controller for a series of random set point changes. Fuzzy logic controller with 5 membership function is excluded from this testing as the output response was very unproductive and that 5 membership function are not sufficient. From figure 28, the result from the testing is very promising. Both of the fuzzy logic controllers react to the set point changes immediately and the responses for all the step changes are mostly similar in form though there is an overshoot from the FLC with 9 membership function. Nonetheless, the result from the simulations demonstrates that using fuzzy logic controller with 7 membership function as the pressure controller to regulate the input exhaust to the HRSG or steam generation system with respect to changes in the steam demand was capable of providing a good control performance as required.

4.4 Discussion on Performance comparison of PI and Fuzzy Logic Controllers

The output responses of both the PI and Fuzzy logic controllers were compared. Table 4 shows the comparison of the overall performances between the output response using the PI and Fuzzy logic controllers with different membership functions. From the analysis and comparison of both controllers, it is observed that Fuzzy logic controller with 9 rules or membership function exhibit relatively much better performances having smaller overshoot, transient frequency response, and integral of absolute error (IAE) compared with the other controllers especially with PI controller. It is also shown in figure 23 that fuzzy logic controller with 9 membership function has faster anticipation in any changes in the process variable.

Though Fuzzy logic controller with 7 rules or membership function produce no overshoot, based on table 4 the analysis of the settling time for the output response of the HRSG system to settle at the desired set point is 276.6s which is much longer compared when using fuzzy logic controller with 9 rules which is189.5s.

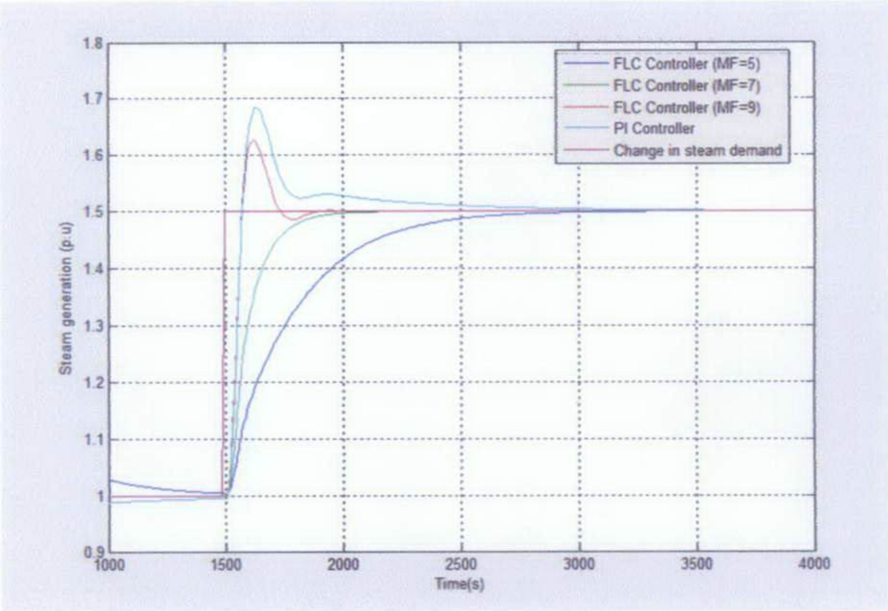

Figure 29: The output response of HRSG with PI and FLC

Table 4: Comparison of performance between conventional PI and Fuzzy Logic Controllers based on the effect of sudden increase in steam demand

Controllers / Parameters	PI	FUZZY LOGIC		
		MFs = 5	MFs = 7	MFs = 9
Rise Time, t_r	72.4s	886.1s	315.4s	69.5s
Settling Time, t_s	471.9s	777.7s	267.6s	189.5s
Maximum Overshoot (M_p)	12.36%	No	No	8.52%
Transient response	Intermediate oscillation	No oscillation	No oscillation	Small oscillation
Final value (p.u)	1.5006	1.5000	1.5000	1.5000

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

As a conclusion, intelligent control is necessary for future development to fully utilize the functioning of a Heat Recovery Steam Generator (HRSG) system in order to fulfill the performance requirements. Using conventional method can still provide the necessary requirements. However the design of the conventional method requires an extensive understanding of the system, an accurate mathematical models and precise numerical values of the respective parameters involved in the system which as a result requires a lot of time to be analyzed and completed.

