SPEED CONTROL OF DC MOTORS

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ABSTRACT

The function of speed control in DC motors is very essential in the achievement of desirable outputs. DC motors are designed for use in industrial and commercial applications such as the pump and blowers, material handling, system and gear drives, and adjustable speed drives. Both the nonlinear and linear of DC motor mathematical model is derived and the system model also represented in the form of continuous state space equation. Four type of controllers namely Proportional-Integral-Derivative (PID) controller, state-feedback controller, fuzzy logic controller and fuzzy PID controller are considered for controlling the speed of dc motor by giving the step input signal. The system is simulated using MATLAB/SIMULINK software. The system responses under the four different controllers are also analysed and discussed in term of their performances.

ABSTRAK

Fungsi kawalan kelajuan motor arus terus adalah sangat penting dalam mencapai objektif yang diingini. Motor arus terus direka untuk digunakan dalam aplikasi industri dan komersial seperti pam dan peniup, pengendalian bahan, sistem dan pemacu gear, dan laras kelajuan memandu. Kedua-dua linear dan ketidaklinearan untuk model matematik motor arus terus diterbitkan dan model sistem ini juga diwakili dalam bentuk persamaan keadaan berterusan. Empat jenis pengawal iaitu pengawal *Proportional-Integral-Derivative* (PID), pengawal suap balik keadaan, pengawal fuzzy dan pengawal fuzzy PID telah dipertimbangkan untuk mengawal kelajuan motor arus mengikut isyarat masukan yang ditetapkan. Pengawal tersebut disimulasi dengan menggunakan perisian MATLAB / SIMULINK. Tindakbalas sistem di bawah empat pengawal yang berbeza juga dianalisa dan dibincangkan dari segi prestasi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Kp	-	Proportional gain
Ki	-	Integral gain
Kd	-	Derivative gain
T_L	-	Torque load
T_f	-	Friction load
F_c		Coulumb friction coefficient
x	-	Position of the cart
θ	-	Angle of the pendulum with respect to vertical axis
T_m	-	motor torque
i	-	armature current
K_t	-	constant factor
e_t	-	back emf
$\dot{\theta}$	-	rotational speed
K_e	-	electromotive force constant
K_m	-	motor constant
L_m	-	Armature inductance
R_m	-	Armature resistance
V	-	Input Voltage
$d\theta/dt$	-	Rotating speed
J	-	Moment of Inertia of the Rotor
b	-	Damping ratio of the mechanical system

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b	-	Damping ratio of the mechanical system

T_S	-	Settling time
T_r	-	Rise time
ζ	-	damping ratio
ω_n	-	natural frequency
A	-	System matrix
B	-	Input matrix
C	-	Output matrix
K_f	-	Forward path gain
A_{cl}	-	Close loop system matrix
B_{cl}	-	Close loop input matrix
$\Delta e(t)$	-	Change of error
e(t)	-	error
u(t)	-	change of voltage

LIST OF ABBREVIATIONS

PID	-	Proportional, Integral and Derivative
DC	-	Direct Current
FIS	-	Fuzzy Inference System
OS	-	Overshoot
NB	-	Negative Big
NM	-	Negative Meddle
NS	-	Negative Small
ZO	-	Zero
PS	-	Positive Small
PM	-	Positive Middle
PB	-	Positive Big
emf	-	Electromotive field

CHAPTER 1

INTRODUCTION

1.1 Project Background

DC motors are designed for use in industrial and commercial applications such as the pump and blowers, material handling, system and gear drives, and adjustable speed drives. These motors are used to give rotary speed and position to a various electromechanical system. The purpose of developing a control system is to enable stable control since it has parameters tuning difficulties, non-linear, poor stability and imprecise control.

The whole system is needed to be modeled first by using a state space equation. It has been found that this system results a non linear model. From this nonlinear model, the linearization process has to be done to simplify the model. After the linearized model has been acquired, the next task to do is to control the DC motor according to the required specifications.

In this project, the main task is to control the speed of the DC motor. If the speed is equal to the reference signal, it can be concluded that the designed controller is successful in controlling the speed of the system become stable. There are four types of controllers considered namely, PID controller, state-feedback controller, fuzzy controller and another one is fuzzy PID controller.

The performance of the controllers in controlling the speed of DC motor system is evaluated via computer simulation using MATLAB/SIMULINK platform.

1.2 Objective of the project

The objectives of this project are as follows:

(i) To formulate the complete mathematical model and state-space representation of the DC Motor.

(ii) To design PID controllers for the DC Motor as a benchmarking controller.

(iii) To design a state feedback controller.

(iv) To design a controller using Fuzzy Logic Approach.

(v) To design a controller using Fuzzy PID Approach.

(vi) To compare the performance of the PID technique, state feedback, fuzzy logic and fuzzy PID controller via simulation results.

1.3 Scope of Works

The work undertaken in this project is limited to the following aspects:

(i). The complete mathematical model of the DC Motor speed controller.

(ii) Simulation work using MATLAB/SIMULINK as a platform to prove the effectiveness of the four designed controllers.

(iii) Comparative study between the PID, Fuzzy Controller, Fuzzy PID controller and state feedback technique will be done

1.4 Research Methodology

The research work undertaken in the following seven development stages:

(i) The development of linear mathematical model for DC motor.

(ii) The design of controller base on PID technique.

(iii) The design of state feedback Controller.

(iv) The design of Fuzzy logic controller.

(v) The design of Fuzzy PID controller.

(vi) Perform simulation using MATLAB/SIMULINK for PID, state feedback, Fuzzy Logic and Fuzzy PID Controller.

(vii) Comparative study of the controllers is done.

1.5 Literature review

The dynamics speed response of DC motors with Fuzzy controller. It was estimated and found that the speed can be controlled effectively. The analysis provides useful parameter and the information for effective use of proposed system. [6]

Three membership functions (center width narrow, center width constant and center width wide) of Fuzzy logic are used to check the speed error of DC motor. The best performance has been recorded when using center width wide Fuzzy Logic Controller.[7]

The fuzzy controller does not required a mathematical model of the process is shown. Rules could be adapted easily to achieve better response. The inputs could be either qualitative or quantitative since it has the fuzziness at its inputs and the rules can be derived from an expert or an operator who has experience of driving the process. [8]

The ability of the fuzzy logic control to adapt against the sensitiveness to variation of the reference speed attention discussed. The fuzzy logic speed controller of DC motor shows increases of optimal performance. The paper also highlights the disadvantage of the conventional control sensitiveness to inertia variation and sensitiveness to variation of the speed with drive system of DC motor. The fuzzy logic proposed to overcome such the problem. [9]

The DC motor speed regulating system with PID control is presented. The DC motor has parameters tuning difficulties, poor stability, and imprecise control. According to the controllers, the fuzzy PID controller was designed to make control system more stable, anti-interference ability stronger, overshoot smaller, response speed faster and robustness stronger. The structure chart of fuzzy PID control had been designed and simulated. Fuzzy rule of Kp, Ki and Kd are also been developed. [4]

The control performance between state-feedback controller with integral control and state feedback controller without integral control is compared. The controller is composed into two parts: the full state feedback with and without integral control with pole placement design via Bass and Gura's approach. The controller design for linear time-varying differential systems is generally a difficult problem, because of the fundamental problems related to the analysis of such systems. [12]

The state feedback theory and solving for Lyapunov equation step by step is shown. The effect of parameter variations and suppression of noise and disturbance can be reduced by a properly designed feedback system. In practice, the state feedback controller is used more widely. [10]

The full state feedback is a pole placement design technique proved by which the desired poles are selected at the start of the design process. The performance of the state feedback is not guaranteed and the forward gain is required to track set point changes. The theory and design procedure of full state feedback with forward gain performance are proposed. [11]

The nonlinear dynamic model of an actual DC motor including the nonlinear friction torque is established. The simplified friction model proposed in order to simplify applications and reproduced the real nonlinear friction of the motor. This model identified more accurate compared to the nonlinear friction proposed by Armstrong-helouvry B. *et al.* (1994). [13]

The classical cascade control architecture of DC motors compared where the state feedback control offers benefits in terms of design complexity, hardware realization and adaptivily. The approach of state space linear control of a DC motor presented successfully for compensation of Coulomb friction. [17]

1.6 Layout of Thesis

This thesis contains eight chapters. Chapter 2 contains a brief introduction of DC motor. The derivation of the mathematical model, which is a nonlinear model of the DC motor system, is also presented. The linear mathematical model of the system is derived and then transformed into the state space representations.

Chapter 3 discusses four type of controllers design namely PID controller using Ziegler-Nichols technique, state feedback controller via Lyapunov Equation, fuzzy Logic controller and fuzzy PID controller.

Chapter 4 presents the results of PID technique, state feedback, fuzzy logic and fuzzy PID controller. For every controller there will be graphs presented namely output of the speed DC motor. At the end of this chapter, the comparison between the PID technique, state feedback, fuzzy logic and fuzzy PID controller is done. The analysis and discussions about the results obtained in this chapter.

Chapter 5 concludes the work undertaken, suggestions for future work are also presented in this chapter.

CHAPTER 2

DC MOTOR

2.1 Introduction

DC motor can be considered as a common actuator in control systems. It directly provides rotary motion and, coupled with wheels or drums and cables, can provide translational motion. DC motors are classified into several categories. The DC motors have separately excited-field where the field winding is separately from the armature. They are either armature-controlled with fixed field or field-controlled with fixed armature current. [1] The control objective of the DC motor is to reach a specified motor speed using signal reference input.

2.2 Mathematical Model of DC Motor System

Figure 2.1 shows the electrical circuit of the armature and free body diagram of the rotor. The model consists of differential equations for the electrical part, mechanical part and the relation of the equations. The current is assumed to flow from the positive terminal to the negative terminal of the source. The analysis of the speed DC motor is done with the input reference, voltage and Load torque, T_L.

The dead nonlinear zone of the motor caused by the friction brings significant effect to the system. A simplified friction model is proposed to simplify DC motor applications and the real nonlinear friction of the motor reproduced precisely. [14]

$$T_f = T_C \operatorname{sgn}(\frac{d\theta}{dt}) + (T_S - T_C).\exp(-\alpha.|\frac{d\theta}{dt}|)\operatorname{sgn}(\frac{d\theta}{dt}) \quad (2.1)$$

where

T_C : Coulomb friction torque (N.m)

T_S : static friction torque (N.m)

α : time constant

$\frac{d\theta}{dt}$: angular speed of the rotor (rad/s)

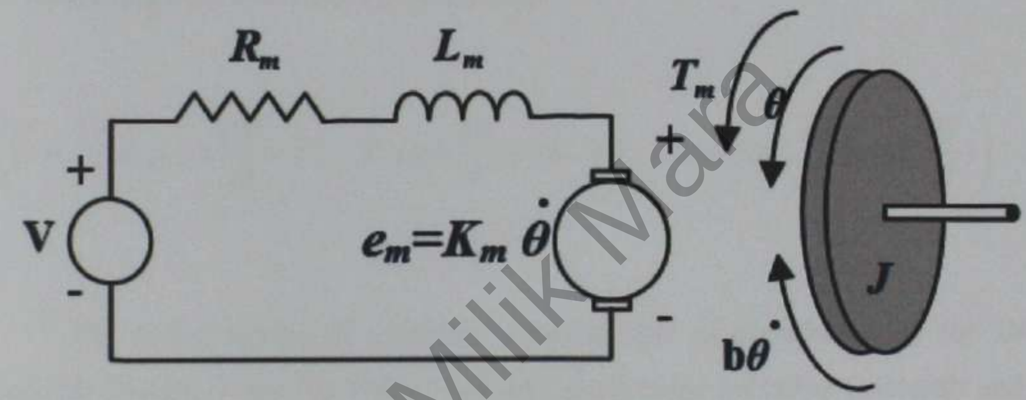

Figure 2.1 DC Motor Structure with electric circuit and free body diagram

The motor torque, T_m is related to the armature current, i, by a constant factor, K_t. This relationship can be expressed as:

$$T_m = K_t i = K_m i \quad (2.2)$$

The back *emf*, e_m, is related to the rotational speed, $\dot{\theta}$

$$e_m = K_e \frac{d\theta}{dt} = K_m \frac{d\theta}{dt} \quad (2.3)$$

Assuming K_t, torque constant and K_e, electromotive force constant are equal with K_m, motor constant. Hence, Friction on the shaft of the motor is approximated as a linear function of the shaft velocity. Newton's Law of motion states, the sum of all torque produces on shaft is linearly related to the acceleration of the shaft by the inertial load of armature, J as defined in equation (2.4).

$$\sum M = J.\frac{d^2\theta}{dt^2} \tag{2.4}$$

Considering the effect of nonlinear friction, the nonlinear friction torque [13,14], which as shown in (2.1) is applied to model the dead zone of DC motor. The nonlinear DC motor model is shown as equation (2.5).

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}\left(K_m i - b\frac{d\theta}{dt} - T_L - T_C \operatorname{sgn}(\frac{d\theta}{dt}) - (T_S - T_C).\exp(-\alpha.|\frac{d\theta}{dt}|)\operatorname{sgn}(\frac{d\theta}{dt})\right) \tag{2.5}$$

The major source of nonlinear characteristic is contributed by the DC motor Coulomb friction. [16] The main frictional phenomena included Coulomb and viscous parts is identified sufficient which depends on the rotation direction as shown in equation (2.6)

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}\left(K_m i - b\frac{d\theta}{dt} - T_L - F_C \operatorname{sgn}(\frac{d\theta}{dt})\right) \tag{2.6}$$

However, the procedure of controllers design required the equation to be linearized by assuming torque load, T_L is zero and neglected the effect of nonlinear friction as shown in equation (2.7):

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}\left(-b\frac{d\theta}{dt} + K_m i\right) \tag{2.7}$$

Based on Kirchhoff's law, the equation for DC motor electrical circuit can be stated as equation (2.8)

$$L_m \frac{di}{dt} + R_m i = V - K_m \frac{d\theta}{dt} \tag{2.8}$$

$$\frac{di}{dt} = \frac{1}{L_m}\left(- R_m i + V - K_m \frac{d\theta}{dt} \right) \tag{2.9}$$

where

K_m : motor constant (Nm/A)

V : Input Voltage (V)

dθ/dt : Rotating speed (rad/s)

i : Armature current (A)

Table 2.1 shows the parameters of excited DC motor with selected values.

Table 2.1 Separately Excited DC Motor parameters

Particular	Value	Unit
Armature resistance (Rm)	0.975	Ω
Armature inductance (Lm)	0.5	H
Torque constant (Kt)	1	Nm/A
Back emf constant (Ke)	1	Vs/rad
Moment of inertia(J)	2	Kgm^2
Mechanical Damping (b)	0.1	Nms/rad
Coulomb friction coefficient	0.02	N.m

2.3 State-Space Model

In the linear state-space model with a multivariable nonlinear input function f(x(t),u(t)), equation (2.6) and equation (2.9) can be expressed by choosing $\dot{\theta}$ and i as the state variable and V as an input. The output is chosen to be $\dot{\theta}$.

$$d\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}=\begin{bmatrix}-\frac{b_m}{J} & \frac{K_m}{J}\\ -\frac{K_m}{L_m} & -\frac{R_m}{L_m}\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}+\begin{bmatrix}0\\ \frac{1}{L_m}\end{bmatrix}V+\begin{bmatrix}\frac{-F_C}{J}\\ 0\end{bmatrix}Sgn(x_2) \tag{2.10}$$

$$\dot{\theta}=\begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}$$

For designing the controller purposed, the nonlinearity part of the model will be neglected.

Based on the values from Table 2.1 and by using equation (2.10), the calculated values for the matrices **A**, **B** and **C** are given as follows:

$$\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}=\begin{bmatrix}-0.05 & 0.5\\ -2 & -1.95\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}+\begin{bmatrix}0\\ 2\end{bmatrix}V+\begin{bmatrix}-0.01\\ 0\end{bmatrix}Sgn(\dot{\theta}) \tag{2.11}$$

$$\dot{\theta}=\begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}$$

From equation (2.11), the nonlinearity terms will be neglected as a part of the procedure to design the state feedback design controller as shown in equation (2.12)

$$\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}=\begin{bmatrix}-0.05 & 0.5\\ -2 & -1.95\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}+\begin{bmatrix}0\\ 2\end{bmatrix}V \tag{2.12}$$

$$\dot{\theta}=\begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\dot{\theta}\\ i\end{bmatrix}$$

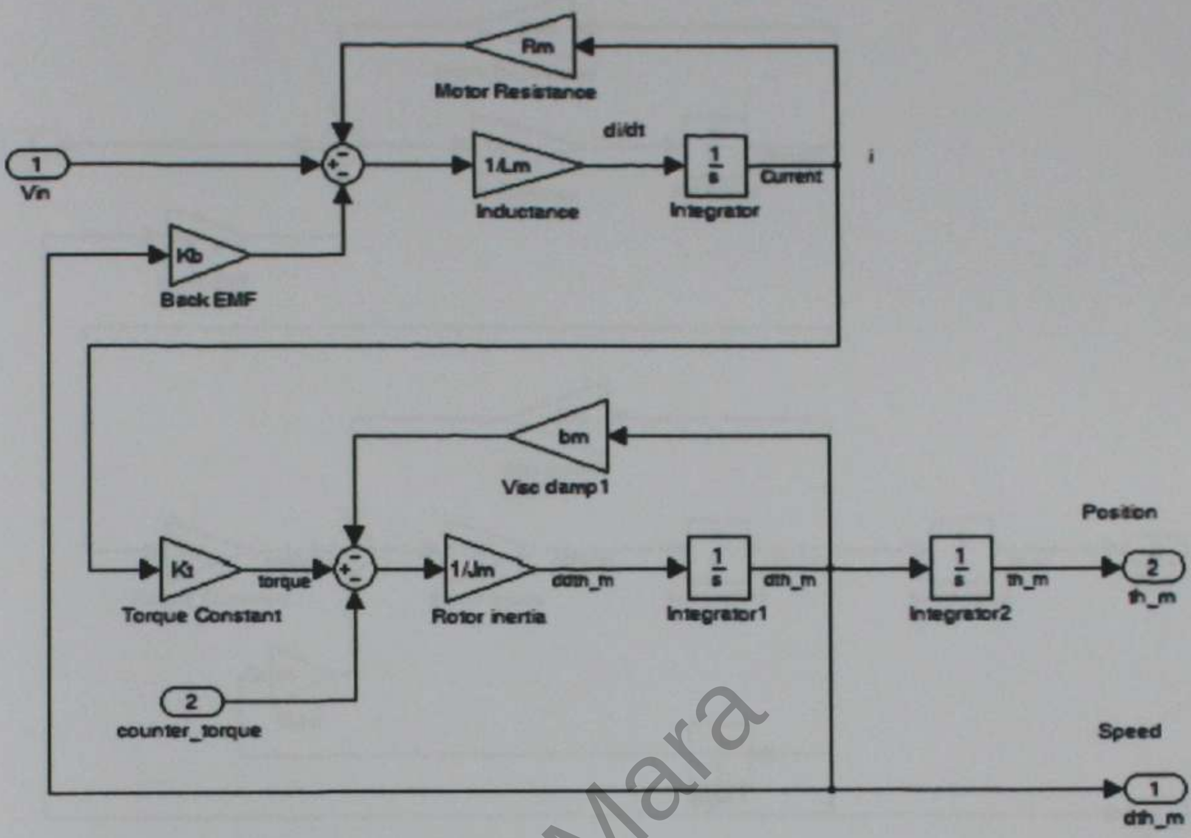

Figure 2.2 Simulink model of linear DC motor with T_L and F_C are neglected.

