DEVELOPMENT OF POSITION TRACKING OF BLDC MOTOR USING ADAPTIVE FUZZY LOGIC CONTROLLER

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ABSTRACT

The brushless DC (BLDC) motor has many advantages including simple to construct, high torque capability, small inertia, low noise and long life operation. Unfortunately, it is a non-linear system whose internal parameter values will change slightly with different input commands and environments. In this proposed controller, Takagi-Sugeno-Kang method is developed. In this project, a FLC for position tracking and BLDC motor are modeled and simulated in MATLAB/SIMULINK. In order to verify the performance of the proposed controller, various position tracking reference are tested. The simulation results show that the proposed FLC has better performance compare the conventional PID controller.

ABSTRAK

Motor arus terus tanpa berus (BLDC) mempunyai banyak kelebihan termasuklah mudah untuk dibina, mempunyai kebolehan keupayaan yang tinggi, inersia yang kecil, daya gangguan yang rendah dan operasi jangka hayat yang panjang. Namun begitu, ia adalah satu sistem bukan linear yang mana nilai parameter dalaman akan mengalami sedikit perubahan selaras dengan perbezaan input dan persekitaran. Bagi pengatur yang dicadangkan melalui projek ini, kaedah Takagi-Sugeno-Kang telah dipilih untuk dibangunkan. Dalam projek ini, pengatur logik kabur untuk pengesanan kedudukan dan motor arus tanpa berus dimodelkan dan disimulasi melalui perisian MATLAB / SIMULINK. Untuk mengesahkan prestasi pengatur yang dicadangkan, pelbagai rujukan pengesanan kedudukan telah diuji. Keputusan simulasi yang diperoleh menunjukkan bahawa pengatur logik kabur yang dicadangkan mempunyai pencapaian yang lebih baik berbanding pengawal perbezaan berkadar penting konvensional.

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LIST OF SYMBOLS AND ABBREVIATION

PID	-	Proportional Integral Derivative Controller
BLDC	-	Brushless DC Motor
R_a	-	Armature resistance
La	-	Armature inductance
$I_a(t)$	-	Motor current
θ_m	-	Position in terms of angle
T_m	-	Motor torque
J_m	-	Motor inertia
B	-	Damping ratio
K_T	-	Torque constant
K_p	-	Proportional gain
K_i	-	Integral gain
K_d	-	Derivative gain
T_p	-	Peak time
T_r	-	Rise time

T_s	-	Settling time
Os%	-	Percentage of overshoot
e_{ss}	-	Steady state error

CHAPTER 1

INTRODUCTION

1.1 Research background

The electric drive system is a vital part to drive any motor. The electric drive system is used to control the position, speed and torque of the electric motors. Many works has been done on power converter topologies, control scheme of the electric drive systems and on the motor types in order to enhance and improve the performance of the electric motors so as to exactly perform and do what is required [1].

BLDC motors have some advantages over conventional brushed motors and induction motors. Some of these are; better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation and higher speed ranges. In addition BLDC motors are reliable, easy to control, and inexpensive. Due to their favourable electrical and mechanical properties, BLDC motors are widely used in servo applications such as automotive, aerospace, medical, instrumentation, actuation, robotics, machine tools, and industrial automation equipment and so on recently [2].

Classical PID controllers are commonly used in industries due to their simplicity and ease of implementation [3]. In linear system model, controller parameters of the PID controller are easy to determine and resulting good control performances. However, for nonlinear system model applications such as BLDC motor drive, control performance of the PID controller becomes poor and difficult to determine the controller parameters [4] .

In order to improve control performance of the BLDC motor drive, intelligence controllers such as fuzzy logic control for BLDC motor is used. Fuzzy logic has many advantages over conventional control. It does not use mathematical model of the system and therefore is less sensitive to system parameter changes. Design objectives that are difficult to express mathematically can be easily incorporated in a fuzzy controller by linguistic rules. In addition, its implementation is simple and straight forward [5].

In this project, a complete simulation model with Takagi Sugeno fuzzy logic (TSFC) control method for BLDC motor drive is proposed using Matlab/Simulink. The Develop TSFC has the ability to learn instantaneously and adapt its own controller parameters based on external disturbance and internal variation of the converter with minimum steady state error, overshoot and rise time of the output voltage.