In this project, the development of a fuzzy logic controller to act as pressure controller for the HRSG has been very successful. From the simulations results, it can be concluded that fuzzy logic controller in which knowledge based design rules can be implemented to control HRSG which is one of the complex system with highly nonlinear characteristic compared to the conventional PI controller. Fuzzy logic controller with 7 membership functions provide better performance in terms of settling time, faster response, less oscillation and overshoot compared to PI controller. Therefore, the objectives of this research have been successfully accomplished.

Fuzzy logic controller can be used to control the heat recovery steam generator system and it is a better choice to replace the existing conventional controller.

5.2 Recommendations

To achieve and ensure better results and performance from the controller for further research, a few recommendations could be made as follows:

i. Using other types of membership function to design fuzzy logic system such as the Gaussian or Bell membership function to observed the output response of the respective controller.
ii. As an alternative of using Mamdani approach, Sugeno approach can be used.
iii. Implementing a fuzzy gain scheduling proportional and integral controller by adjusting the gains of the PI controller according to disturbances in the system outputs.
iv. Supervisory controller by using fuzzy PI to control pressure can also be implemented.

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APPENDICES

APPENDIX I

Table I.1: HRSG model parameters

Parameters		Value
Csh	Pressure drop	2.864
Tm	Steam generation system time constant	10.00
Tv	HRSG drum time constant	136
Tu	Super heater time constant	53
Blspm	Gas turbine exhaust input supply	1.0
Pr	Pressure controller set point	1.0