Alternatively, the state space form of the DC motor model as shown in Figure 2.2 can be easily extracted by using MATLAB function *linmod*. (Appendix A)

Figure 2.3 shows the nonlinear simulation diagram of a speed DC motor including all the parameters with Coulomb friction torque.

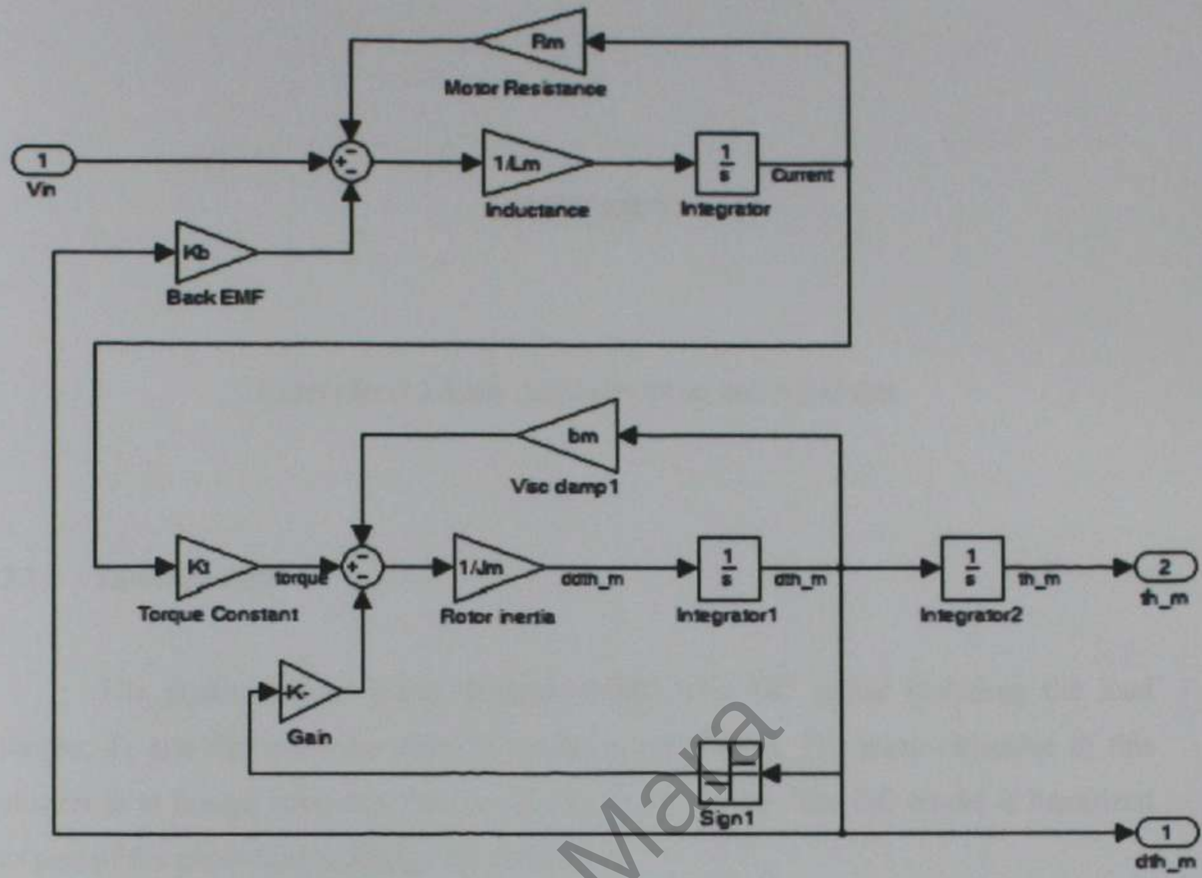

Figure 2.3 Simulink model of nonlinear DC motor with Coulomb friction, *Fc*

2.3 Summary

In this chapter, the complete derivation of both the nonlinear and linear DC motor speed model has been presented. The developed model includes the nonlinear dynamic model of DC motor namely Coulomb friction torque. The formulation of the design covers the linear system with torque load based on the certain parameters and represented in state space form. The final model derivation is used for the analysis of the controllers in Chapter 3.

CHAPTER 3

CONTROLLERS DESIGN FOR DC MOTOR

3.1 Introduction

The nonlinear and linear dynamic model of a DC motor including the load torque, T_L and the nonlinear friction torque is established. The main objective of this chapter is to design controller for the speed of a DC motor. The DC model is linearized as part of the procedure to design the controllers.

3.2 PID Controller

The linear model of DC motor speed derived in the previous chapter to design the conventional controller namely Proportional, Integral and Derivative (PID). More than half of the industrial controllers used PID controllers. Many difference types of tuning rules have been proposed in the literature. Using these tuning rules, slight and fine tuning of PID parameters controllers can be made on-site. The PID is designed using First Method Ziegler-Nichols tuning rules. A set of parameters namely K_P, T_i and T_d will provide stability of the system which need fine tunings until acceptable transient response achieved. Figure 3.1 shows the block diagram of the principle chart of PID controller.

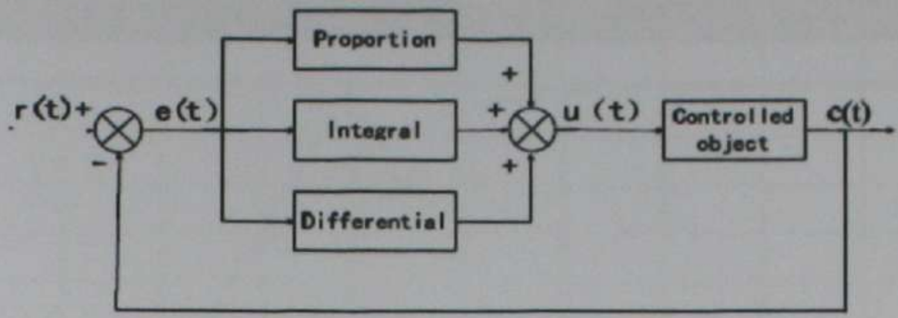

Figure 3.1 Principle chart of PID controller

Lastly, after obtaining the PID parameters K_P, K_I and K_d, the computer simulation diagram using MATLAB/SIMULINK can be constructed.

3.2.1 Ziegler-Nichols (Type 1)

The values of the proportional gain, K_P, integral time, T_i and derivative time, T_d are determined based on the open loop transient response characteristics of the DC motor. The response of the DC motor is obtained experimentally to a step input as shown in Figure 3.2.

The S-shaped curve is characterized by two constant, delay time L and time constant, T. The delay time and time constant are determined by drawing a tangent line at the inflection point of the S-shaped curve and determining the intersections of the tangent line with the time axis and line y axis, speed=K, as shown in Figure 3.2.

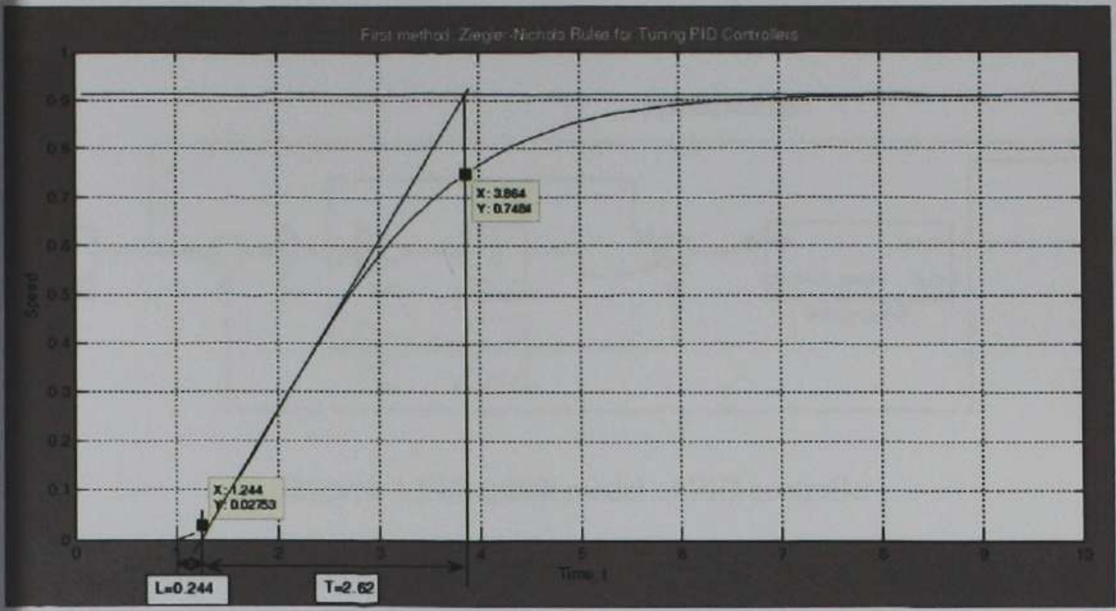

Figure 3.2 S-shaped response curve with delay time, L and time constant, T.

The values of K_p, T_i and T_d suggested by Zeigler-Nichols Type 1 based on the formula shown in Table 3.2. However, Table 3.3 shows the value of PID parameters such as K_P, K_I and K_d.

Table 3.1 Ziegler-Nichols Tuning Rule Based on step Response of plant (Type 1)

Type of controller	Kp	Ti	Td
PID	1.2T/L=12.885	2L=0.488	0.5L=0.122

Table 3.2 Ziegler-Nichols Tuning Rule Parameters

K_p	K_i	K_d
12.885	**K_p/T_i = 26.404**	**$K_p.T_d$ = 1.572**

3.2.2 Simulink Model of PID Controller

Figures 3.3 & 3.4 show the Matlab-Simulink diagram of the PID controller. The simulation included the linear model of DC motor speed system, proportional gain, Integral gain and derivative gain.

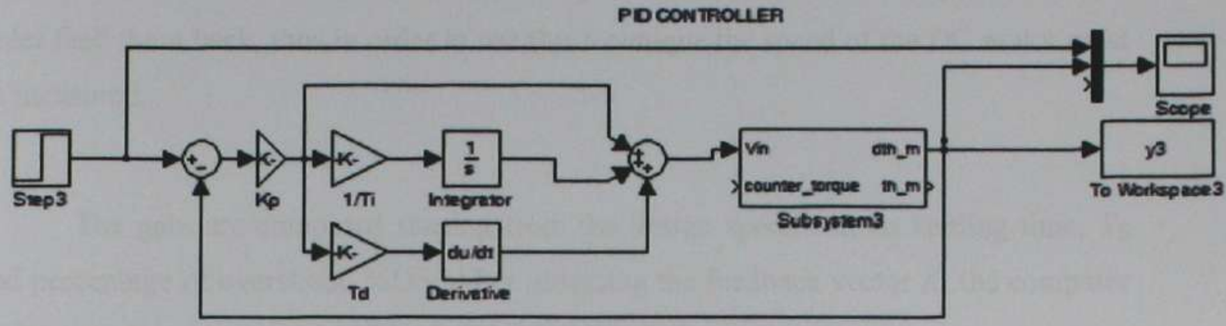

Figure 3.3 Simulink model of PID controller

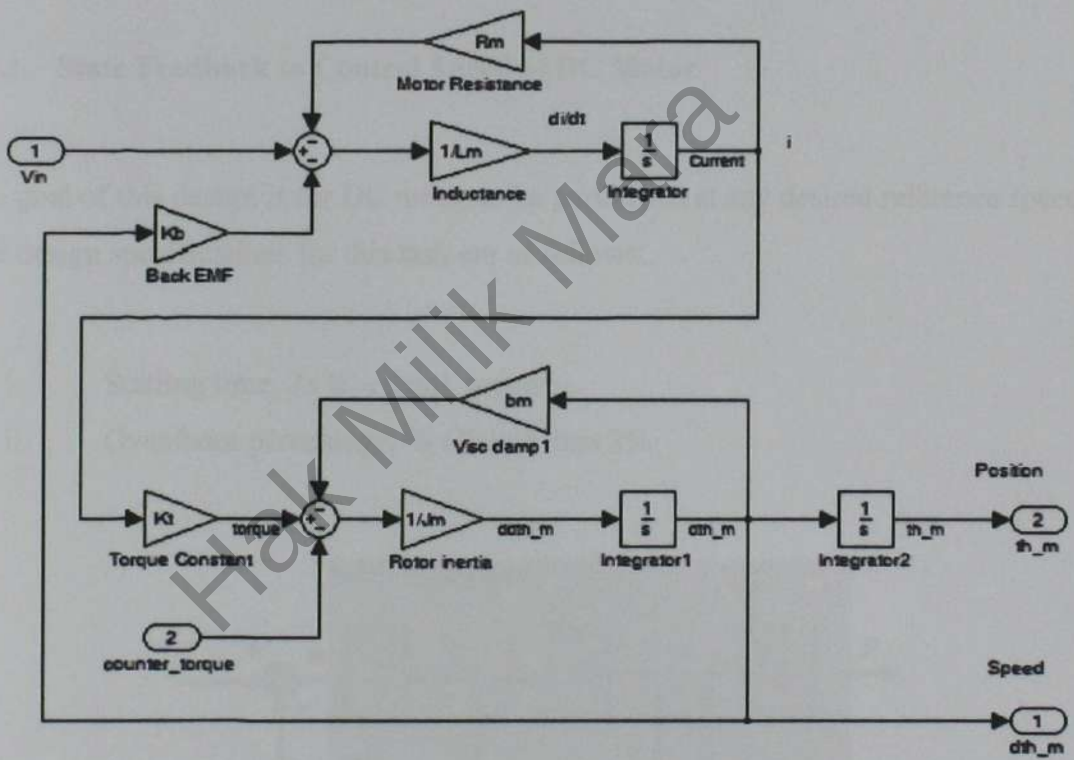

Figure 3.4 Subsystem of the DC motor model

3.3 State Feedback Controller Design

The state feedback design via Lyapunov Equation using the linearized model derived in the previous chapter.

State feedback will be in used to obtain target closed loop performance criteria. Figure 3.5 shows clearly the state feedback requires measurements of all system states in order feed them back, thus in order to use this technique the speed of the DC motor must be measured.

The gain are computed starting from the design specifications settling time, T_S and percentage of overshoot, %OS. After obtaining the feedback vector *K*, the computer simulation diagram using MATLAB/SIMULINK can be simulated.

Finally, the forward gain must be designed to reduce the steady state error, e_{ss}.

3.3.1 State Feedback to Control Speed of DC Motor

The goal of this design is for DC motor to be performed at any desired reference speed. The design specifications for this task are as follows:

i. Settling time, *Ts* less than1 second
ii. Overshoot percentage, % *OS* less than 2%

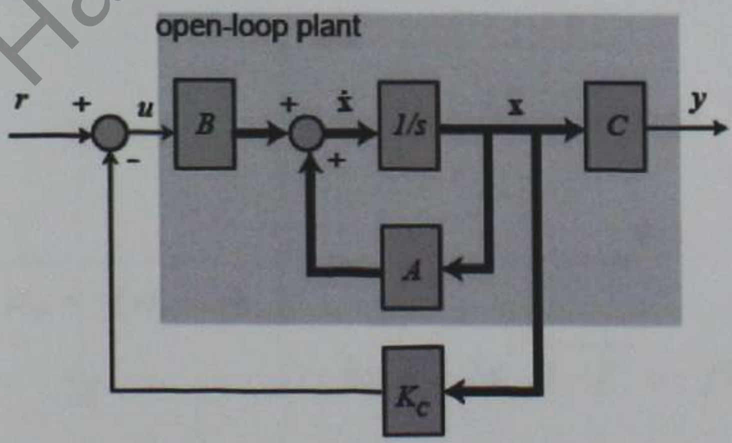

Figure 3.5 Basic state feedback controller

The damping ratio, ζ, can be computed as:

$$\xi = \frac{-\ln(\%OS/100)}{\sqrt{\pi^2 + \ln^2(\%OS/100)}} = \frac{-\ln(5/100)}{\sqrt{\pi^2 + \ln^2(5/100)}} = 0.78$$

(4.1)

The system natural frequency, ω_n is:

$$\omega_n = \frac{4}{T_s \xi} = \frac{4}{(1)(0.78)} = 5.13 \quad (4.2)$$

By using these two parameters, the desired transfer function can be as follows:

$$G(s)_{desired} = \frac{\omega_n^{\;2}}{s^2 + 2\xi\omega_n s + \omega_n^{\;2}} \quad (4.3)$$

Substitute ζ =0.78 and ω_n=5.13 rad/sec into equation (4.3):

$$G(s)_{desired} = \frac{(5.13)^2}{s^2 + 2(0.78)(5.13)s + (5.13)^2} \quad (4.4)$$

$$G(s)_{desired} = \frac{26.32}{s^2 + 8s + 26.32} \quad (4.5)$$

The poles are, $P_{1,2} = -4 \pm j3.21$ as the system only has 2nd order equations.

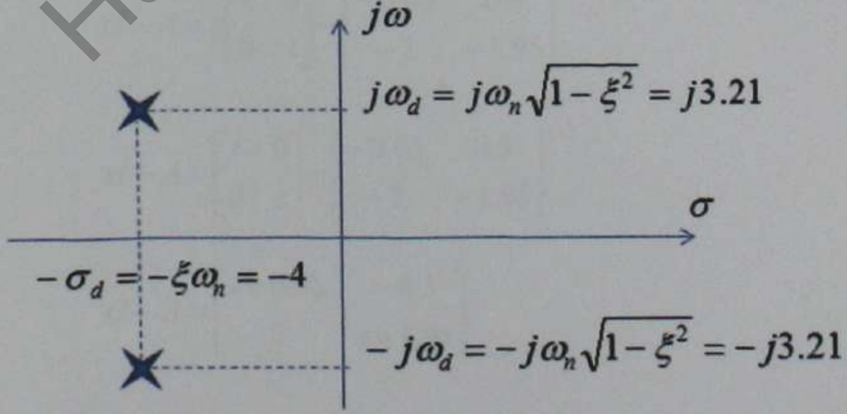

Figure 3.6 Location of the poles in s plane

Figure 3.6 shows the location of the poles in s plane with considering real and imaginary values obtained.

State feedback gains are computed for eigenvalues assignment. However, this method has the restriction that the selected eigenvalues cannot contain any eigenvalues of the system.