1.2 Problems statement

The brushless dc motors are gradually replacing dc motors and ac motors because of their small size, high operating speed, high efficiency, less maintenance and excellent speed torque characteristics. They are used in robotics, computer disk drives, machine tools, electric vehicle and battery powered applications. The conventional control scheme such as proportional (P), proportional integral (PI) and proportional integral derivative (PID) have been developed for position control of BLDC motors.

However, these controllers need an accurate mathematical model and can be applied only to highly linear systems. These controllers fail to yield better performance when the system becomes non-linear and it is a cumbersome process to tune these controllers. As we know, the BLDC motor control systems are non-linear because of the variation in their parameters and varying loads, so in this project we will focus on how to develop the position control of BLDC motor by using Takagi

Sugeno Fuzzy Logic controller (TSFLC). Why we use this algorithm? Well, TSFLC are very suited to control system with uncertain, complex, inaccurate or non-linear dynamics such as BLDC motor control systems. TSFLC can be easily designed and implemented knowing the behaviours of the system and it can greatly reduce the effects of non-linearity on the BLDC motor control systems. Besides that, we also concentrate on how to develop the modelling of controller, inverter and BLDC motor.

1.3 Objectives of study

The objectives of this project are;

a) To develop dynamic model of BLDC motor.
b) To develop the position controller using intelligent control.

1.4 scopes

This project is primarily concerned with the several aspects for easier troubleshoot due to problems occur during the project implementation. The scope of this project is:

a) Develop the simulation model using Matlab Simulink.
b) Develop the position control of BLDC motor using Adaptive Fuzzy Logic Controller method.

CHAPTER 2

LITERATURE REVIEW

2.1 Technology Developments

From the previous research work, knowledge of how others people construct their project and how they specified particular application. These researches that are relevant to this project discussed next to demonstrate continuity from previous researches.

2.1.1 Development and Control of BLDC Motor using Fuzzy Models

This project presents the design and control of a small brushless Direct Current (BLDC) Motor. In order to control the developed BLDC motor, Adaptive Fuzzy Control (AFC) scheme via Parallel distributed Compensation (PDC) is developed for the multi-input/multi-output plant model represented by the Takagi-Sugeno (TS) model. The alternative AFC scheme is proposed to provide asymptotic tracking of a reference signal for the systems with uncertain or slowly time-varying parameters. The developed control law and adaptive law guarantee the boundedness of all signals in the closed-loop system. In addition, the plant state tracks the state of the reference model asymptotically with time for any bounded reference input signal. The suggested design technique is applied to the velocity control of a developed small BLDC motor.

2.1.2 Realization of Fuzzy Logic Controlled Brushless DC Motor Drives Using Matlab/Simulink

In this project, an efficient simulation model for fuzzy logic controlled brushless direct current motor drives using Matlab/Simulink is presented. The brushless direct current (BLDC) motor is efficiently controlled by fuzzy logic controller (FLC). The control algorithms, fuzzy logic and PID are compared. Also, the dynamic characteristics of the BLDC motor (i.e. speed and torque) and as well as currents and voltages of the inverter components are easily observed and analyzed by using the developed model.

2.1.3 Adaptive Position Tracking Control of a BLDC Motor Using a Recurrent Wavelet Neural Network.

An adaptive position tracking control (APTC) system which is composed of a neural controller and a robust controller is proposed in this project. The neural controller uses the recurrent wavelet neural network structure to online mimic and ideal controller, and the robust controller is designed to achieve L_2, tracking performance with desired attenuation level. The adaptive laws of APTC system are derived based on the Lyapunov stability theorem and gradient decent method. This project also proposed APTC method that applied to a brushless DC (BLDC) motor.

2.1.4 High Performance Speed and Position Tracking of Induction Motors Using Multi-Layer Fuzzy Control

An electric drive system is considered high performance when the rotor position or shaft speed can be made to follow a preselected track at all times. The design of tracking controllers for induction motors is difficult due to motor nonlinearities and unknown load dynamics. An extension to fuzzy control, Multi-Layer Fuzzy Control

(MLFC), is proposed and applied to high performance tracking of induction motors. The MLFC has two layers. The first layer is the execution layer which is made up of small subcontrollers. The second layer is the supervisor layer which fuzzily combines the execution layer subcontrollers to achieve the system objectives. The design and the tuning of the controller is simpler because of the layered topology.