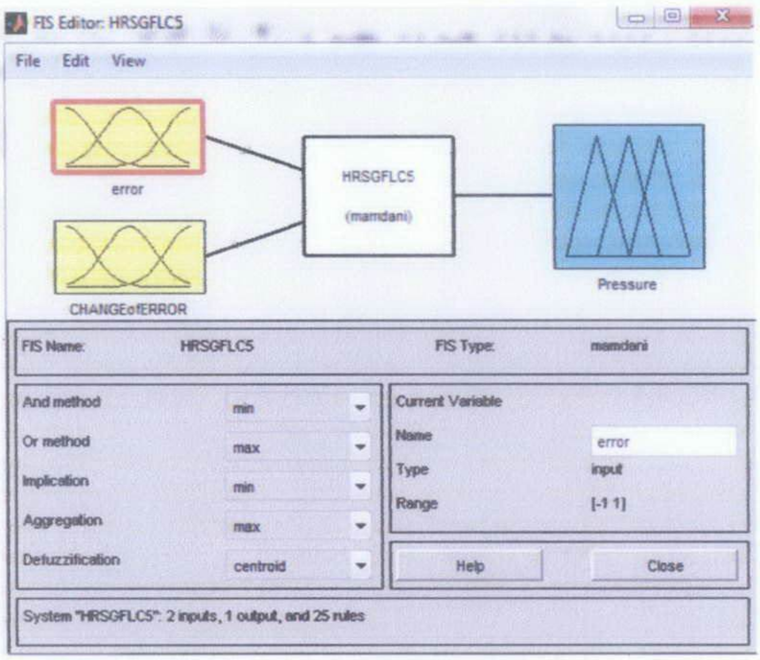

Figure I.1: Fuzzy inference system editor for FLC with 5 MFs

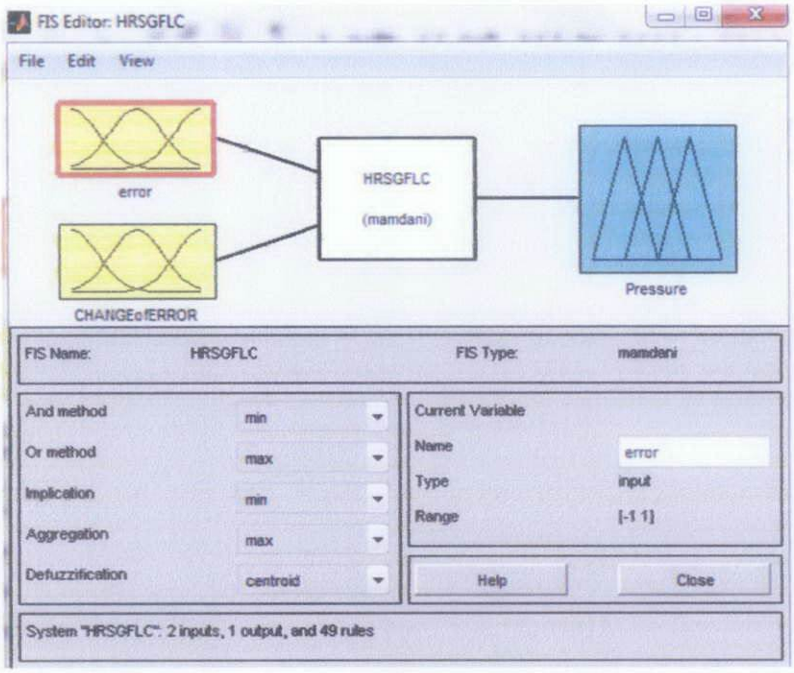

Figure I.2: Fuzzy inference system editor for FLC with 7 MFs

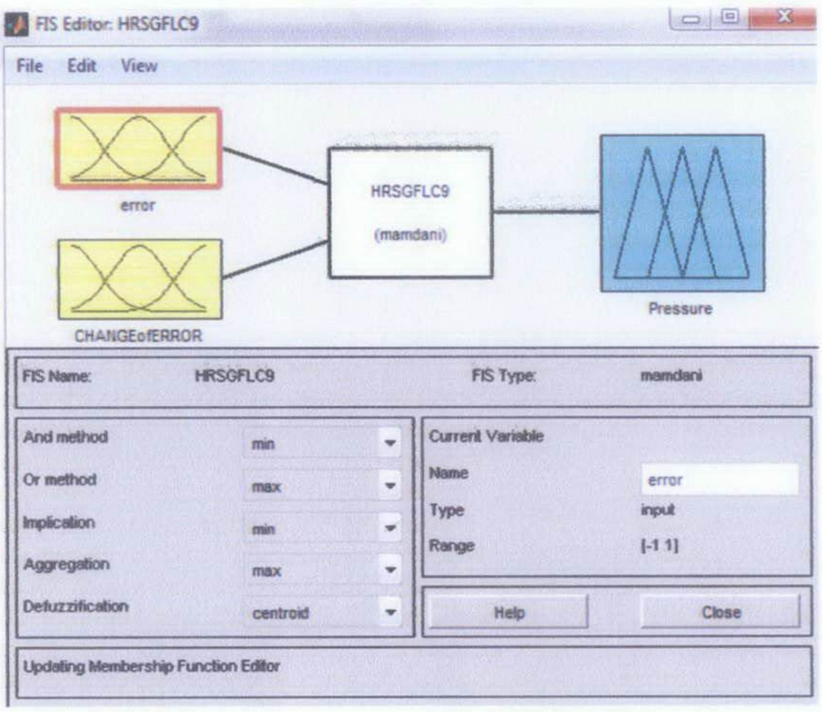

Figure I.3: Fuzzy inference system editor for FLC with 9 MFs

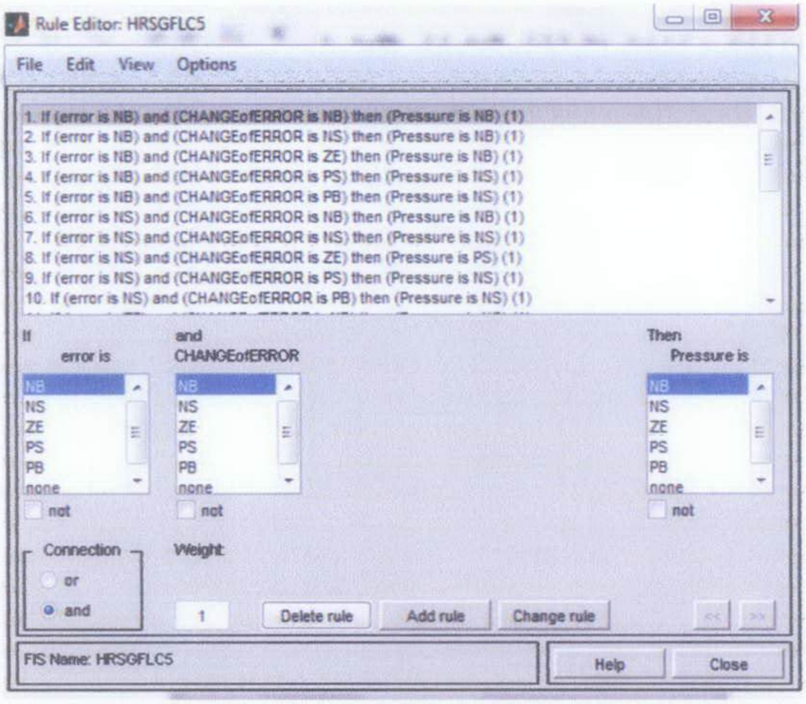

Figure I.4: Rule base for Fuzzy logic controller with 5 MFs

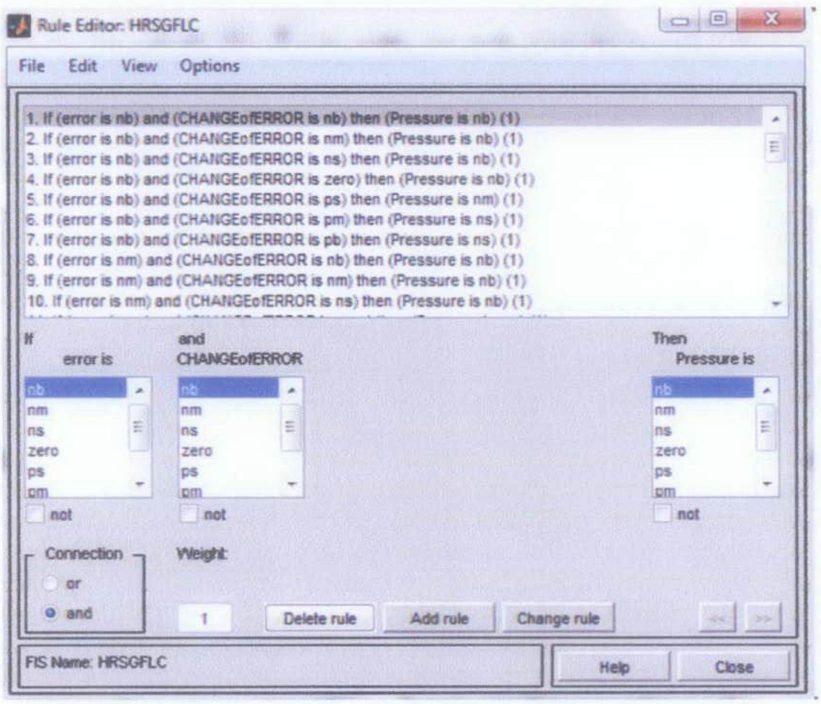

Figure I.5: Rule base for Fuzzy logic controller with 7 MFs