Step 1: The pair of matrix A and B must be controllable.

$$C = [B \quad AB] = \begin{bmatrix} 0 & 1 \\ 2 & -3.9 \end{bmatrix} \tag{4.6}$$

where,

$$AB = \begin{bmatrix} -0.05 & 0.5 \\ -2 & -1.95 \end{bmatrix} \begin{bmatrix} 0 \\ 2 \end{bmatrix} = \begin{bmatrix} 1 \\ -3.9 \end{bmatrix} \tag{4.7}$$

$$|C| \neq 0$$

The system found to be controllable based on the determinant of C is not equal to zero.

$$sI - A = s\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} -0.05 & 0.5 \\ -2 & -1.95 \end{bmatrix} \tag{4.8}$$

$$sI - A = \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} -0.05 & 0.5 \\ -2 & -1.95 \end{bmatrix} \tag{4.9}$$

$$sI - A = \begin{bmatrix} s+0.05 & -0.5 \\ 2 & s+1.95 \end{bmatrix} \tag{4.10}$$

$$sI - A = (s+0.05)(s+1.95)+1 \tag{4.11}$$

$$sI - A = s^2 + 2s + 1.0975 \tag{4.12}$$

It is shown that the desired eigenvalues are same with eigenvalues of the system.

$$s_{1,2} = -1 \pm j0.3122 \tag{4.13}$$

Step 2: Select an 2x2 matrix **F** that has the set of desired eigenvalues.

$$F = \begin{bmatrix} \alpha_1 & \beta_1 \\ -\beta_1 & \alpha_1 \end{bmatrix} = \begin{bmatrix} -4 & 3.21 \\ -3.21 & -4 \end{bmatrix} \tag{4.14}$$

Where the desired eigenvalues are $P_{1,2} = -4 \pm j3.21$

Step 3: Select an arbitrary 1x2 vector $\bar{k}$ such that $(F, \bar{k})$ is observable.

$$\bar{k} = [1 \quad 1] \tag{4.15}$$

$$O_{\bar{k}} = \begin{bmatrix} \bar{k} \\ \bar{k}F \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -7.21 & -0.79 \end{bmatrix} \tag{4.16}$$

where

$$\bar{k}F = [1 \quad 1] \begin{bmatrix} -4 & 3.21 \\ -3.21 & -4 \end{bmatrix} \tag{4.17}$$

$$\bar{k}F = [-7.21 \quad -0.79] \tag{4.18}$$

The system found to be observable based on the determinant of O is not equal to zero.

$$|O_{\bar{k}}| \neq 0$$

Step 4: Solve the unique matrix, T in Lyapunov equation

$$AT - TF = B\bar{k} \tag{4.19}$$

$$\begin{bmatrix} -0.05 & 0.5 \\ -2 & -1.95 \end{bmatrix} \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} - \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} -4 & 3.21 \\ -3.21 & -4 \end{bmatrix} = \begin{bmatrix} 0 \\ 2 \end{bmatrix} [1 \quad 1] \tag{4.20}$$

$$\begin{bmatrix} (-0.05t_{11}+0.5t_{21}) & (-0.05t_{12}+0.5t_{22}) \\ (-2t_{11}-1.95t_{21}) & (-2t_{12}-1.95t_{22}) \end{bmatrix} - \begin{bmatrix} (-4t_{11}-3.21t_{12}) & (3.21t_{11}-4t_{12}) \\ (-4t_{21}-3.21t_{22}) & (3.21t_{21}-4t_{22}) \end{bmatrix} \tag{4.21}$$
$$= \begin{bmatrix} 0 & 0 \\ 2 & 2 \end{bmatrix}$$

$$\begin{bmatrix} (3.95t_{11}+3.21t_{12}+0.5t_{21}) & (-3.21t_{11}+3.95t_{12}+0.5t_{22}) \\ (-2t_{11}+2.05t_{21}+3.21t_{22}) & (-2t_{12}-3.21t_{21}+2.05t_{22}) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 2 & 2 \end{bmatrix} \tag{4.22}$$

$$\begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \begin{bmatrix} 0.055 & -0.048 \\ -0.123 & 0.736 \end{bmatrix} \tag{4.23}$$

Step 5: Compute the feedback gain, k

$$K = \bar{k}.T^{-1} = [1 \quad 1]\begin{bmatrix} 21.2860 & 1.3880 \\ 3.5570 & 1.5910 \end{bmatrix} = [24.843 \quad 2.979] \tag{4.24}$$

$$T^{-1} = \frac{\begin{bmatrix} 0.736 & -3.5570 \\ -1.3880 & 0.055 \end{bmatrix}}{|T|} \tag{4.25}$$

where,

$$T^{-1} = \begin{bmatrix} 21.2860 & 1.3880 \\ 3.5570 & 1.5910 \end{bmatrix} \tag{4.26}$$

3.3.2 Forward Path Gain

$$A_{cl} = A - BK = \begin{bmatrix} -0.05 & 0.5 \\ -2 & -1.95 \end{bmatrix} - \begin{bmatrix} 0 \\ 2 \end{bmatrix}[24.843 \quad 2.979] \tag{4.27}$$

$$A_{cl} = A - BK = \begin{bmatrix} -0.0500 & 0.5000 \\ -51.6860 & -7.9080 \end{bmatrix} \tag{4.28}$$

$$B_d = B = \begin{bmatrix} 0 \\ 2 \end{bmatrix} \tag{4.29}$$

$$(A_{cl})^{-1} = \frac{\begin{bmatrix} -7.9080 & -0.5000 \\ 51.6860 & -0.0500 \end{bmatrix}}{|A_{cl}|} \tag{4.30}$$

$$(A_{cl})^{-1} = \begin{bmatrix} -0.30 & 0 \\ 1.97 & 0 \end{bmatrix} \tag{4.31}$$

$$K_f = -\left[\begin{bmatrix} 0 & 1 \\ 2 & -3.9 \end{bmatrix}\begin{bmatrix} -0.30 & 0 \\ 1.97 & 0 \end{bmatrix}\begin{bmatrix} 0 \\ 2 \end{bmatrix}\right]^{-1} = 26.2384 \tag{4.32}$$

$$K_f = -\left[C(A_{cl})^{-1}B_d\right]^{-1} = 26.2384 \tag{4.33}$$

3.3.3 Simulink Model of State Feedback Controller

Figure 3.7 shows the Matlab/Simulink model of the State Feedback controller. The simulation included the state space form which is system matrix A, input matrix, B and output matrix, C.

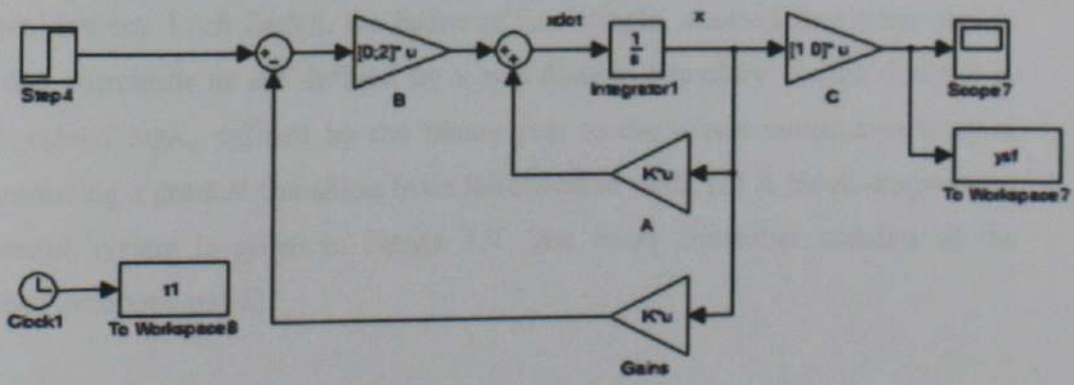

Figure 3.7 Simulink Model of state feedback controller

Figure 3.8 shows the Matlab/Simulink model of the State Feedback controller with forward gains. The difference between Figure 3.7 compared with Figure 3.8 is shown where the forward path gains are added.

The forward path gain introduced to reduce the steady state error to zero. The forward path gain is implemented by adding a gain to the simulation block diagram used for the state feedback as in Figure 3.7. This complete state feedback with the forward gain is shown in Figure 3.8

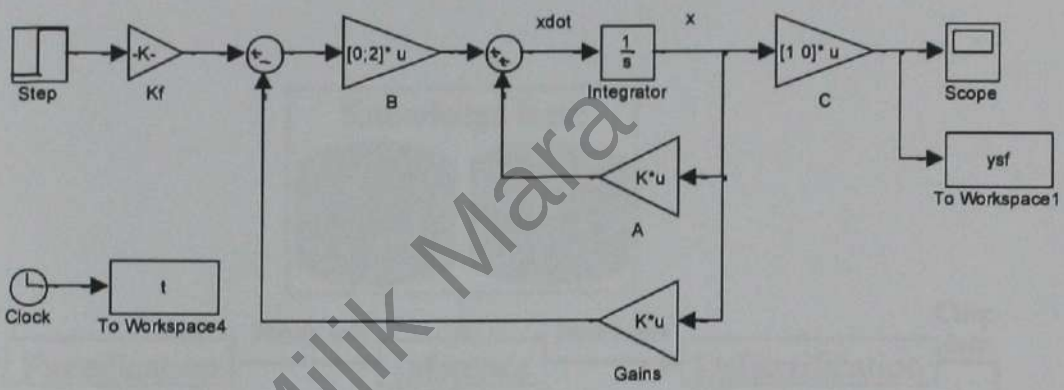

Figure 3.8 Simulink model of state feedback controller with forward gain

3.4 Fuzzy Logic Controller Design

This chapter contains the introduction and the design of a fuzzy logic controller for DC motor system. Lotfi Zadeh, the father of fuzzy logic, claimed that many sets in the world that surrounds us are defined by a non-distinct boundary. Zadeh decided to extend two valued logic, defined by the binary pair to the whole continuous interval thereby introducing a gradual transition from falsehood to truth. [2] A block diagram for a fuzzy control system is given in Figure 3.9. The fuzzy controller consists of the following four components [3]:

1. Rule base: set of fuzzy rules of the type "if-then" which use fuzzy logic to

quantify the expert's linguistic descriptions regarding how to control the plant.

2. Inference mechanism: emulates the expert's decision-making process by interpreting and applying existing knowledge to determine the best control to apply in a given situation.

3. Fuzzification interface: converts the controller inputs into fuzzy information that the inference process can easily use to activate and trigger the corresponding rules.

4. Defuzzification interface: converts the inference mechanism's conclusions into exact inputs for the system to be controlled.

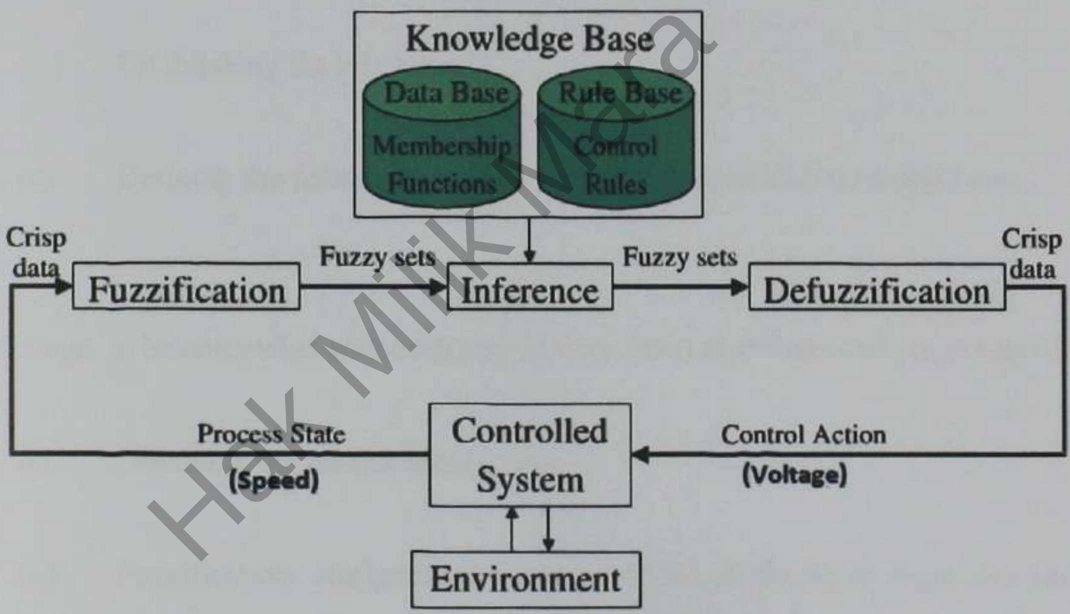

Figure 3.9: Block diagram of fuzzy logic system

The error, e and error change, Δe are manipulated in the Fuzzy system to achieved optimum results.

3.4.1 Fuzzy Logic Design Procedure

The procedure for implementing fuzzy techniques to control system consists of two very different stages:

First stage, to be completed before the control algorithm is executed, and consisting of:

(i) Establishing the controller's input and output variables (linguistic variables).

(ii) Defining each variable's fuzzy sets.

(iii) Defining the sets' membership functions.

(iv) Establishing the rule base.

(v) Defining the fuzzification, inference and defuzzification mechanisms.

Second stage, to be completed with each step of the control algorithm, and consisting of:

(i) Obtaining the precise input values.

(ii) Fuzzification: Assigning the precise values to the fuzzy input sets and calculating the degree of membership for each of those sets.

(iii) Inference: Applying the rule base and calculating the output fuzzy sets inferred from the input sets.

(iv) Defuzzification: Calculating the precise output values from the inferred fuzzy sets. These precise values will be the controller's outputs (commands) and be applied to the system to be controlled.

Figure 3.10 shows the Fuzzy Logic Toolbox using Mamdani method. The DC motor system consists of two inputs and a output function. The range 0, 20 is based on speed of the output DC motor

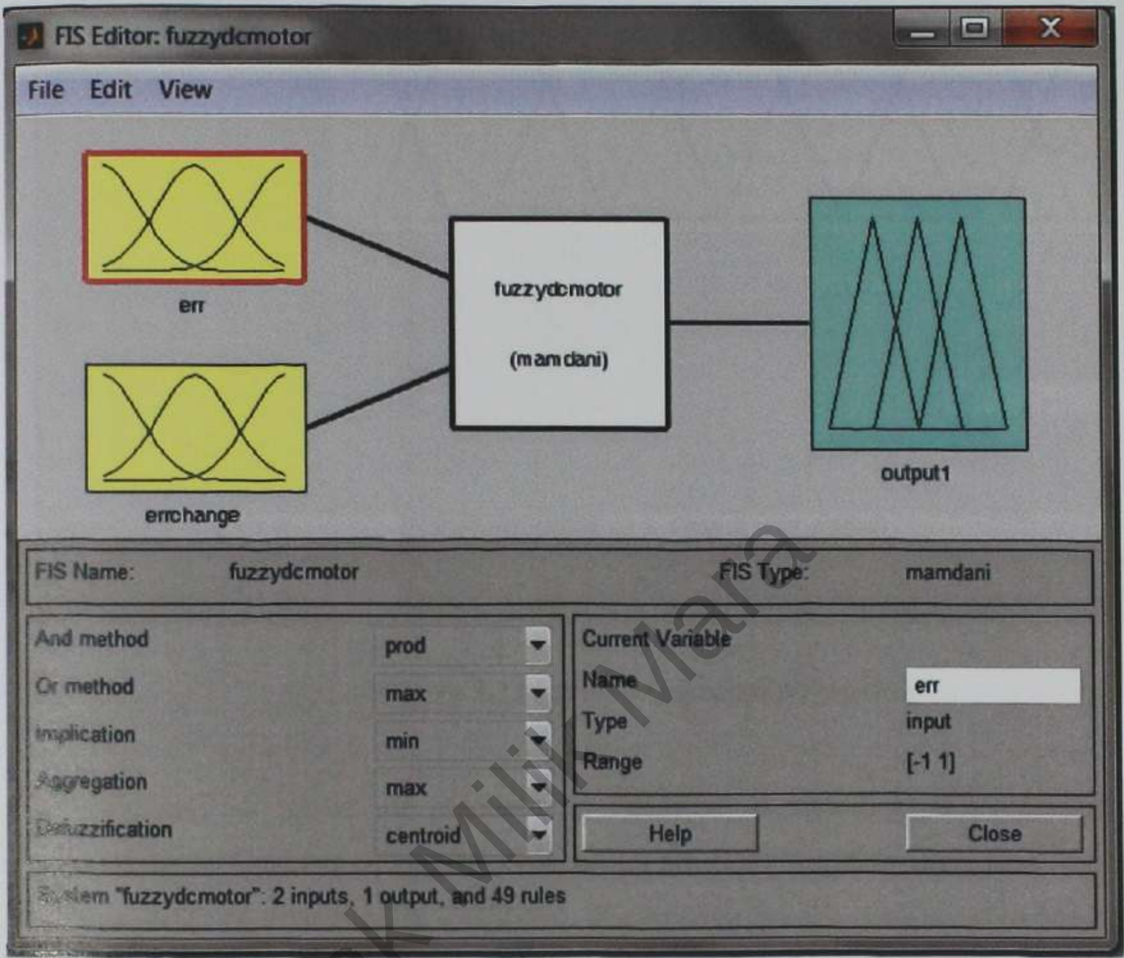

Figure 3.10 FIS editor for fuzzy

Figure 3.11 shows the membership functions of input1. Input1 represent the error. Consists of the function which are NB (Negative Big), NM(Negative Medium), NS(Negative Small), ZO(Zero), PS(Positive Small), PM(Positive Medium), PB(Positive Big) with respect to the error of the output.

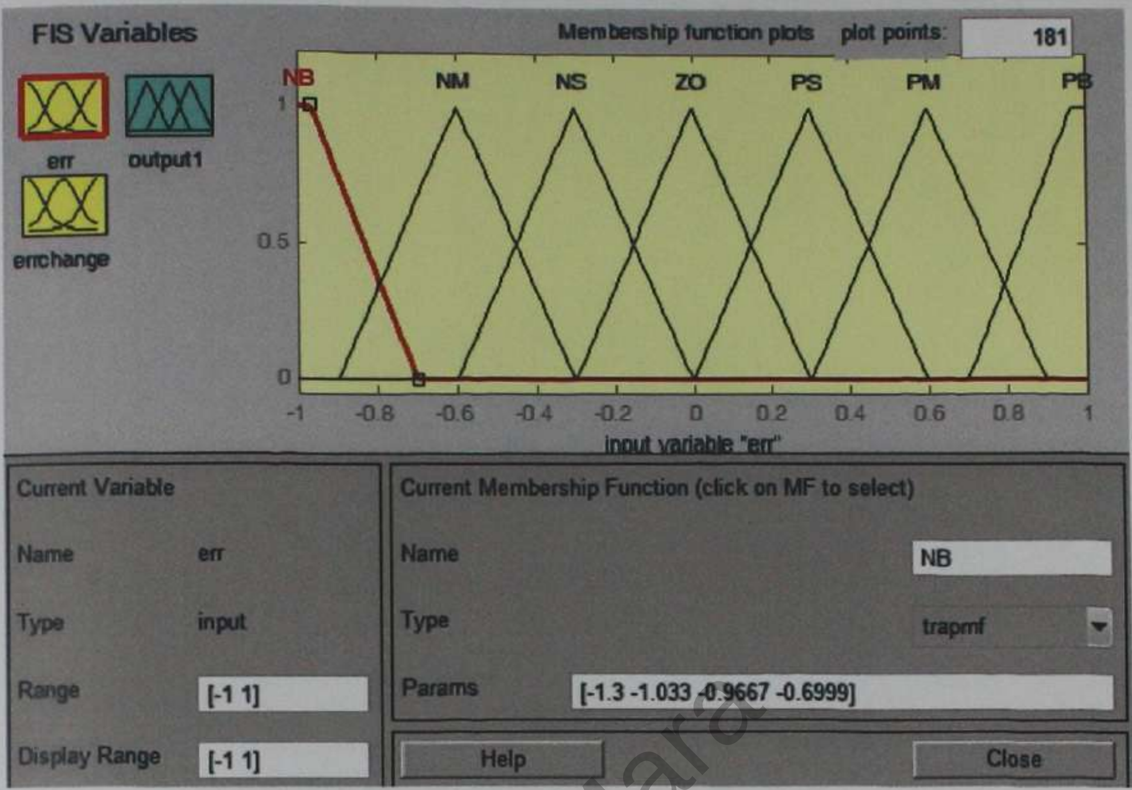

Figure 3.11 Input1 Membership Function

Figure 3.12 shows the membership functions of input2. Input2 represent the change of error. Consists of the function which are NB (Negative Big), NM(Negative Medium), NS(Negative Small), ZO(Zero), PS(Positive Small), PM(Positive Medium), PB(Positive Big) with respect to the change error of the output.