2.1.5 Repetitive Tracking Control of DC motors Using a Fuzzy Iterative Learning Controller

The theoretical design of a fuzzy iterative learning controller for sampled-time linear time invariant systems is presented in this project. The project also investigates of digital circuit implementation of the proposed controller with application to repetitive position tracking control of DC servo motors. The stability and convergence of the learning system are analyzed under uncertainties of initial state errors, input disturbance and output measurement error. This project also stress that the learning error will converge to a residual set whose level of magnitude will depend on the size of the uncertainties. The learning error will asymptotically converge to zero if all uncertainties disappear. To improve the learning performance, a concept of fuzzy learning gain is introduced which is designed based on the tracking error in the current and past iteration.

In addition to the theoretical analysis, the fuzzy iterative learning controller is realized by a digital circuit to prove its feasibility. VHDL is used as the circuit design tool. The designed circuit is then downloaded into an FPGA chip. The chip is then applied to a repetitive position tracking control of DC motors to verify the learning effect.

2.2 Brushless Direct Current (BLDC) Motor

The Brushless Direct Current (BLDC) motor is rapidly gaining popularity by its utilization in various industries, such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. As the name implies, the BLDC motors do not use brushes for commutation; instead, they are electronically commutated. The BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque response
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in application where space and weight are critical factors. The torque of the BLDC motor is mainly influenced by the waveform of back-EMF (the voltage induced into the stator winding due to rotor movement). Ideally, the BLDC motors have trapezoidal back-EMF waveform and are fed with rectangular stator currents, which give a theoretically constant torque.

2.2.1 Construction and Operating Principles

The BLDC motor is also referred to as an electronically commuted motor. There are no brushes on the rotor and the commutation is performed electronically at certain rotor positions. The stator magnetic circuit is usually made from magnetic steel sheets. The stator phase windings are inserted in the slots (a distributed winding), or can be wound as one coil on the magnetic pole. The magnetization of the permanent magnets and their displacement on the rotor are chosen in such a way that the back-EMF shape is trapezoidal. This allows the three-phase voltage system, with a rectangular shape, to be used to create a rotational field with low torque ripples. In this respect, the BLDC motor is equivalent to an inverted DC commutator motor, in that the magnet rotates while the conductors remain stationary.

In the DC commutator motor, the current polarity is reversed by the commutator and the brushes, but in the brushless DC motor, the polarity reversal is performed by semiconductor switches which are to be switched in synchronization with the rotor position. Besides the higher reliability, the missing commutator brings another advantage. The commutator is also a limiting factor in the maximal speed of the DC motor. Therefore the BLDC motor can be employed in applications requiring high speed [1], [3]. Replacement of a DC motor by a BLDC motor place higher demands on control algorithm and control circuit. Firstly, the BLDC motor is usually considered as a three phase system. Thus, it has to be powered by a three-phase power supply. Next, the rotor position must be known at certain angles, in order to align the applied voltage with the back-EMF. The alignment between the back-EMF and commutation events is very important. In this condition the motor behaves as a DC motor and runs at the best working point. But the drawbacks of the BLDC motor caused by necessity of power converter and rotor position measurement are balanced by excellent performance and reliability, and also by the ever-falling prices of power components and control circuits.

2.3 Fuzzy Logic Controller System

A fuzzy control is a controller that is intended to manage some vaguely known or vaguely described process. The controller can be used with the process in two modes:

i Feedback mode when the fuzzy controller determination act as a control device.

ii Feed forward mode where the controller can be used as a prediction device.

Figure 2.1 shows a fuzzy logic control system in a closed loop control. there are four important elements in the fuzzy logic controller system structure which are fuzzifier, rule base, inference engine and defuzzifier. Details of the fuzzy logic controller system structure can be seen in in figure below. Firstly, a crisp set of input data are gathered and converted to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms and membership functions. This step also known as fuzzification. Afterwards, an inference is made base on a set of rules. Lastly, the resulting fuzzy output is mapped to a crisp output using the membership functions, in the defuzzification step.