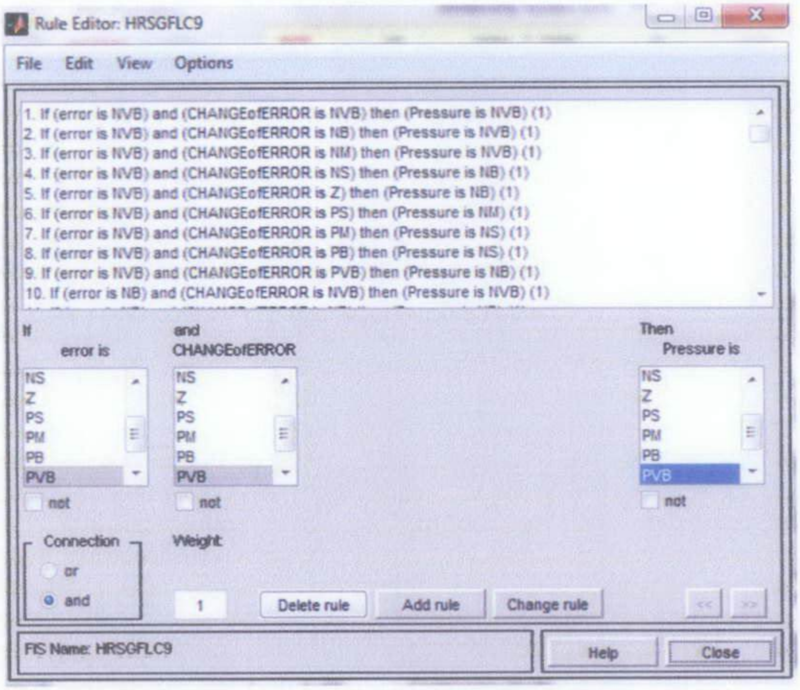

Figure I.6: Rule base for Fuzzy logic controller with 9 MFs

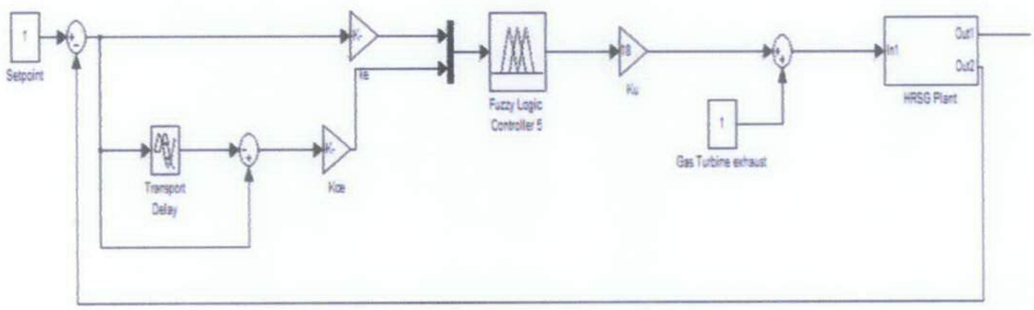

Figure I.7: SIMULINK representation of FLC with 5 MFs

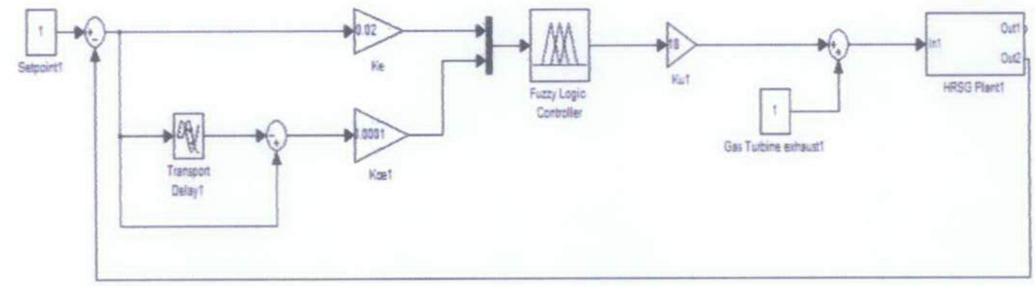

Figure I.8: SIMULINK representation of FLC with 7 MFs

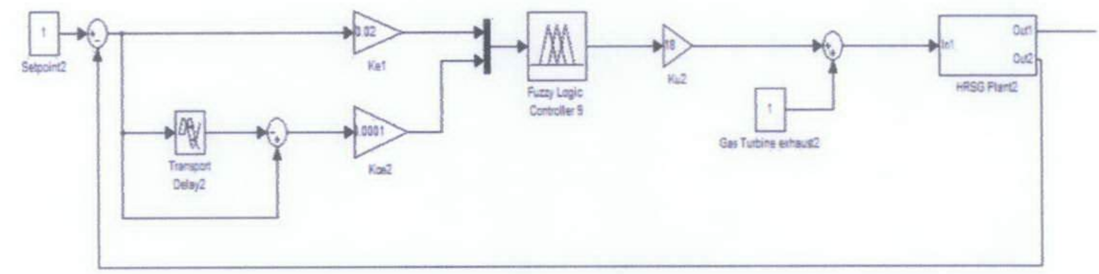

Figure I.9: SIMULINK representation of FLC with 9 MFs

APPENDIX II

GANTT CHART FOR FINAL YEAR PROJECT 2

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Modeling of HRSG plant using MATLAB															STUDY WEEK		EXAM WEEK		
2	Designing PI and Fuzzy logic Controller																			
3	Submission of Progress Report 2								●											
4	Seminar (compulsory)																			
5	Simulation & Analysis																			
6	Poster Exhibition										●									
7	Submission of Dissertation (soft bound)												●							
8	Oral Presentation														●					
9	Submission of Project Dissertation														●					