Figure 3.13 shows the membership functions of output1. Output1 represent the output speed variables. Consists of the function which are NB (Negative Big), NM(Negative Medium), NS(Negative Small), ZO(Zero), PS(Positive Small), PM(Positive Medium), PB(Positive Big) with respect to the speed of the DC motor.

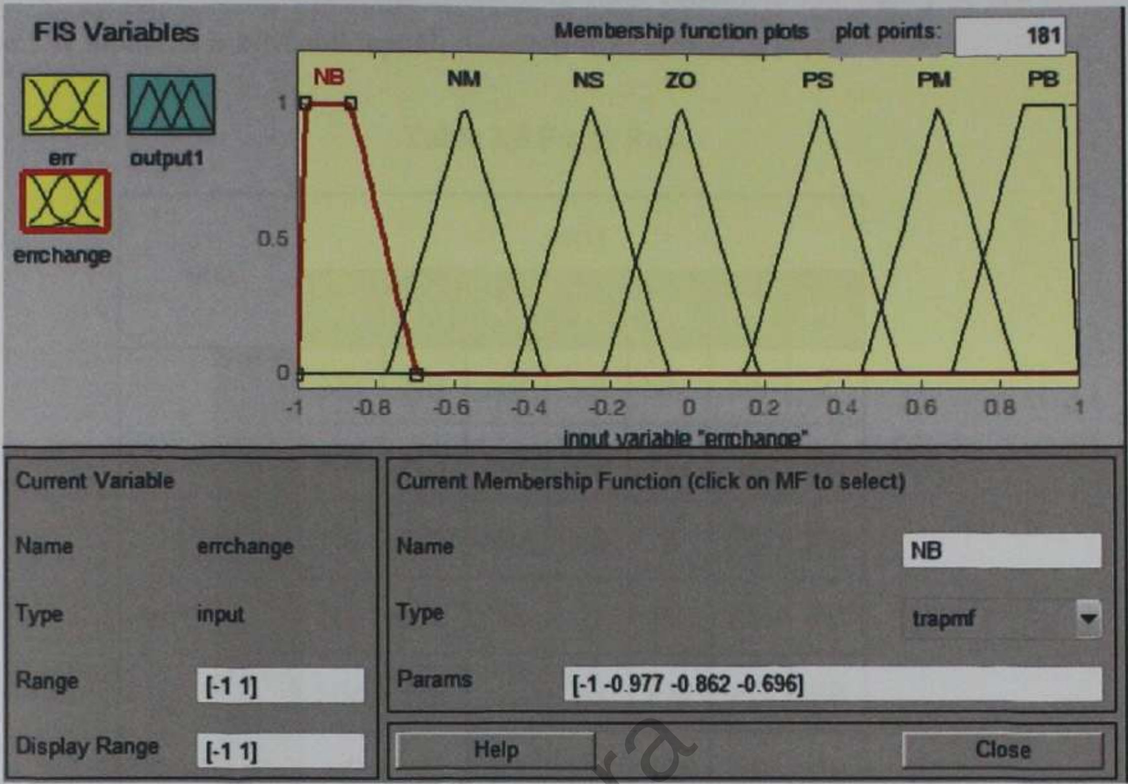

Figure 3.12 Input2 Membership Function

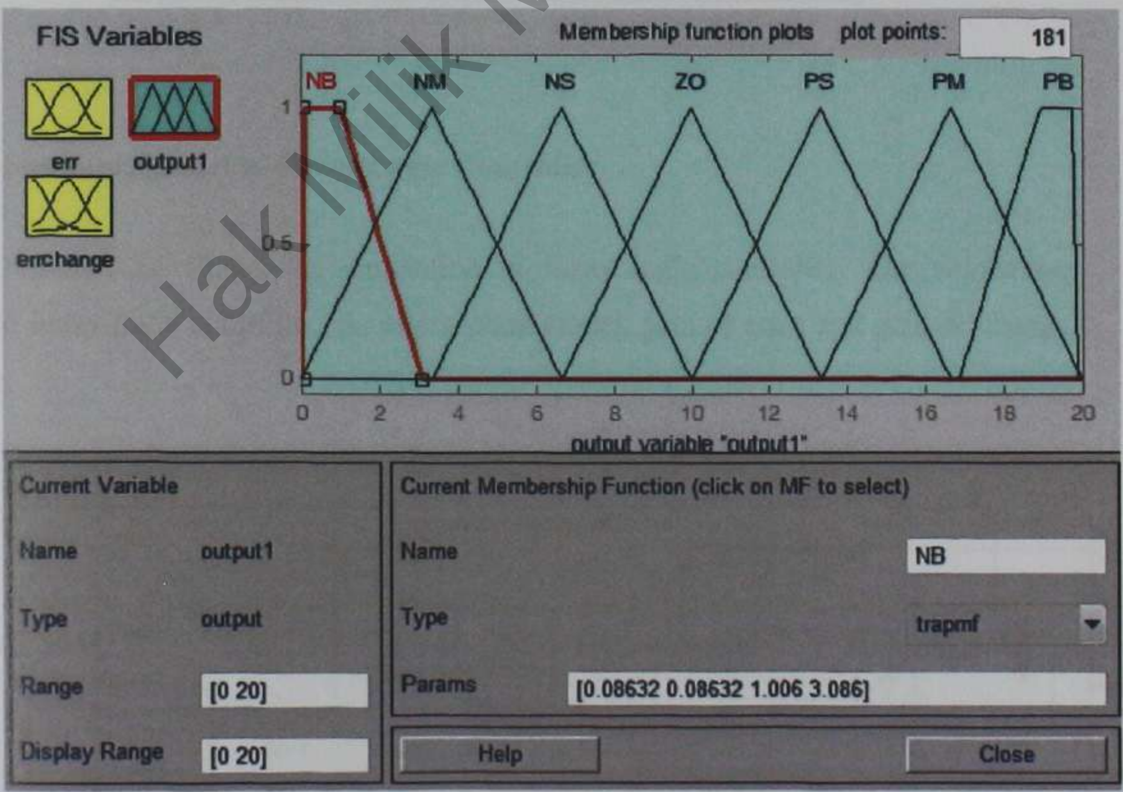

Figure 3.13 Output Membership Function

Table 3.3 shows the rule based of the fuzzy logic controller for the DC motor.

Consist of forty nine rule based using If-and-then rules condition. For example, one of the rules " If Input1, e is NM and Input2, Δe is NB then output1,u is NB.

Table 3.3 Fuzzy Rule

u(t)		e(t)						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
Δe(t)	**NB**	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

3.4.2 Simulink Model of Fuzzy Logic Controller

Figure 3.14 shows the simulation of fuzzy logic controller. The simulation included fuzzy logic controller, dc motor plant model, gain of error and gain of change of error.

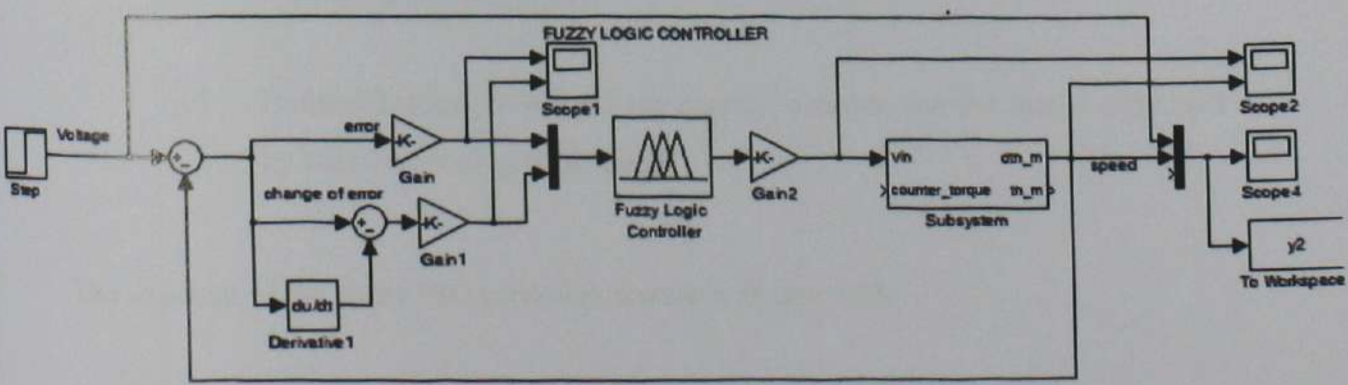

Figure 3.14 Simulation of Fuzzy System Model

3.5 Fuzzy PID Controller Design

The fuzzy PID control has more advantage compared with the conventional classic PID control, fuzzy PID controller is selected in control of non-linear, time-varying system, high control precision, upper sensitivity and fast response speed. [4]

3.5.1 Fuzzy PID Design Procedure

Fuzzy PID control utilized expert adjusting knowledge to establish adjustment rules if-then model, and uses fuzzy logic reasoning to adjust PID parameters in real time, this process makes the speed of DC motor achieved ideal control speed.

As previous chapter, Fuzzy controller is the main of the fuzzy PID control system and fuzzy controller is made up of:

(i) Fuzzification: the fuzzed transforms accurate quantity of input to fuzzy quantity.

(ii) Rule base: to control the rule sets that are obtained by experience or suitable methods.

(iii) Fuzzy reasoning: explain and utilizes expert experience of rule base to achieve optimum control.

(iv) Defuzzification; transform the outputs accurate amount that is converted by fuzzy reasoning conclusion.

The structure of the fuzzy PID control is shown in Figure 3.15.

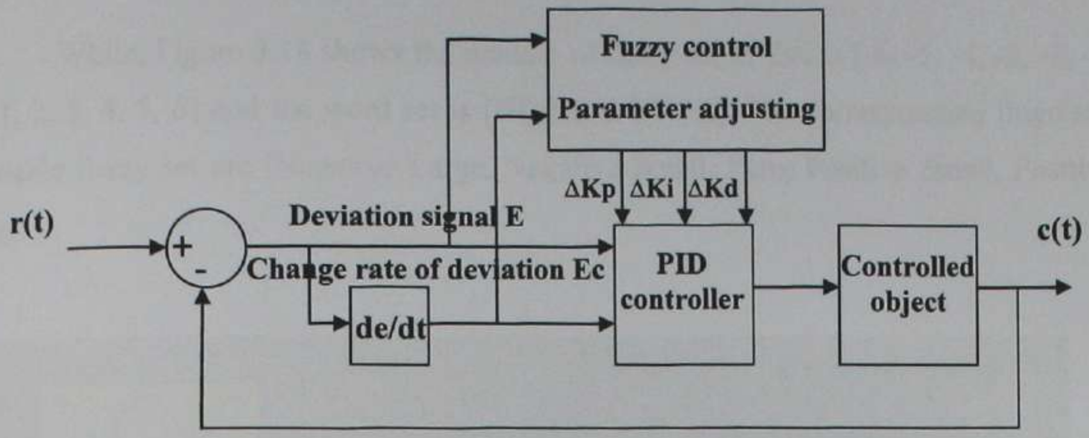

Figure 3.15 Structure chart of fuzzy PID control

Figure 3.15 shows the system consists 2 controllers that are fuzzy logic controller and PID controller. Deviation signal, E and the change rate of deviation are the input of fuzzy control system and PID controller. The changes of the three PID parameters are the outputs. From the established rules of the fuzzy control, fuzzy reasoning can be made and the value of PID parameters can be modified on-line. Because of the on-line modification, PID parameters can be self tuning achieved. Hence, the controlled object has a good dynamic and static performance.

Fuzzy PID control method finds the relations among the three parameters Kp, Ki, Kd of PID controllers and the value of deviation |E| and the value of deviation change rate |Ec|.

The value of |E| and value of |Ec| are continuously detected in the control process, then the three parameters are modified on-line based on the fuzzy logic control rules to meet the control requirements.

Figure 3.16 shows FIS editor for fuzzy PID including the setting of And method, Or method, Implication, Aggregation, and defuzzification. Figure 3.17, Figure 3.19, Figure 3.20 and Figure 3.21 show the domain of fuzzy set of |E| and Kp, Ki, Kd are [-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6] and the word set are [NB NM NS Z PS PM PB]. The correspond linguistic variable fuzzy set are [Negative Large, Negative Middle, Negative Small, Zero, Positive Small, Positive Middle, Positive Big].

While, Figure 3.18 shows the domain of fuzzy set of |Ec| is [-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6] and the word set is [NB NS Z PS PB]. The corresponding linguistic variable fuzzy set are [Negative Large, Negative Small, Zero, Positive Small, Positive Big].