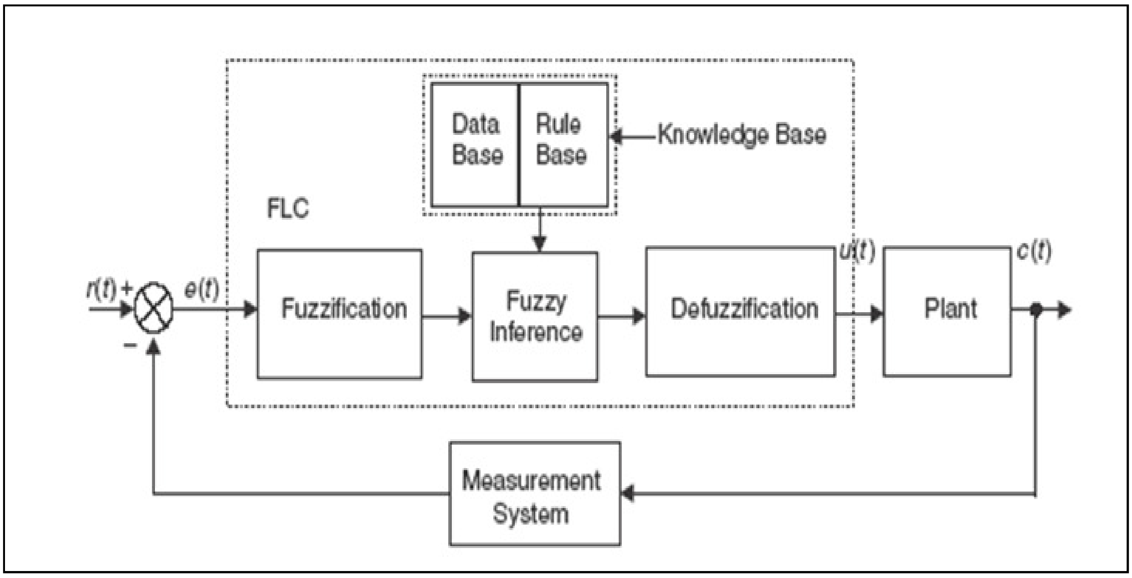


Figure 2.1: Structure of fuzzy logic controller system

2.3.1 Fuzzification

The first block of the fuzzy controller is fuzzification, which converts each piece of input data to degrees of membership by a lookup in one or several membership functions. The fuzzification block thus matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input instance. There is a degree of membership for each linguistic term that applies to that input variable.

2.3.2 Rule Base

In a fuzzy logic control system, a rule base is constructed to control the output variable. A fuzzy rule is a simple IF-THEN rule with a condition and conclusion. It can be represented by the matrix table. Let say, the air controller system with two input linguistic variables of temperature and humidity and one output linguistic variable of motor speed as shown on Table 2.1.

Table 2.1 : Example of rule base for air conditioner system

Motor Speed		Humidity		
		low	moderate	High
Temperature	cold	medium	slow	Slow
	warm	fast	medium	Slow
	hot	fast	fast	Medium

Row caption in the matrix contain the values that current room temperature can take while column caption contain the values for humidity in the room. Each cell is the resulting command when the input variables take the values in that row and column. Based on the Table 2.1, the maximum numbers of rules are nine. For instance, the cell (3,3) can be read as follows : IF temperature is hot and humidity is high THEN motor speed is medium.

2.3.3 Inference engine

In general, inference is a process of obtaining new knowledge through existing knowledge. In the context of fuzzy logic control system, it can be defined as a process to obtain the final result of combination of the result of each rule in fuzzy value. There are many methods to perform fuzzy inference method and the most common two of them are Mamdani and Takagi Sugeno Kang method.

Takagi Sugeno Kang method was introduced in 1985 and it is similar to the Mamdani method in many aspects. The first two parts of fuzzy inference processes which are fuzzifying the inputs and applying the fuzzy operator are exactly the same but, the main difference is that the Takagi Sugeno Kang output membership function is either linear or constant. A typical rule in Takagi Sugeno Kang fuzzy model has the form as follows;

IF input 1= x AND input 2 = y

THEN output z = ax + by + c

For a zero order Takagi Kang model, the output z is a constant (a=b=0). The output of z_i of each rule is weighted by the firing strength w_i as follows;

$$Wi = AndMethod(F_1(x), F_2(y))$$

Where $F_1(x)$ and $F_2(y)$ are membership functions for input1 and input2 respectively. The final output of the system is the weighted average of all rule outputs, computed as;

$$\text{Final Output} = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i}$$

2.3.4 Defuzzification

Defuzzification is a process that maps a fuzzy set to a crisp set and has attracted far less attention than other processes involved in fuzzy systems and technologies. Four most common defuzzification methods:

- Max membership method
- Center of gravity method
- Weight average method
- Mean-max membership method

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section will discuss the method that used in this project. The work scheme need to be built to ensure the project development is smooth. In complete this projects, we need to study the theory and how to apply the tools and also the software. The researches have been design and implement after gathering information from internet and journal. The flowchart that used to develop fuzzy controller design for position control describes below.

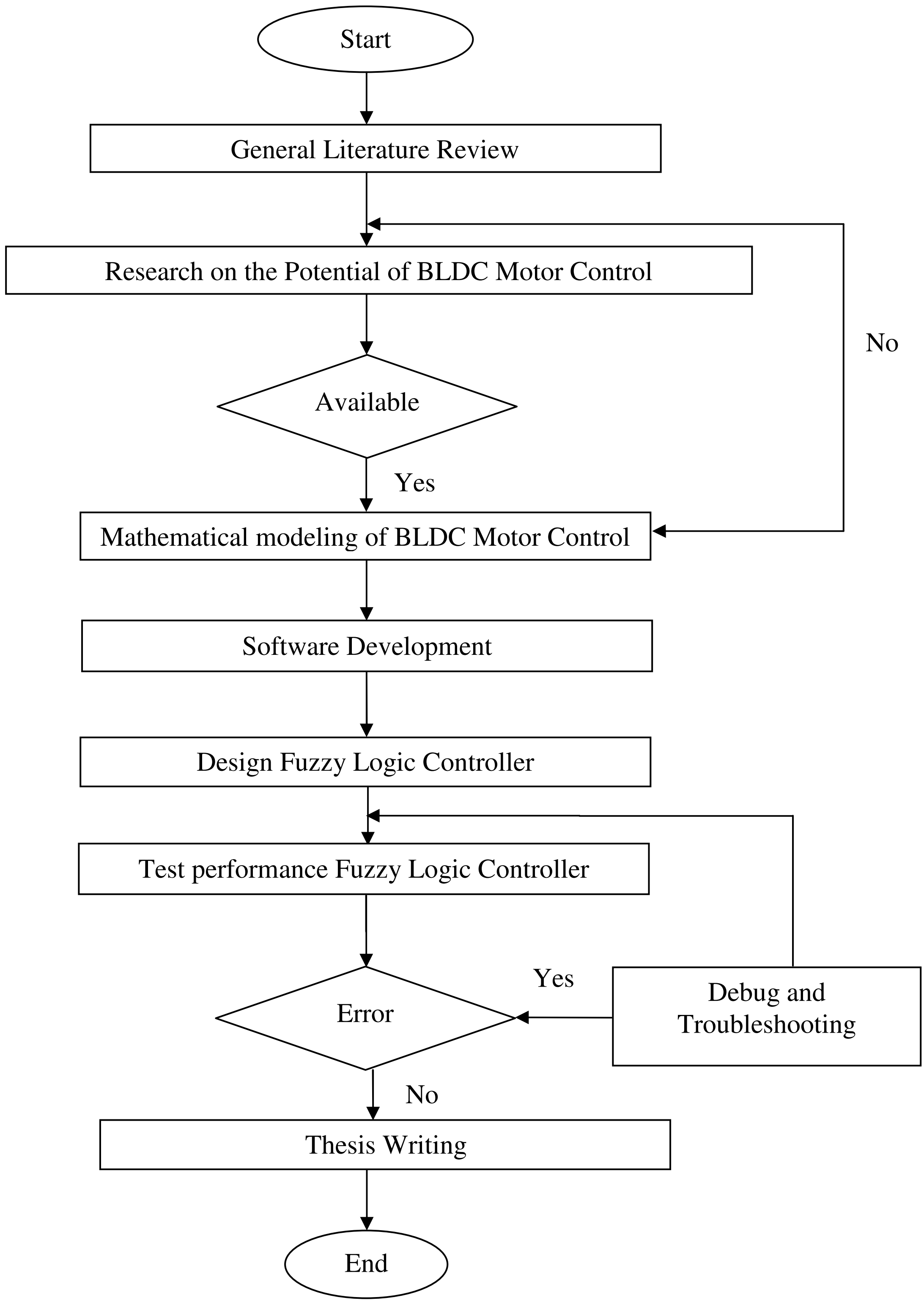


Figure 3.1: The fuzzy controller design for position control project methodology

3.2 BLDC Motor Modelling

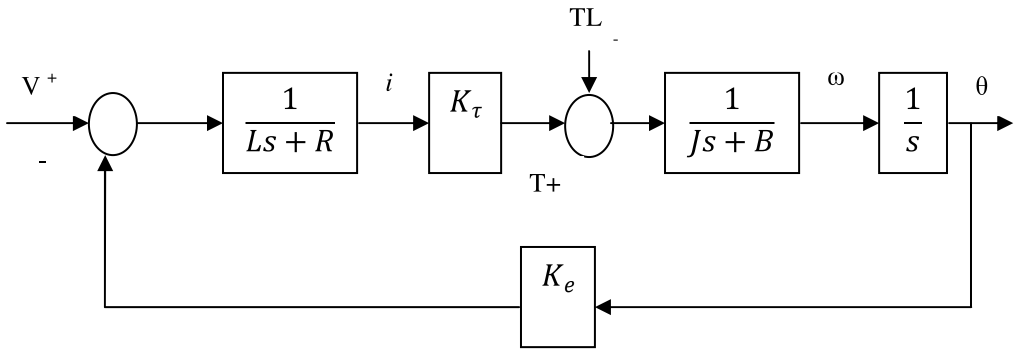


Figure 3.2: Circuit diagram of BLDC motor

The analysis of BLDC motor is based on the assumption for simplification and accuracy. The BLDC motor is type of unsaturated. To perform the simulation of the position control, an appropriate model needs to be established. Based on the equivalent circuit of BLDC motor shown in Figure 3.2, the dynamic equations of BLDC motor using the assumption can be derived as

The motor torque, T_m is related to the armature current I_a by a constant factor of *K;*

$$T_m = KI_a \tag{3.1}$$

The back emf, e_b is relative to angular velocity, ω_m by;