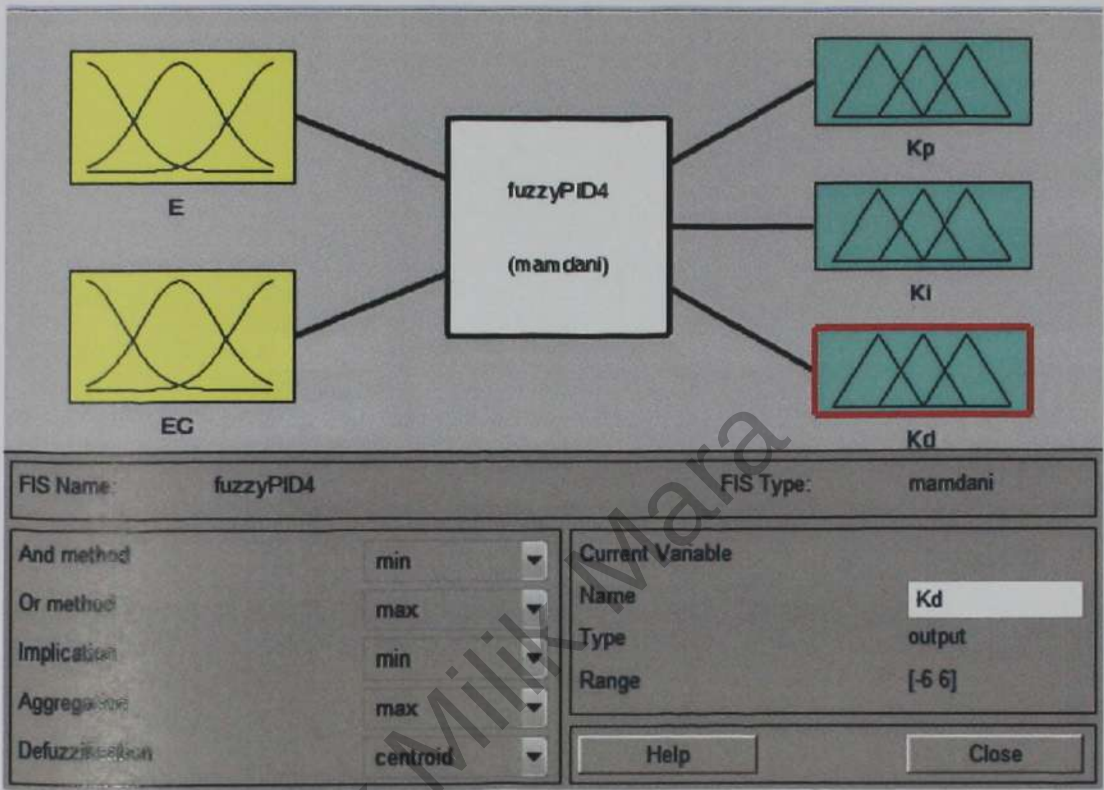

Figure 3.16 FIS editor for fuzzy PID

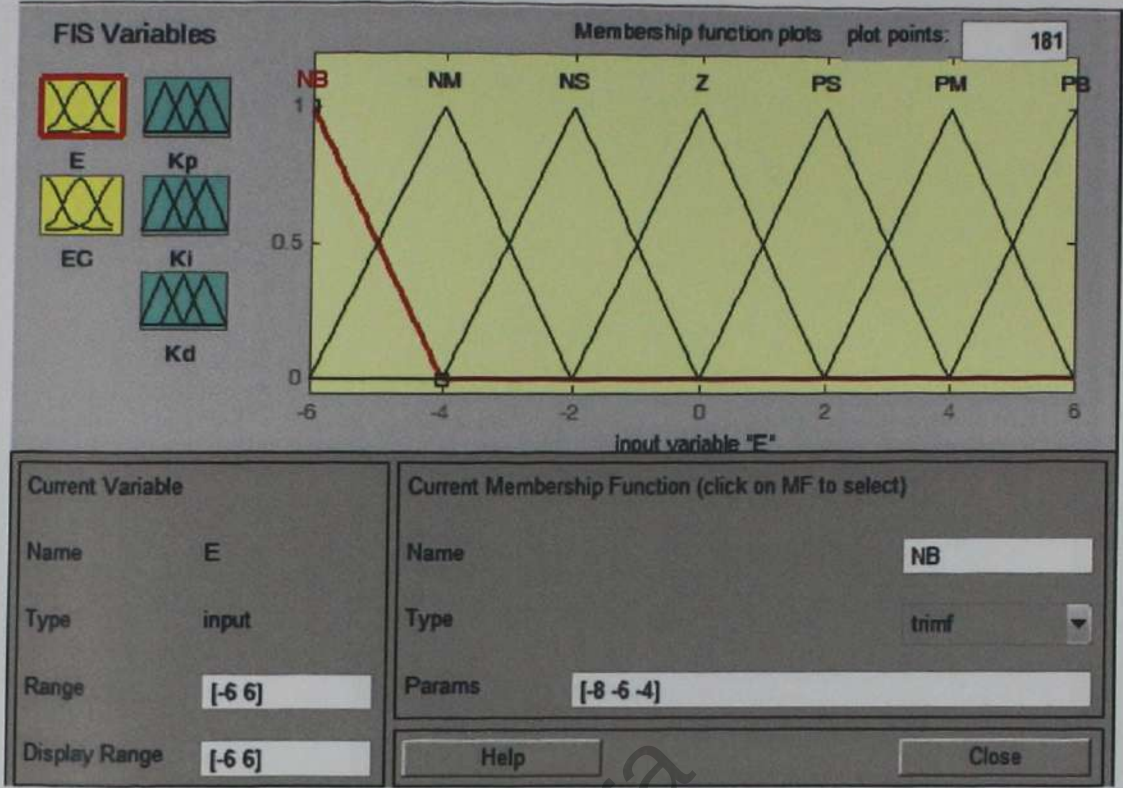

Figure 3.17 Input1 Membership Function, |E|

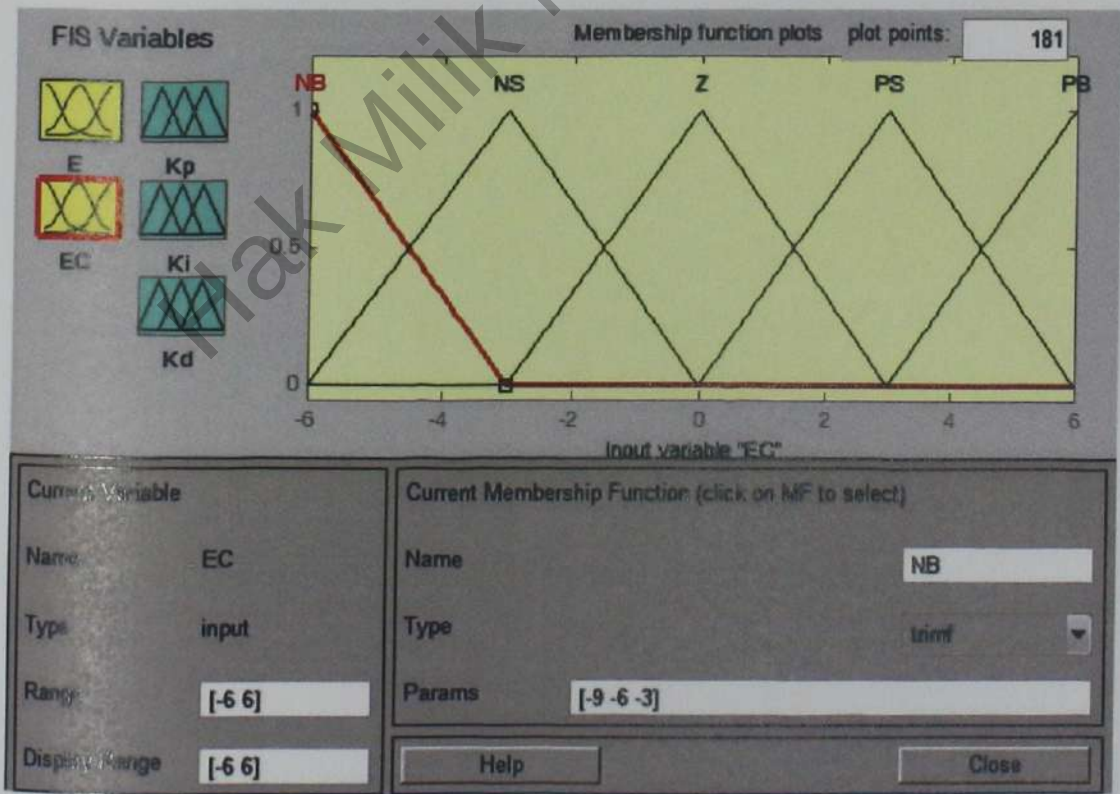

Figure 3.18 Input2 Membership Function, |Ec|

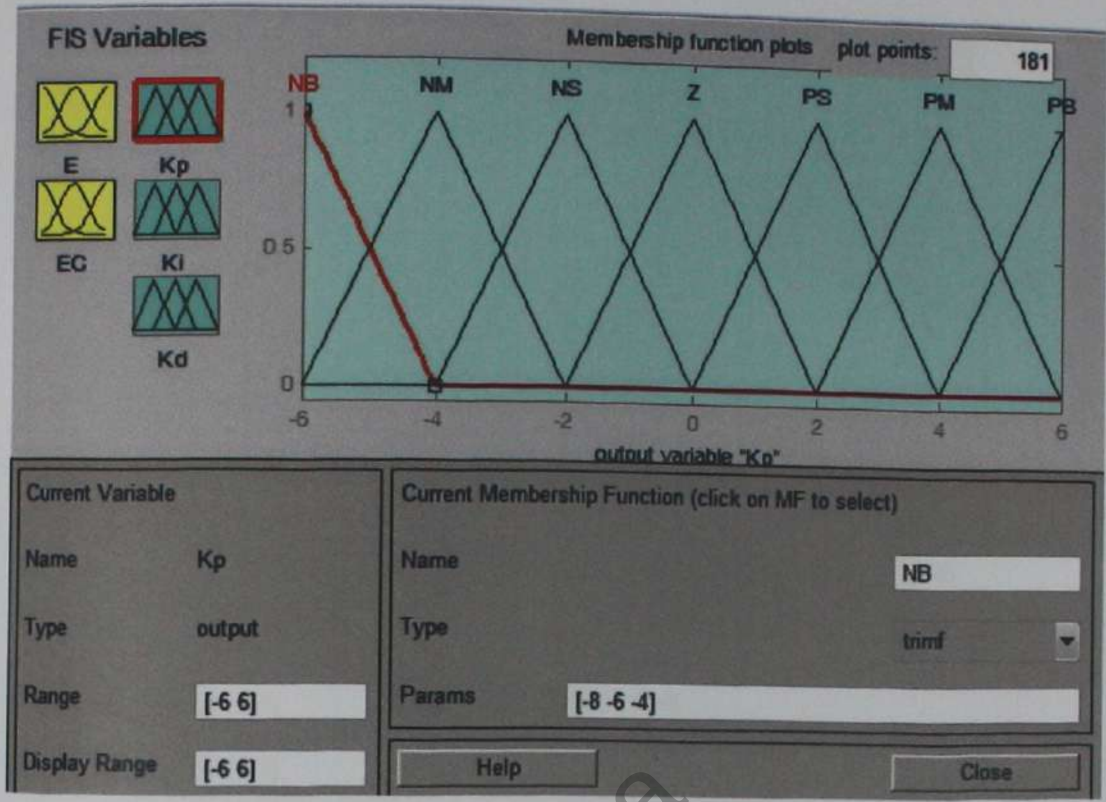

Figure 3.19 Output1 Membership Function, Kp

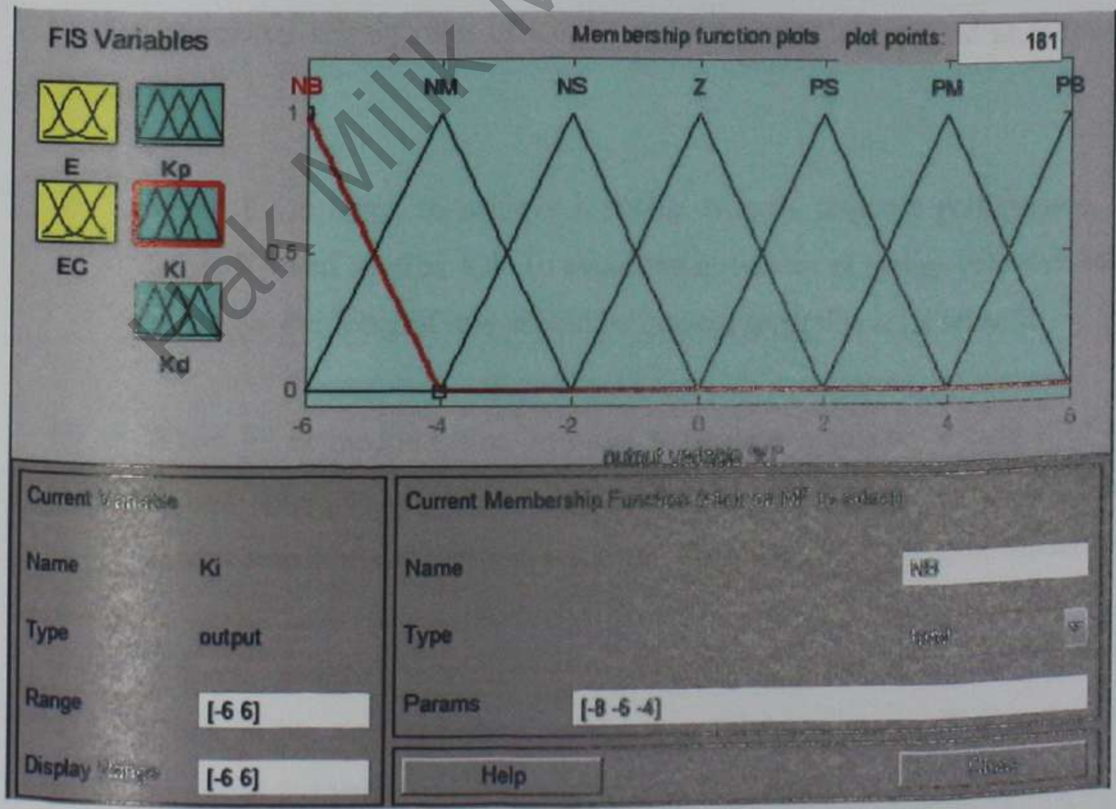

Figure 3.20 Output2 Membership Function, Ki

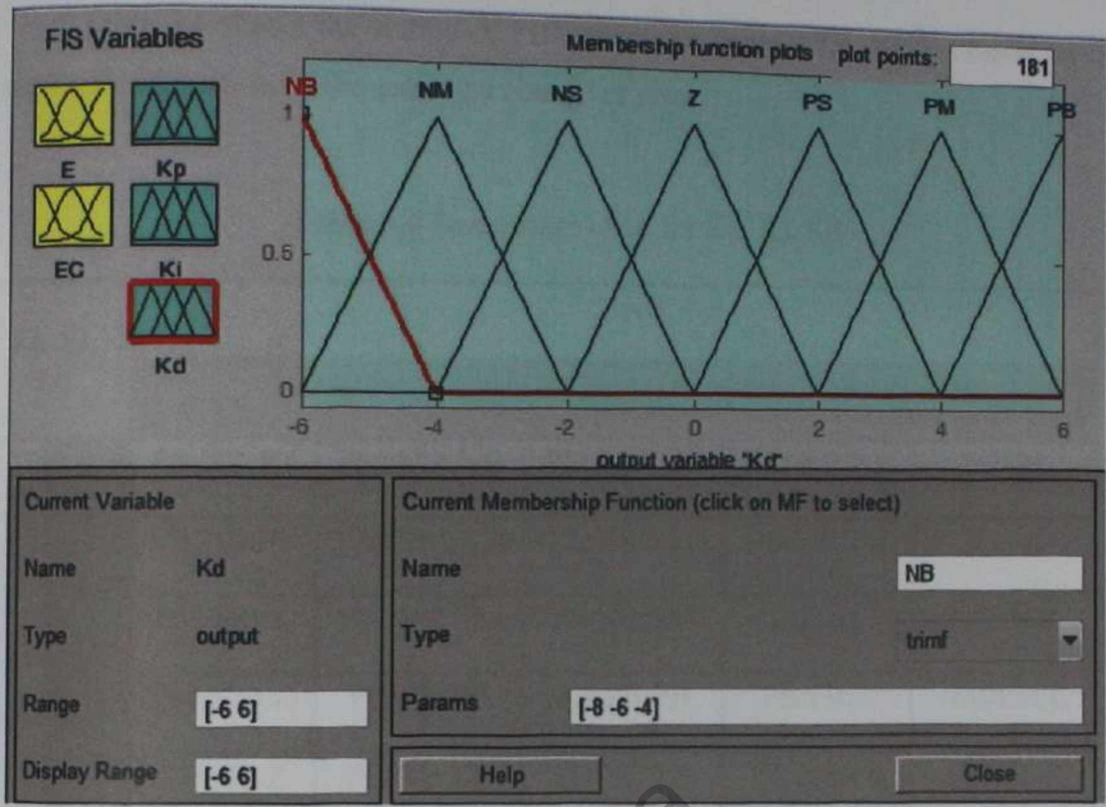

Figure 3.21 Output3 Membership Function, Kd.

The parameter setting rules of Kp, Ki and Kd can be summarized as following conditions [4]:

(i) When |E| is large, to achieve a strong dynamic response performance, set larger Kp and smaller Kd. To avoid the overshoot of system response being too large, the Integral role should be limited, generally, Ki is set as 0.

(ii) When |E| is medium size, in order to achieve a smaller overshoot of the system response, Kp can be set smaller. At this time, the value of Kp has greater impact for the system response. The value of Ki should be moderate.

(iii) When |E| is small, to make the system stable, the value of Kp and Ki should be set larger. At this point, in order to avoid the system oscillation near the set value, the value of Kd should refer to the value of |Ec|. When the value of |Ec| is small, the value of Kd can be larger. When the value of |Ec| is larger, the value of Kd can be small, usually medium.

Table 3.4 shows the setting of PID parametes namely Kp, Ki, Kd based on the membership functions of the error and change of error.

Table 3.4 Fuzzy rules chart for Kp, Ki, Kd

Kp, Ki, Kd		Δe(t)				
		NB	**NS**	**Z**	**PS**	**PB**
e(t)	**NB**	PB:NB:PS	PM:NM:NB	PM:NM:NB	NM:NB:NB	Z:Z:PS
	NM	PB:NB:PS	PM:NM:NB	PS:NS:NM	PS:NS:NM	Z:Z:Z
	NS	PM:NB:Z	PM:NS:NM	PS:NS:NM	Z:Z:NS	NS:PS:Z
	Z	PM:NM:Z	PB:PB:PB	PB:PB:PB	PB:PB:Z	NM:PM:Z
	PS	PS:NM:Z	PB:NB:PB	PB:NB:PB	PB:NB:PB	NM:PB:Z
	PM	PS:Z:PB	PB:NB:PB	PB:NB:PB	PB:NB:PB	NM:PB:PM
	PB	Z:Z:PB	NM:PS:PM	NM:PM:PM	NM:PM:PS	NB:PB:PB

3.5.2 Simulink Model of Fuzzy PID Controller

Figure 3.22 shows the Matlab-Simulink diagram of the fuzzy PID controller. The simulation included DC motor system, fuzzy logic controller and a PID controller

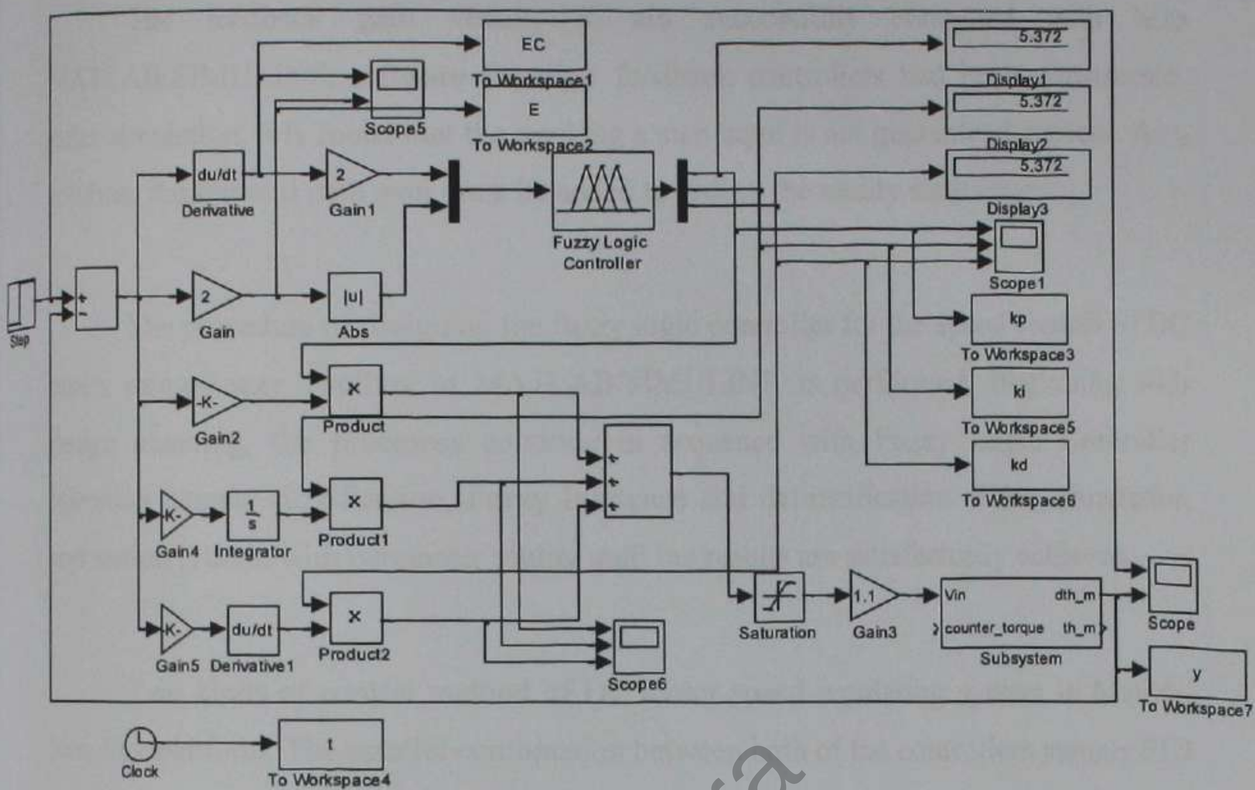

Figure 3.22 Simulation of Fuzzy PID control System Model

3.6 Summary

The PID controller design method with Ziegler-Nichols tuning (type 1) have been widely used in the process control systems where the plant dynamics are not precisely known. It is a time-domain method and very useful. The S-shaped curve had been obtained in order to get important parameter delay time, L and time constant, T. In designing a system using the PID approach, formula was suggested by Ziegler-Nichols that will give stable operation and fine tuning still required until an acceptable results is achieved. The simulation diagram for PID controller had also been successfully constructed.

Meanwhile, state feedback technique is chosen by which all desired poles can be selected at the start of the design process. The solving of Lyapunov Equation procedures are followed by considering proper matrix solutions.

The feedback gain vector, **K** are successfully computed with help MATLAB/SIMULINK software the state feedback controllers had been constructed. After simulation, it is found that the tracking a step input is not guaranteed success. As a solution, the forward path gain must be added to reduce the steady state error.

The procedure of designing the fuzzy logic controller for the speed control of DC motor using Fuzzy Toolbox in MATLAB/SIMULINK is performed. Beginning with design planning, the processes continue in sequence with Fuzzy Logic Controller operation namely fuzzification, Fuzzy Inference and defuzzification. Then, simulation and testing is done with parameter tuning until the results are satisfactorily achieved.

Two kinds of control method of DC motor speed regulating system in Matlab-Simulink platform. The parallel combination between both of the controllers namely PID and fuzzy are adopted in the system. The difference between the input r and the output v is the e(k), and both the value e(k) and its change of error, Δe is send to the fuzzy controller. The PID parameter kp, ki and kd is calculated out according to offline rules in fuzzy controller, at the same time, the kp also refined by p controller which is the immune PID controller. Hence, the PID parameters can be continuous updated based on the error, e and its change of error, Δe. The simulation is done separately for a conventional PID controller and the Fuzzy-PID controller. [5] Then, simulation and testing is done with parameter tuning until the results are satisfactorily achieved. All he simulation results are shown in Chapter 4.

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

4.1 Introduction

This chapter contains all of the results of the simulation mentioned in the previous chapters. For every controller simulation, there will be simulation to obtain improved motor speed regulation and transient response based on graph presented. In order to meet these objectives, simulation works using MATLAB with SIMULINK® is performed and the responses of the speed under various system parameters are illustrated. The graph represents the output speed of the DC motor measured in rad/s with refer to the time, t for stability analysis.

4.2 Simulation Using Open Loop of the Separately Excited Linear DC Motor

In this section, the simulation is carried out without the controller. The DC motor System simulated with and without Coulomb friction, F_C.

Figure 4.1 shows the simulation of the open loop nonlinear DC motor model. The simulation consists only the DC motor model with step input signal. Figure 4.2 shows the subsystem nonlinear model of the DC model that included all the important parameters as in equation (2.6) and equation (2.9).