$$e_b = K\omega_m = K\frac{\delta\theta_m}{\delta t} \tag{3.2}$$

From the figure 3.2, the following equations can be written based on Newton's Second Law combined with Kirchoff's Law;

Newton's Second Law,

$$T_m = J_m \frac{\delta^2 \theta_m}{\delta t} + B_m \frac{\delta \theta_m}{\delta t} \tag{3.3}$$

Substitution equation (3.1) into equation (3.3) to obtain;

$$J_m \frac{\delta^2 \theta_m}{\delta t} + B_m \frac{\delta \theta_m}{\delta t} = KI_a \tag{3.4}$$

Khirchoff's Law,

$$L \frac{\delta Ia}{\delta t} + R = V_a - e_b \tag{3.5}$$

Substitute equation (3.2) into equation (3.5) to obtain;

$$\mathrm{L} \frac{\delta Ia}{\delta t} + \mathrm{R} = \mathrm{Va} = \mathrm{K} \frac{\delta \theta_m}{\delta t} \tag{3.6}$$

By taking Laplace Transform, equation (3.5) and (3.6) can be expressed in term of s as;

$$JmS^2\theta_m(s) + Bm\mathrm{S}\theta_m(s) = KI_a(s) \tag{3.7}$$

$$LsI_a(s) + RI_a(s) = V_a(s) - KS\theta_m(s) \tag{3.8}$$

From equation (3.7), $I_a(s)$ can be expressed as;

$$I_a(s) = \frac{S\theta_m(s)[\, Jms + Bm]}{K} \tag{3.9}$$

Substitute equation (3.9) into equation (3.8) to obtain;

$$V_a(\mathrm{s}) = \frac{s\theta_m[Jms + Bm][Ls + R] + K^2}{K} \tag{3.10}$$

Therefore, from the equation (3.10), the transfer functions where the position, θ_m as an output and the voltage, V_a (s) as an input can be obtained;

$$\frac{\theta m(s)}{Va(s)} = \frac{\text{K}}{\text{s[Jms + Bm][Ls+R] +K2}}$$

(3.11)

The constants value of voltage, V_a, torque constant factor, K, rotor inertia, J_m, damping ratio, B_m, resistance R and inductance, L for BLDC motor must be known. The specifications of BLDC motor which will use are described in the Table 3.1 below:

Table 3.1 : Parameter of BLDC Motor

Symbol	Description	Value	Unit
Rs	Phase resistance	4.31	Ohm(Ω)
Ls	Phase resistance	2.758×10^{-6}	H
$K_T = K_e = K$	Torque constant	36.8	mNm/A
J_m	Rotor inertia	11×10^{-6}	Kgm^2
Vdc	Rated voltage	36	V
P	Pole pairs	1	
T	Peak torque	154	mNm
B_m	Damping ratio	0.708×10^{-4}	Nms

Thus, when substitute these parameter values into equation (3.11), the transfer function of BLDC motor as below;

$$\frac{\theta_m(s)}{V(s)} = \frac{776.2076}{s^2 + 6.4364s} \qquad (3.12)$$

3.3 PID Controller Design

A PID (proportional-integral-derivative) controller is one of the most commonly used controllers because it is simple and robust. This controller is extremely popular because they can usually provide good closed loop response characteristics, can be tuned using relatively simple rules and easy to construct using either analogue or digital components. Figure 3.3 below illustrates the block diagram of PID controller.

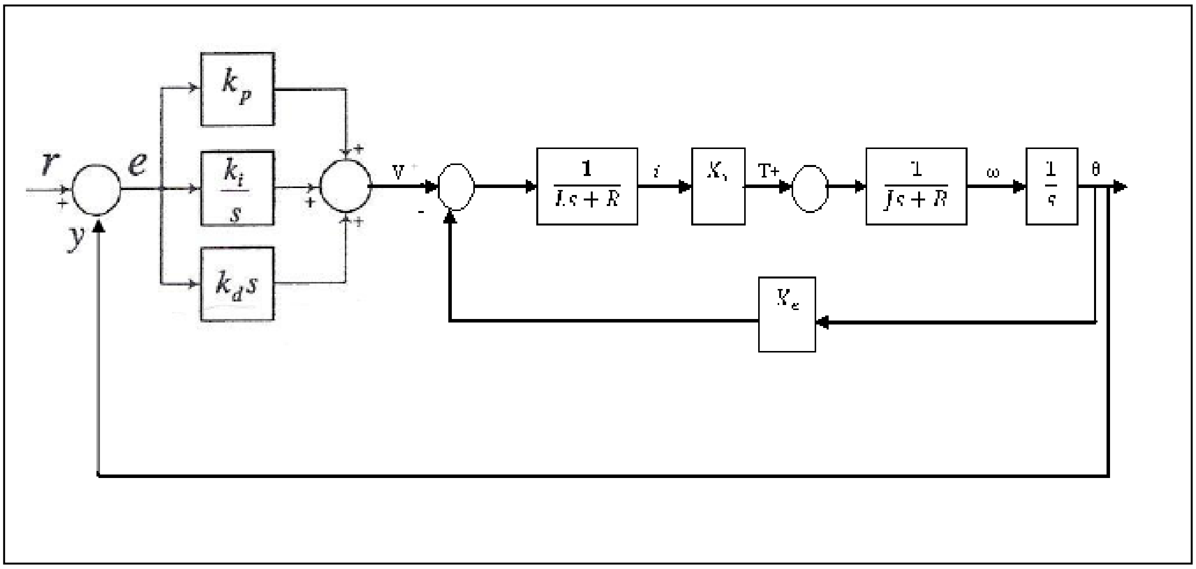


Figure 3.3: Block diagram of the closed loop BLDC motor with PID controller

The PID controller can be defined as equation (3.13) by the following relationship between controller input e(t) and the controller output V(t) that is applied to the motor armature.

$$V(t) = K_p\, e(t) + K_i \int_0^t e(t)\, dt + K_d \frac{de(t)}{dt} \tag{3.13}$$

By using the Laplace transform, the transfer function of PID controller as following in equation (3.14).

$$\frac{V(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d\, s \qquad (3.14)$$