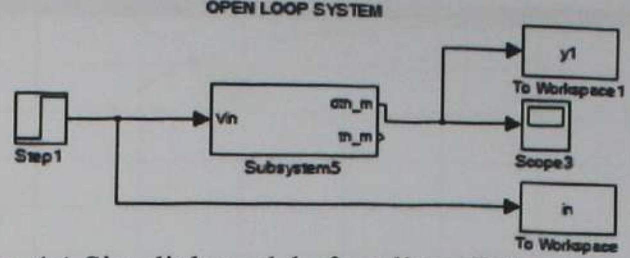

Figure 4.1 Simulink model of nonlinear DC motor model

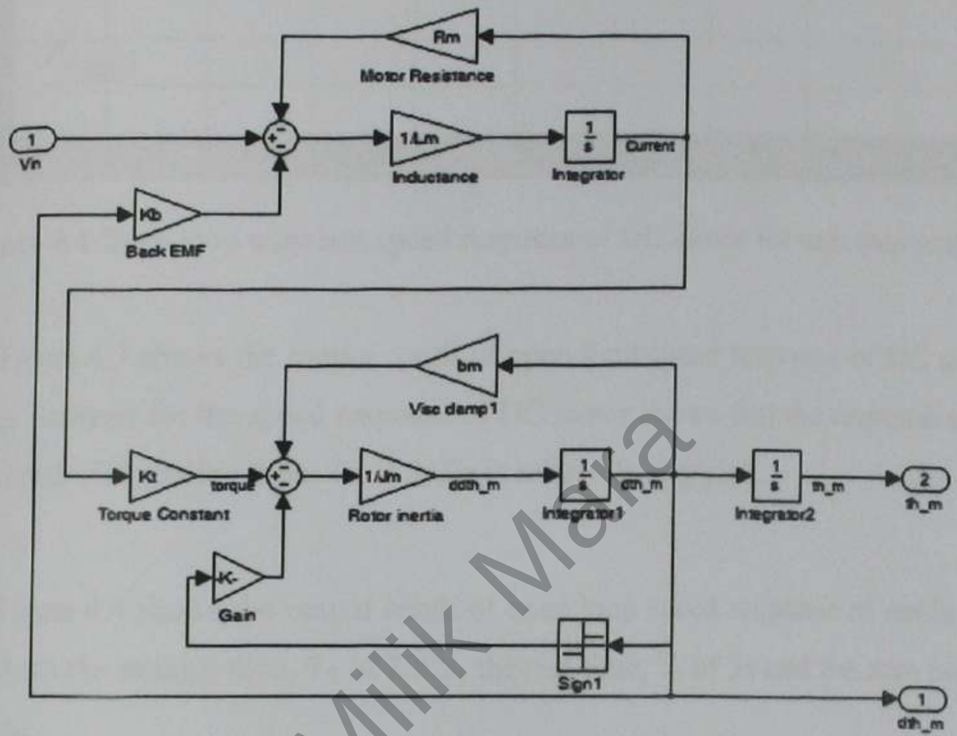

Figure 4.2 The subsystem of the DC motor

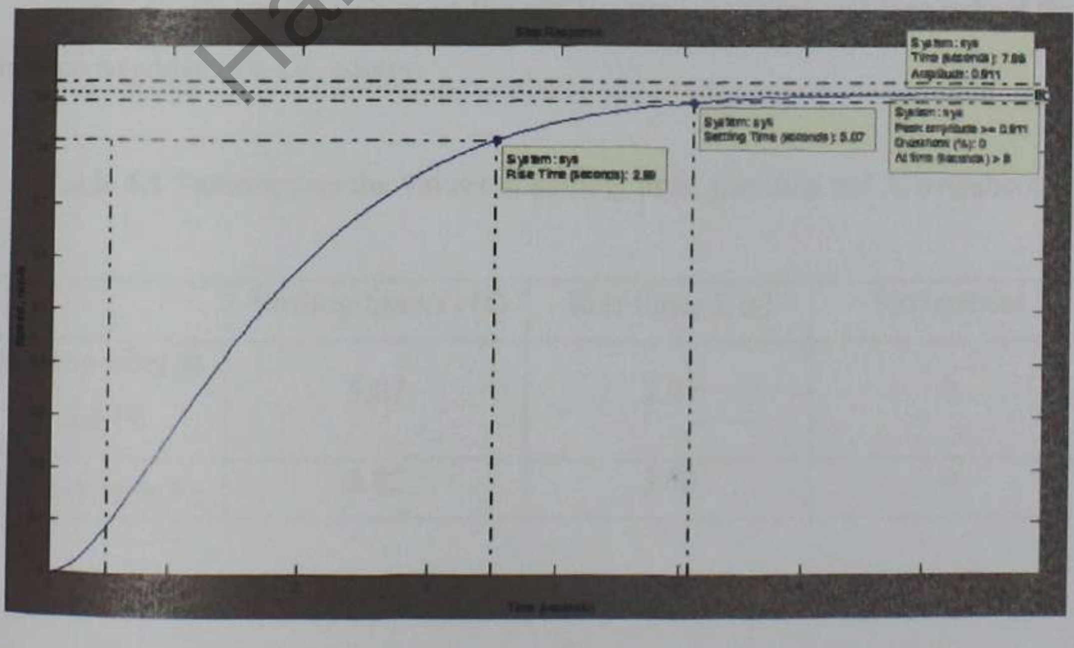

Figure 4.3 Open loop transient speed response of DC motor for unit step without F_C

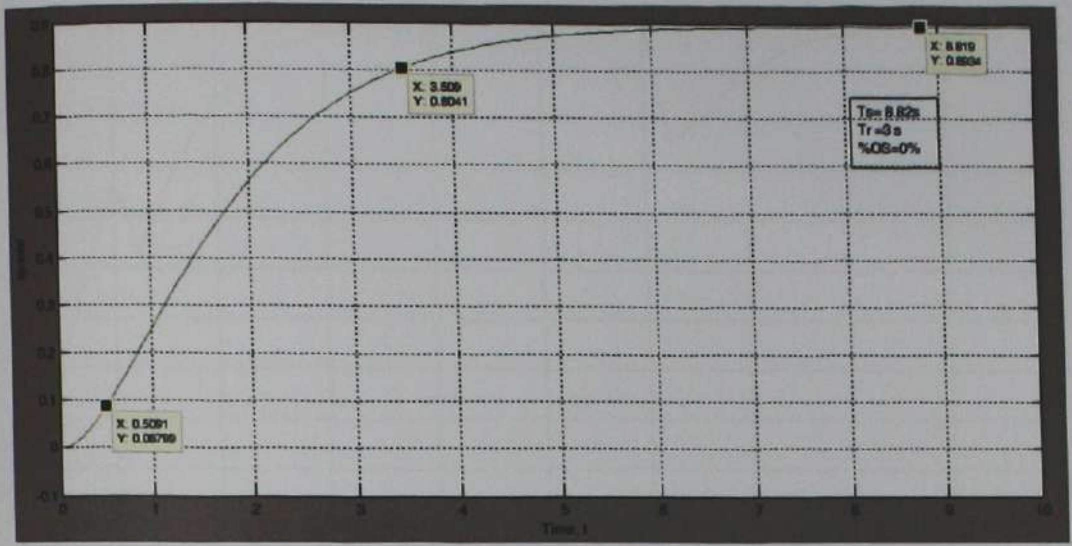

Figure 4.4 Open loop transient speed response of DC motor for unit step with F_C

Figure 4.3 shows the output result of open loop speed response of DC motor for unit step. Analysis for the speed response of DC motor shows that the response is highly over damped with settling time, Ts of 5.07s is relatively sluggish.

Figure 4.4 shows the output result of open loop speed response of nonlinear DC motor which the settling time, T_S of 8.82s, the rise time, T_r of 3s and the zero percent of overshoot.

Table 4.1 shows the values of the settling time, rise time and %overshoot for the open loop response of a DC motor.

Table 4.1 Summarizes the values of settling time, rise time and % overshoot

	Settling time, T_S (s)	Rise time, T_r (s)	%overshoot
Open loop without F_C and TL	5.07	2.99	0
Open loop with F_C	8.82	3.00	0

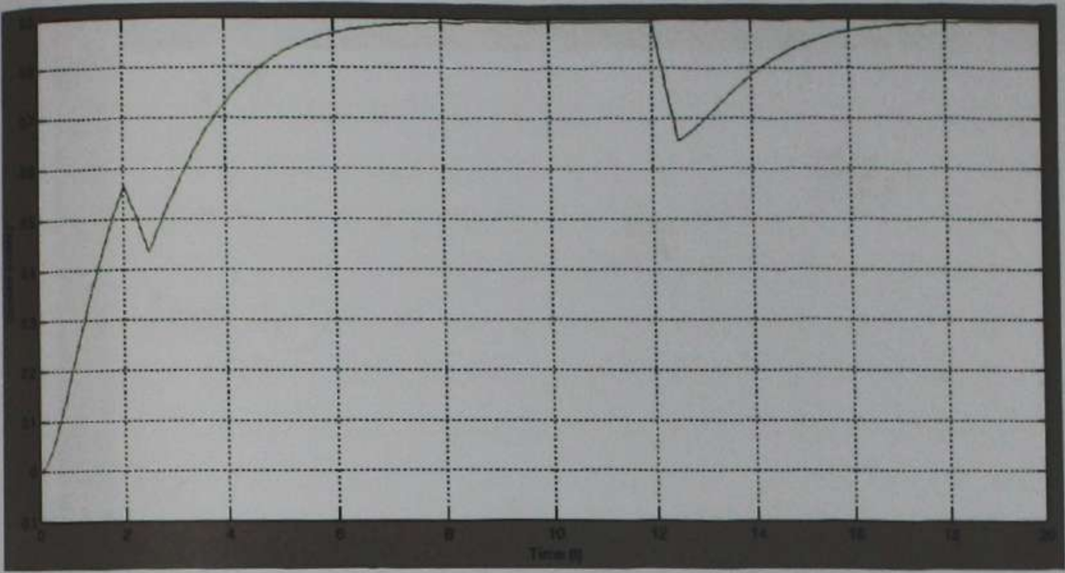

Figure 4.5 Speed response of the DC motor with T_L and F_C

Figure 4.5 shows the response of the speed of the DC motor with fuzzy logic controller with load torque, T_L and Coulomb friction, F_C. The unit pulse setting is shown below:

Amplitude	= 1
Period	= 10secs
Pulse width (% of period)	= 5
Phase delay	= 2 secs

4.3 Simulation Using PID Controller Tuning with Ziegler-Nichols technique

Figure 4.6 shows the simulink diagram of the nonlinear DC motor model with PID controller.

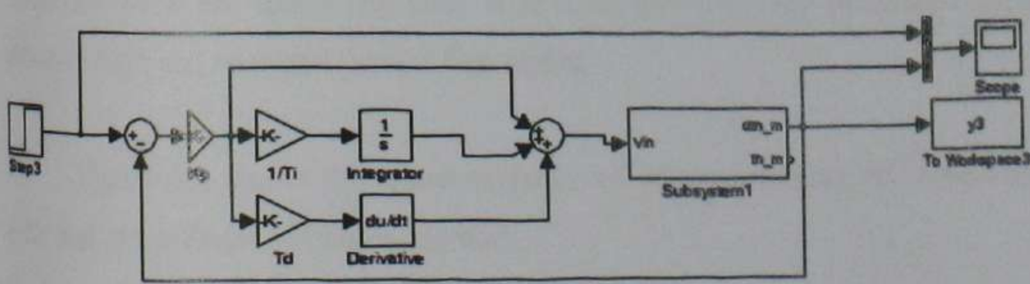

Figure 4.6 Simulink model of nonlinear motor model with PID controller

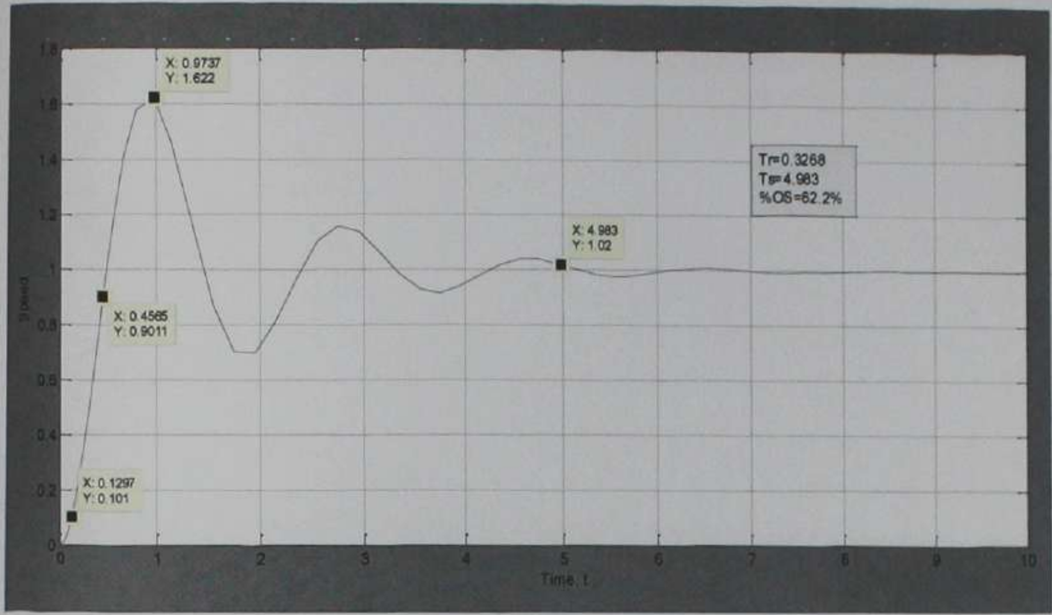

Figure 4.7 Speed of the DC motor for PID Controller without F_C

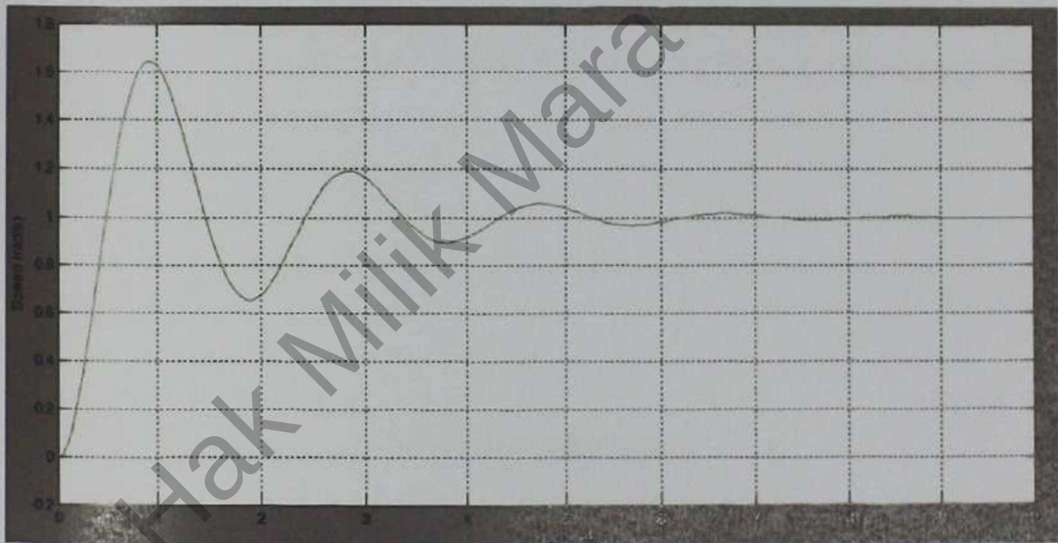

Figure 4.8 Speed of the DC motor for PID Controller with F_C

Figure 4.7 shows the speed settling time is at 4.983seconds with a 62.2% overshoot while the speed rise time is at 0.3268seconds. The percentage overshoot is obtained high and required further fine tuning.

Figure 4.8 shows the speed response of DC motor using PID controller tuning with first order Ziegler-Nichols method.

Figure 4.9 Speed of the DC motor for Fuzzy Logic Controller with T_L and FC

Figure 4.9 shows the response of the speed of the DC motor with fuzzy logic controller with load torque, T_L and Coulomb friction, F_C. The unit pulse setting is shown below:

Amplitude	= 1
Period	= 10secs
Pulse width (% of period)	= 5
Phase delay	= 2 secs

4.3 Simulation Using State Feedback Controller

Figure 4.10 shows the simulink diagram of the nonlinear DC motor model with state feedback controller.

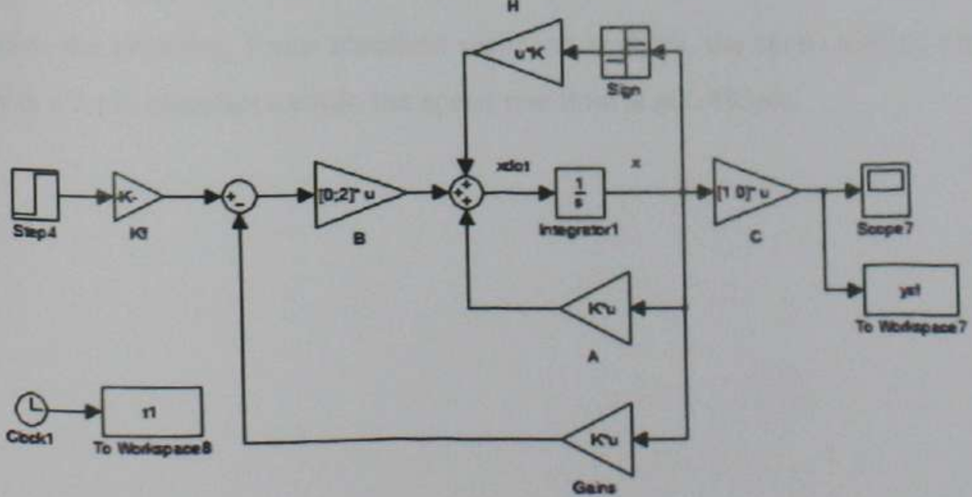

Figure 4.10 Simulink model of nonlinear motor model with state feedback controller

Figure 4.11 shows the simulation response for state feedback controller without forward path gain, Kf.

From transient response analysis, it is shown the state feedback controller alone didn't provided perfect tracking of a reference input.

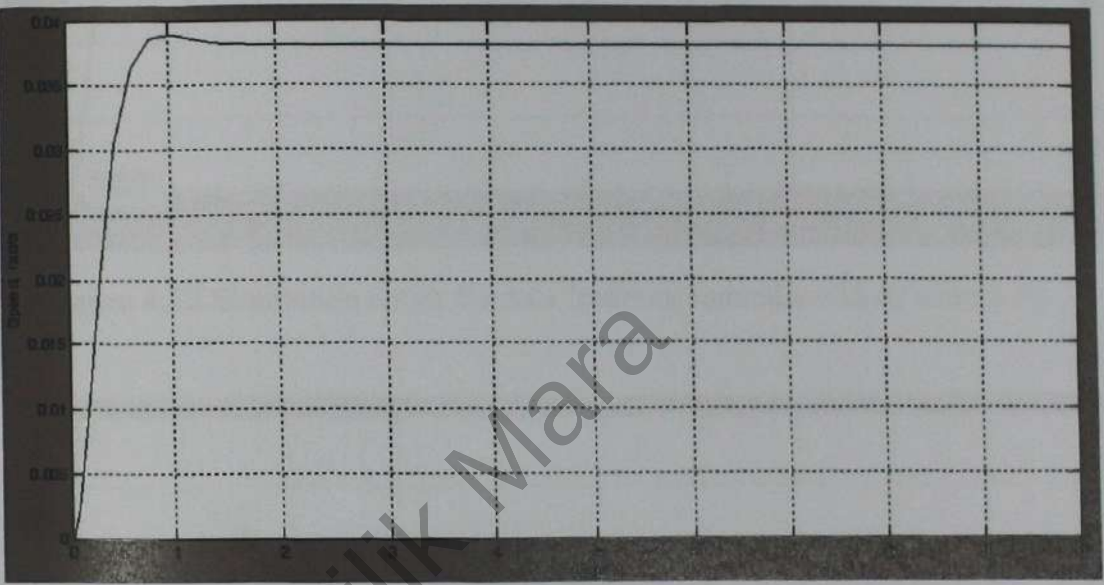

Figure 4.11 Simulation result for state feedback controller without Kf

Figure 4.12 shows the output result of state feedback controller tuning with forward path gain.

To solve the issue of the steady state error, forward gain, Kf is introduced to solve the problem. From transient response analysis, the speed settling time is at 1sec with a 2.1% overshoot while the speed rise time is at 0.495sec.

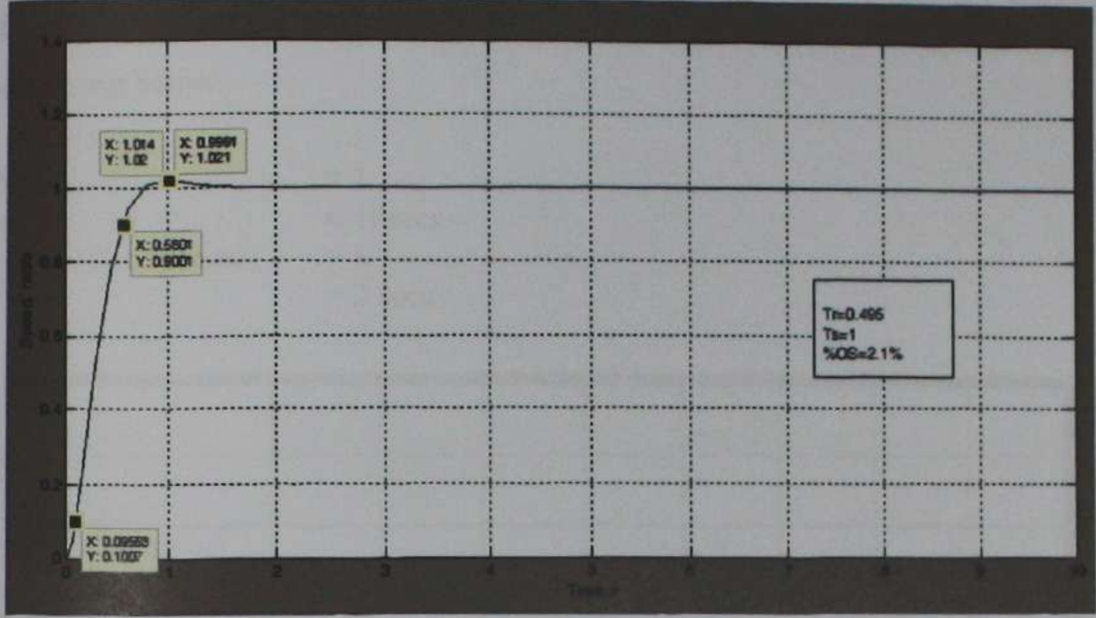

Figure 4.12 Simulation result for state feedback controller with *Kf* without F_C

Figure 4.13 Speed of the DC motor for state feedback controller with F_C

Figure 4.13 shows the response of the DC motor for state feedback controller with Coulomb friction. It is shown the step response for the controller which gives settling time of 1.11 sec, the rise time of 0.46 sec and percentage overshoot of 0.3%

Figure 4.14 shows the speed response of the DC motor using state feedback controller with load torque, T_L and Coulomb friction F_C. It is shown when the unit pulse is given the speed of DC motor will be dropped until 0.7 rad/s. The speed increases consistently until the speed reaches steady state condition. The unit pulse setting is shown below:

Amplitude	= 1
Period	= 10secs
Pulse width (% of period)	= 5
Phase delay	= 2 secs

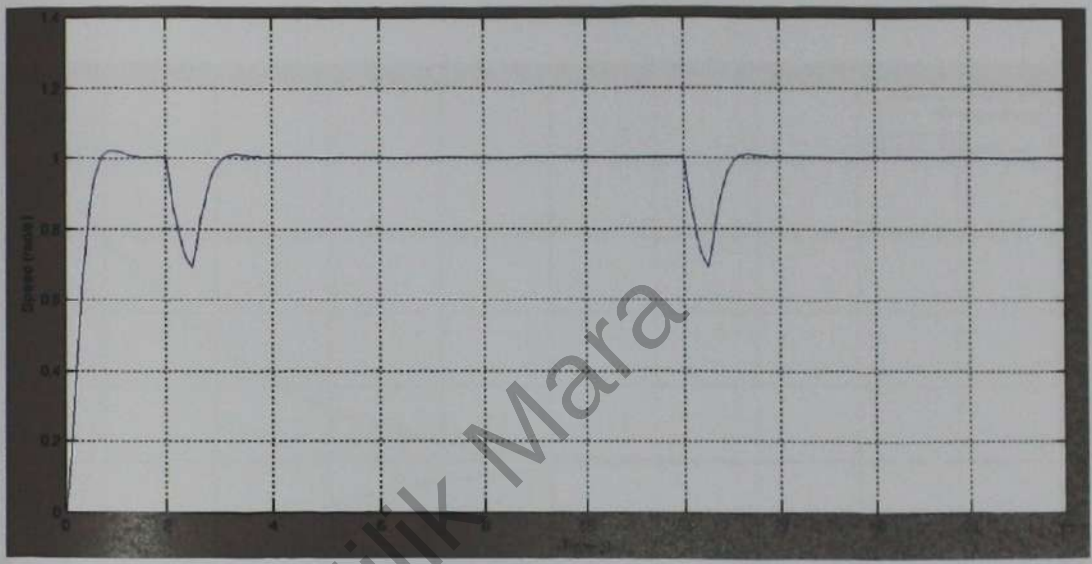

Figure 4.14 Speed of the DC motor for state feedback controller with T_L and F_C

4.5 Simulation Using Fuzzy Logic Controller

Figure 4.15 shows the simulink diagram of the nonlinear DC motor model with fuzzy logic controller.

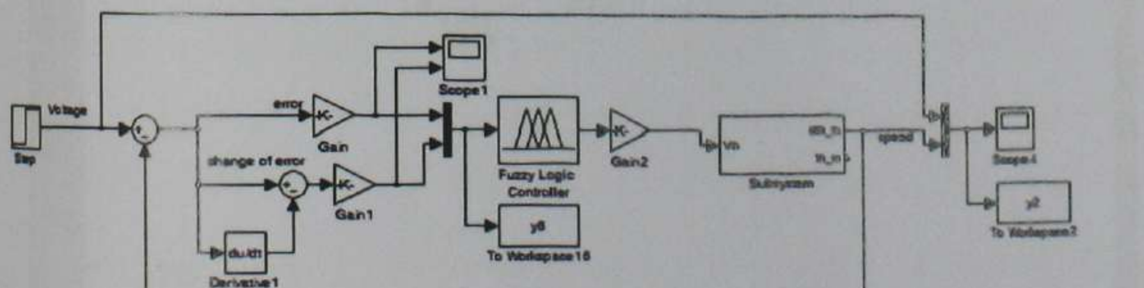

Figure 4.15 Simulink model of nonlinear motor model with fuzzy logic controller

Figure 4.16 shows the response of error and change of error for Fuzzy logic controller with refer to the time, t. It is proven that the system achieves desired performance in which the values of error and change of error reaches zero indicated it is stabilized.

Figure 4.17 shows the transient response of DC motor speed control for Fuzzy Logic Controller without Coulomb friction, F_C. It shows the speed settling time is at 4.432seconds with a 0% overshoot while the speed rise time is at 2.71seconds.

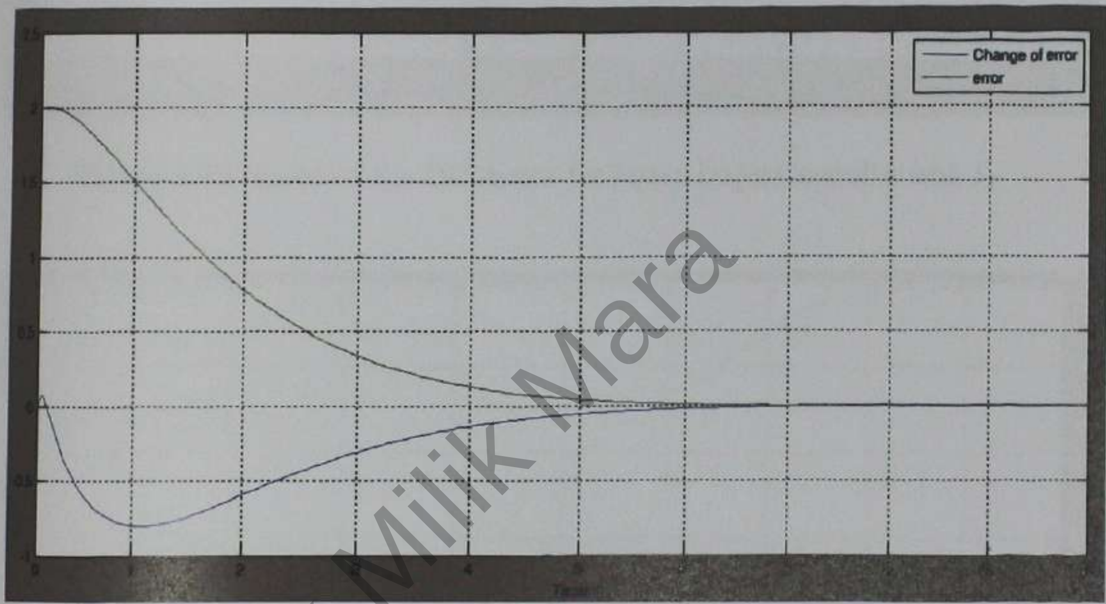

Figure 4.16 Response of error and change of error for Fuzzy controller

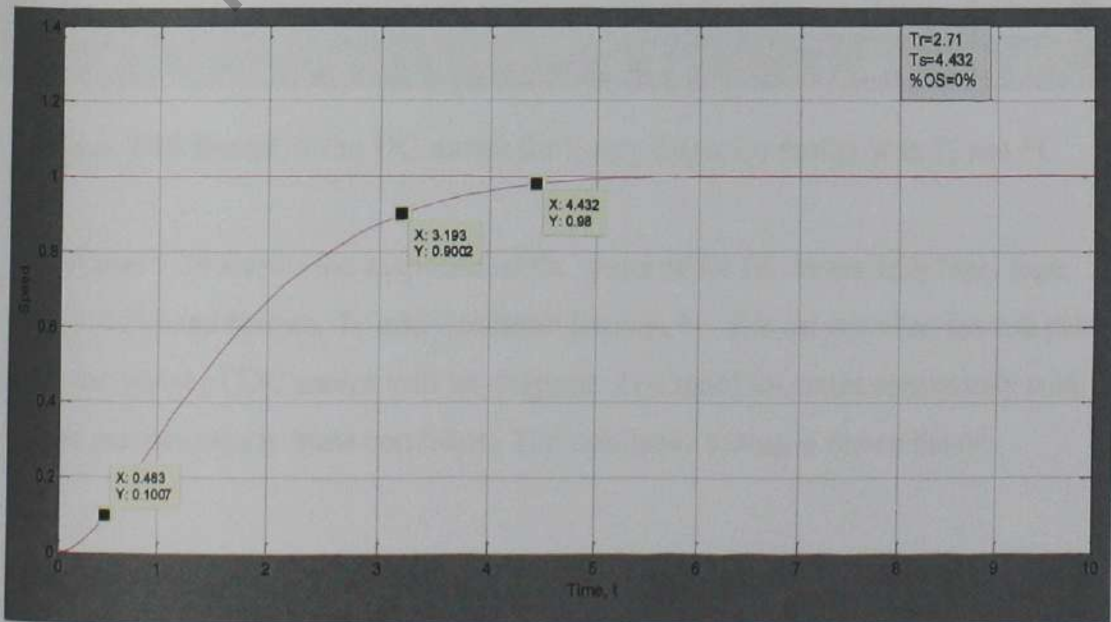

Figure 4.17 Speed of the DC motor for Fuzzy Logic Controller without F_C

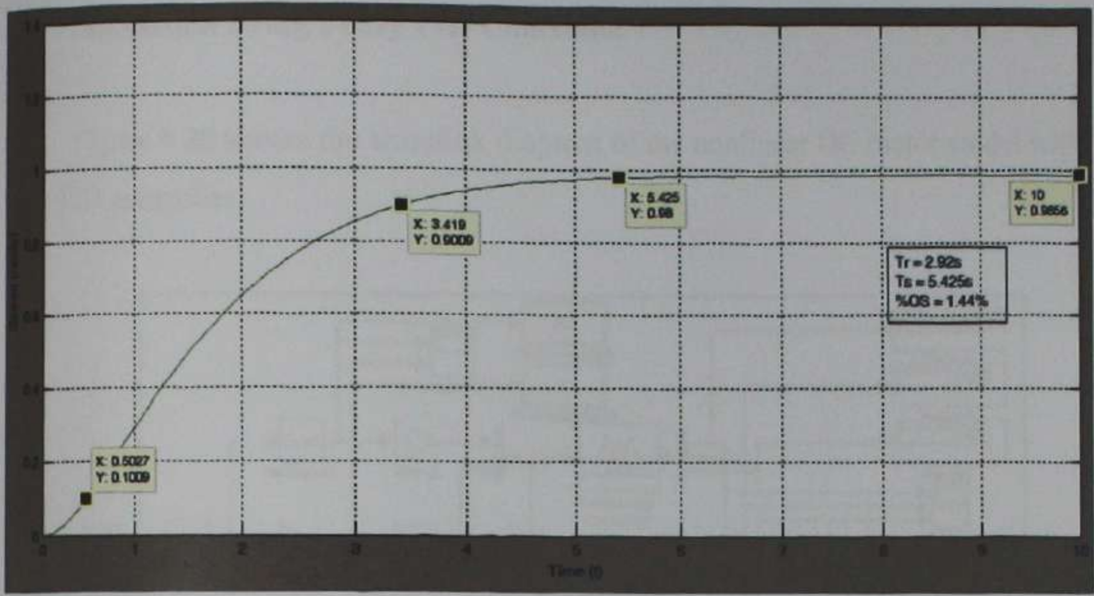

Figure 4.18 Speed of the DC motor for Fuzzy Logic Controller with F_C

Figure 4.19 Speed of the DC motor for Fuzzy Logic Controller with T_L and FC

Figure 4.19 shows the response of the speed of the DC motor with fuzzy logic controller with load torque, T_L and Coulomb friction, F_C. It is shown when the unit pulse is given the speed of DC motor will be dropped. The speed increases consistently until the speed reaches steady state condition. The unit pulse setting is shown below:

Amplitude	= 1
Period	= 10secs
Pulse width (% of period)	= 5
Phase delay	= 2 secs

4.6 Simulation Using Fuzzy PID Controller

Figure 4.20 shows the simulink diagram of the nonlinear DC motor model with fuzzy PID controller.

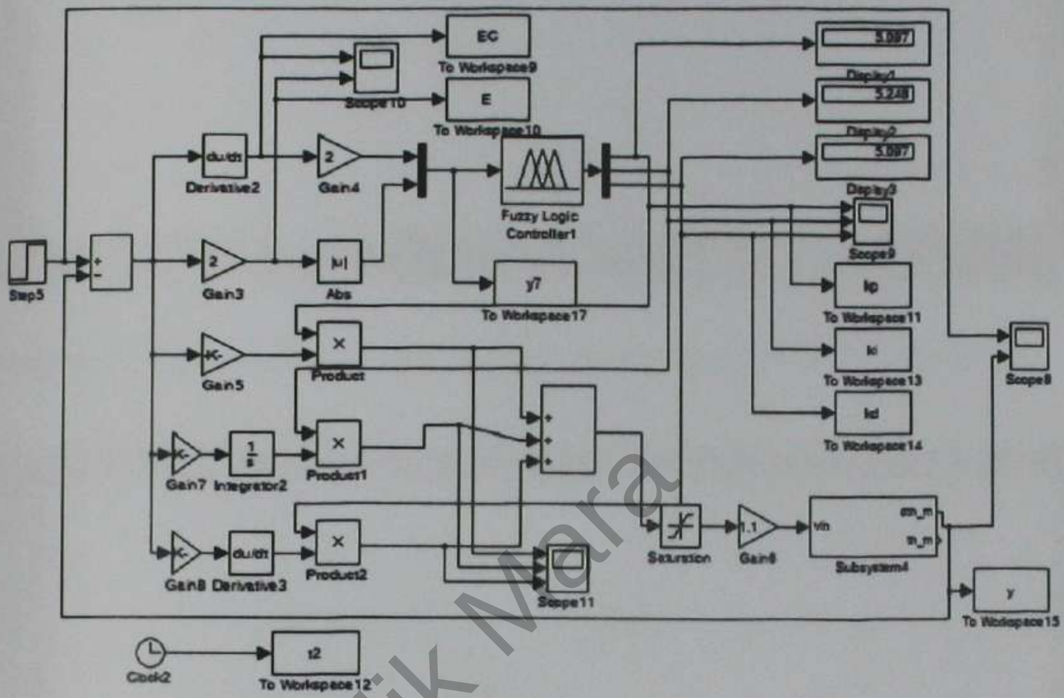

Figure 4.20 Simulink model of nonlinear motor model with fuzzy logic controller

Figure 4.21 shows the response of error and change of error for Fuzzy PID controller with refer to the time, t. It is proven that the system achieves desired performance in which the values of error and change of error reaches zero indicated it is stabilized.

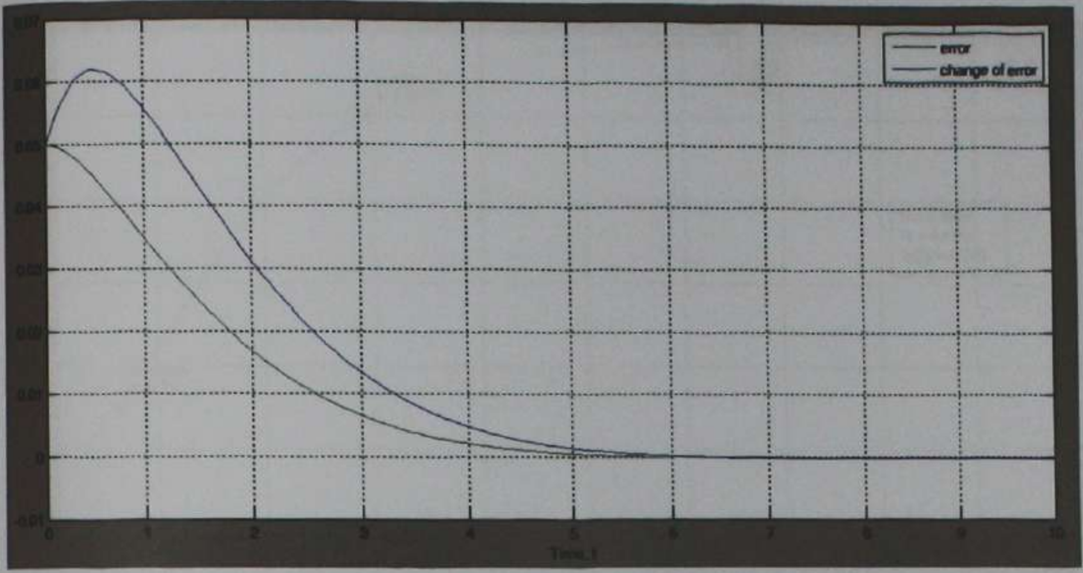

Figure 4.21 Response of error and change of error for Fuzzy PID controller

Figure 4.22 Speed of the DC motor for fuzzy PID controller without F_C

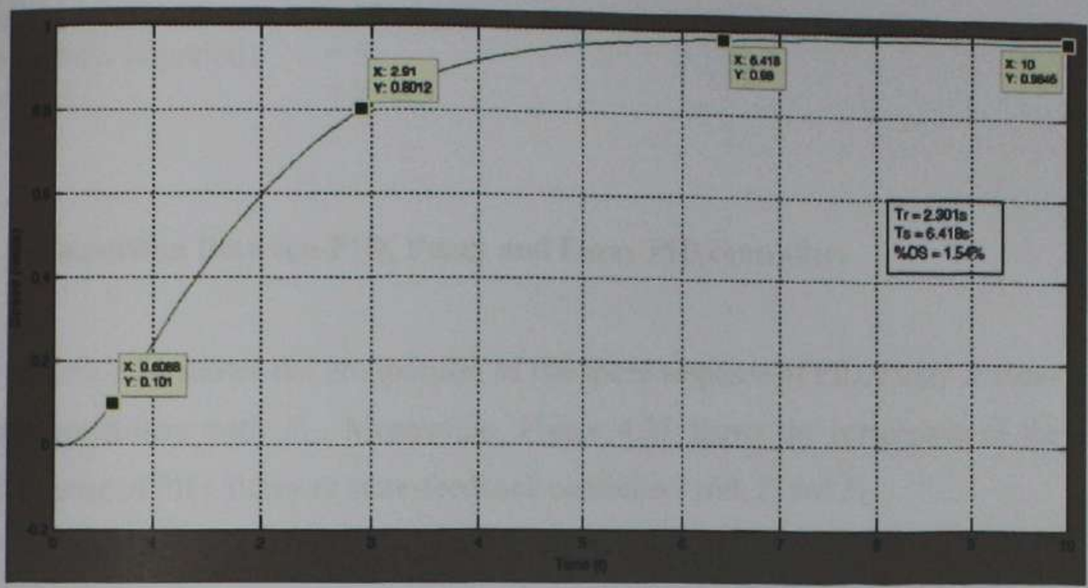

Figure 4.23 Response of DC motor speed control for Fuzzy PID Controller.

Figure 4.23 show the transient response of DC motor speed control for Fuzzy PID Controller.

From Figure 4.22, the speed settling time is at 5.0790seconds with a 0% overshoot while the speed rise time is at 3.0413seconds.

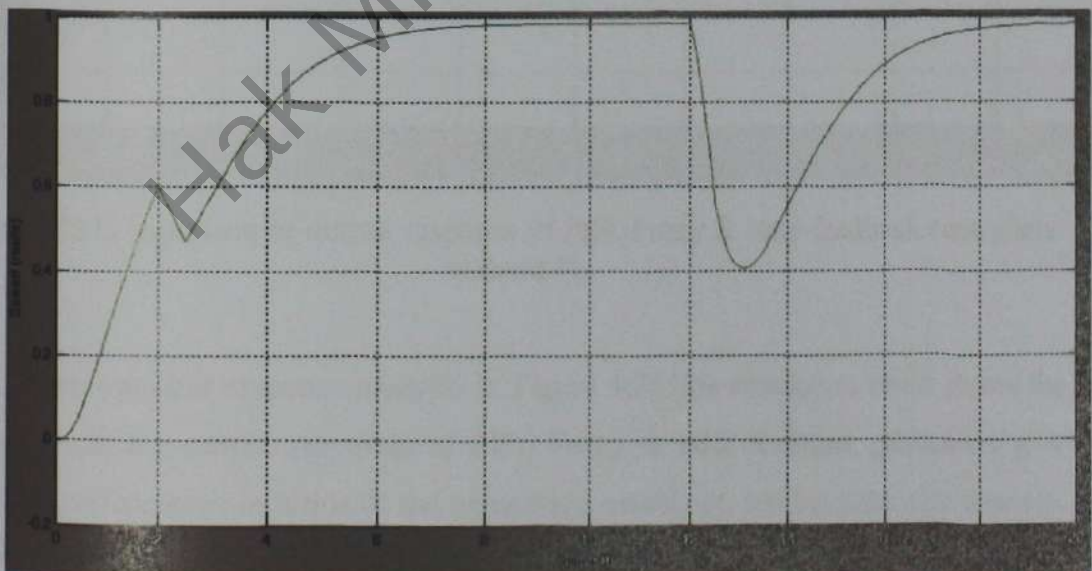

Figure 4.24 Speed of the DC motor for fuzzy PID logic Controller with T_L and FC

Figure 4.24 shows the response of the speed of the DC motor with fuzzy PID logic controller with load torque, T_L and Coulomb friction, F_C.

Amplitude = 1

Period = 10secs
Pulse width (% of period) = 5
Phase delay = 2 secs

4.7 Comparison Between PID, Fuzzy and Fuzzy PID controllers

Figure 4.26 shows the comparison of the speed response of PID, Fuzzy & state-feedback controllers with F_C. Meanwhile, Figure 4.27 shows the comparison of the speed response of PID, fuzzy & state-feedback controllers with T_L and F_C.

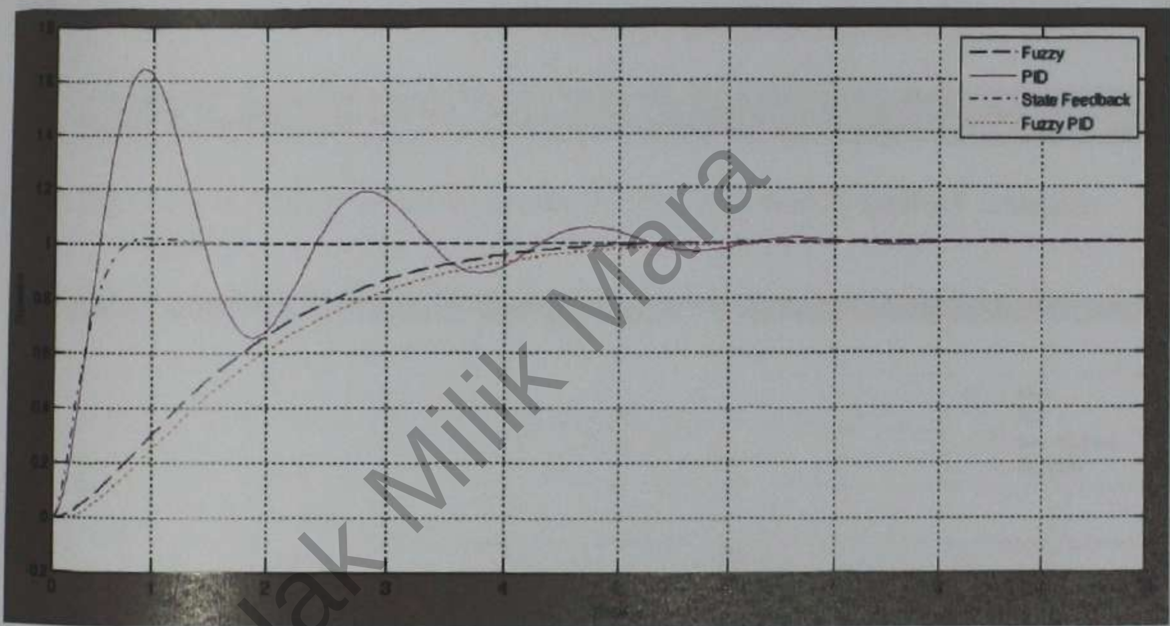

Figure 4.25 Comparison of output response of PID, Fuzzy & state-feedback controllers without F_C

From transient response analysis in Figure 4.25, the simulation result shows the comparison of the output response of PID, Fuzzy & state-feedback controllers give difference performance in terms of the percentage overshoot, settling time, rise time etc. before the system achieve the steady state.

The both fuzzy and fuzzy PID controllers have fast dynamic response and zero overshoot. Meanwhile, the PID controllers has large overshoot at the beginning and require further manual fine tuning after Ziegler-Nichols technique had been applied in order to ensure the system achieves the optimum performance. State space has fastest response and less overshoot as the design specification requirements.

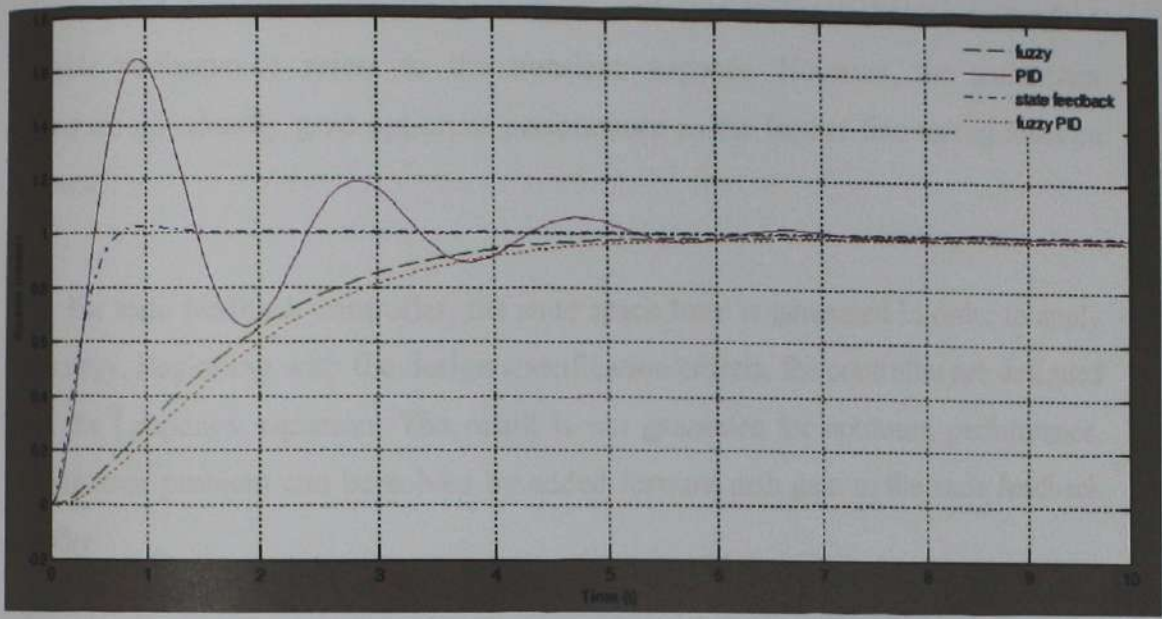

Figure 4.26 Comparison of output response of PID, Fuzzy & state-feedback controllers with F_C

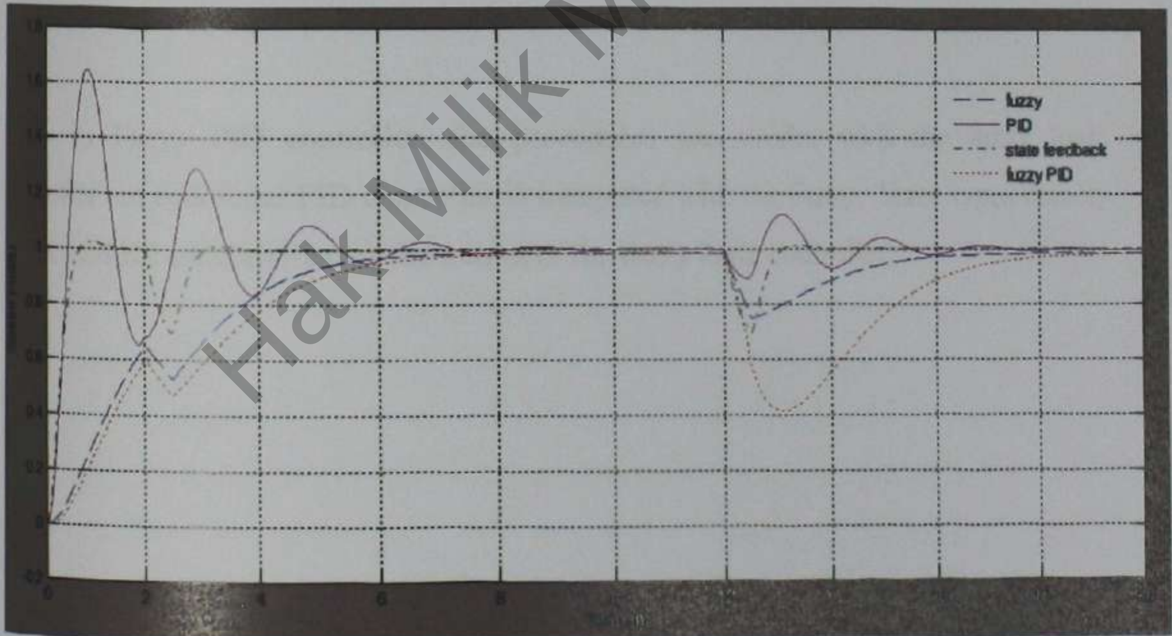

Figure 4.27 Comparison of output response of PID, fuzzy & state-feedback controllers with T_L and F_C

7.8 Summary

For PID controller, Ziegler-Nichols is used as a tuning technique to produce acceptable performance refers to the transient response. However, the parameters obtained are not exactly give optimum performance as the further fine tuning must be performed.

For state feedback controller, the state space form is generated in order to apply this strategy. Beginning with the design specification criteria, the controller are designed follow the Lyapunov equation. The result is not guarantee for optimum performance. Tracking error problem can be solved by added forward path gain in the state feedback controller.

For fuzzy logic controller, the design planning is implemented, the fuzzy logic operations are selected, and the parameters are tuned. Then, the simulation and testing are performed.

In Fuzzy PID controller, the procedures are similar with the fuzzy logic controller but additional PID controller is integrated with the fuzzy. Three types namely Kp, Ki and Kd are classified as the output of the fuzzy logic controller.

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS

5.1 Introduction

In this chapter, the conclusion of the project is provided to summarize the outcomes of the project. The suggestions are made in order to highlight the future development actions needed to concentrate furthermore.

5.2 Conclusions

The objectives of this project have been achieved. The mathematical modeling of the DC motor speed control has been formulated using differential equations and represented in the state space form. The PID with Ziegler-Nichols tuning, state feedback via Lyapunov equation, fuzzy and fuzzy PID controllers are successfully designed. The effects of the nonlinear friction model and load torque of the DC motor have also been investigated. Matlab-Simulink has been done to investigate the performance of the controllers.

The performances of the speed of DC motor are observed based on the transient response. The state feedback controller via Lyapunov equation clearly indicates efficiency and fast response. Both of the fuzzy and fuzzy PID controllers gives better response with no overshoot recorded. The PID controller gives high overshoot and settling time.The methodology used covers the classical, modern and intelligent controllers.

5.3 Suggestions

For further development for the speed of DC motor system, the mathematical model of speed of DC motor with Torque Load, noise and disturbances are strongly recommended as it will improve the robustness of the system.

The controller of position of DC motor is suggested because the integral block of Simulink-Matlab is only needed from the modelling of speed of DC motor.

The controllers that are simulated are totally by software simulation, it is suggested by implementing real time simulation on laboratory experimental test of different types of DC motors.

REFERENCES

1. K.Ogata, "Modern Control Engineering", Prentice-Hall, 1970

2. J. Jantzen, *Tutorial on Fuzzy Logic*, Technical University of Denmark: Department of Automation, Technical report number 98-E 868, 19 Aug 1998, URL: http://www.iau.dtu.dk/

3. R.M. Aguilar, V. Muñoz and Y. Callero, *Control Application Using Fuzzy Logic: Design of a Fuzzy Temperature Controller*, University of La Laguna, 2012. URL: http://www.intechopen.com/

4. A. Shi, M. Yan, J. Li, W. Xu, Y. Shi, *The Research of FUZZY PID Control Application in DC Motor of Automatic Doors*, Jurnal of Institute of Electrical and Electronics Engineers, pp. 1354-1358, 2011

5. S. Zhang, X. Wang, Study of Fuzzy-PID Control in MATLAB for Two-phaase Hybrid Stepping, Proceedings of the 2nd International Conference On Systems Engineering and Modelling (ICSEM-13), pp. 1011-1014, 2013

6. M. Muruganandam and M. Madheswaran, *Modeling and Simulation of Modified Fuzzy Logic Controller for Various types of DC Motor Drive*, international conference on control, automation, communication and energy conservation, 4th-6th June 2009 pp. 1-6

7. H. L. Tan, N. A. Rahim and W. P. Hew, *A Dynamic Input Membership Scheme for a Fuzzy logic DC Motor Controller*, The IEEE International Conference on Fuzzy Systems, St. louis, Missouri, USA , pp. 426-429, 2003

8. N. Mort, M. F. Abbod and D. A. Linkens, *Comparative Study of Fuzzy DC Servo Motors and Stepper Motors for Mechatronic System*, IEEE, UK, 1995

9. Nagendra Singh, *Speed Control of DC Motor by Fuzzy Controller*, IEEE Transactions on Systems, Man, and Cybernatics, 1999

10. T.S. Chi, *Linear System Theory and Design,* Oxford University Press, pp231-241, 1999

11. J.P. Anderson, *State-space modeling, system identification and control of a 4th order rotational mechanical system* . Master Thesis. Naval Postgraduate School, California, 2009

12. M.S.Ramli, M.F. Rahmat, M.S. Najib, *Design and modelling of Integral Control State-feedback Controller for Implementation on Servomotor Control*, 6th WSEAS International Conference on circuits, systems, electronics, control, control & signal processing, Cairo, Egypt, Dec 29 31,pp. 208-213, 2007

13. S. Cong, A. De Carli, *Two advanced control strategies for dynamic friction compensation*, Acta Automatic Sinica, vol. 24, no. 2, pp. 236-240, 1998. (in Chinese)

14. S. Cong, et al., *Establishment of simulation model system for nonlinear DC motor,* Journal of system simulation, vol. 13, no. 1, pp.25-27, Jan. 2001. (in Chinese)

15. B.Armstrong-helouvry, P.Dupont, C. Wit Canudas, *A survey of models, analysis tools and compensation methods for the control of machines with friction*, Automation, vol. 30, no. 7, pp. 1083-1138, 1994.

16. M. Knudsen and J. G. Jensen, *Estimation of nonlinear DC motor models using a sensitivity approach*, In Proc. 3, European Control Conference ECC'95, Rome, Italy, 1995.

17. M. Ruderman, J. Krettek, F. Hoffmann, T. Bertram, *Optimal State Space Control of DC Motor*, Proceedings of the 17th World Congress The International Federation of Automatic Control Seoul, Korea, 2008