Assumed that the $K_p = K$, $K_i = \frac{K}{t_i}$ and $K_d = Kt_d$

Then, the transfer function of PID controller is depend by the following equation below;

$$K(s) = \frac{Kt_d}{s}\left(s^2 + \frac{1}{t_d}\, s + \frac{K}{t_d\, t_i}\right) \qquad (3.1)$$

The values of K_p, K_i and K_d are calculated by using the Ziegler Nichols tuning algorithm. This method gives automatic oscillation of the process to compute the proportional, integral and derivative gains. The PID controller has been simulated using MATLAB simulink to ensure the manual calculation is correct. The values of Kp, Ki and Kd are as follow:

$K_p = 10$
$K_i = 5$
$K_d = 0.5$

3.4 Proposed Controller

The structure of the proposed controller for BLDC motor is shown in Figure 3.4. The proposed controller consists of fuzzy logic controller for position control in the completed closed loop system. The designation of fuzzy logic controller is based on expert knowledge which mean the knowledge of skillful operator during the handling of BLDC motor system is adopted into the rule based design of fuzzy logic controller.

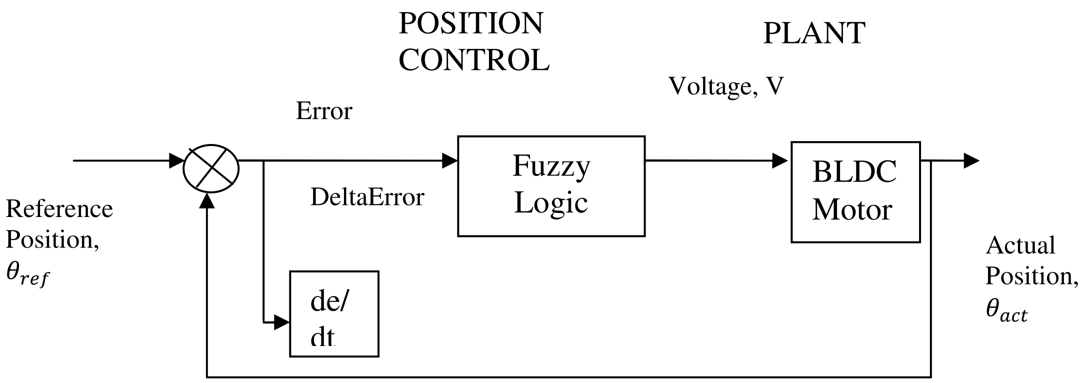


Figure 3.4: Structure of proposed controller

3.5 Fuzzy Logic Controller Design

There are four elements to be considered in order to design the fuzzy logic controller which are fuzzification interface, fuzzy rule, fuzzy inference mechanism and defuzzification interface.

3.5.1 Fuzzification

The most important step in fuzzification interface element is to determine the state variables or input variables and the control variables or output variables. There are two input variables for BLDC motor system in terms of position control which are error and delta of error. Error can be described as a reference of position set point minus actual position. Meanwhile, delta of error or change of error is error in process minus previous error. The voltage applied to the BLDC motor system is defined as output variable.

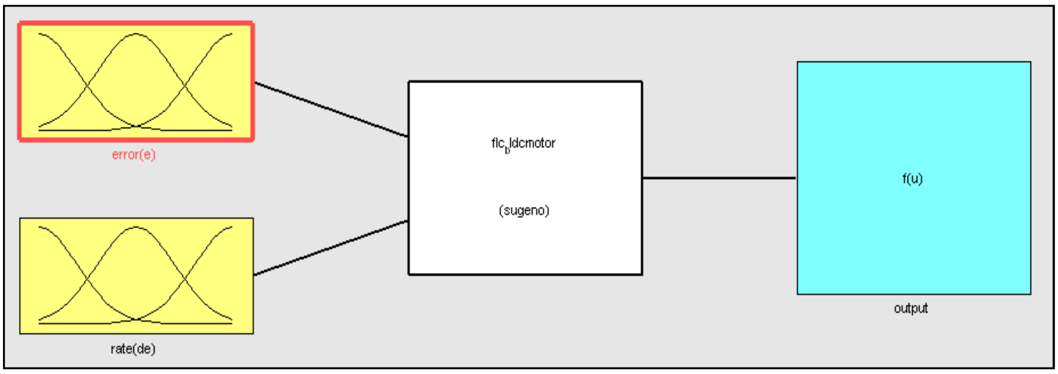
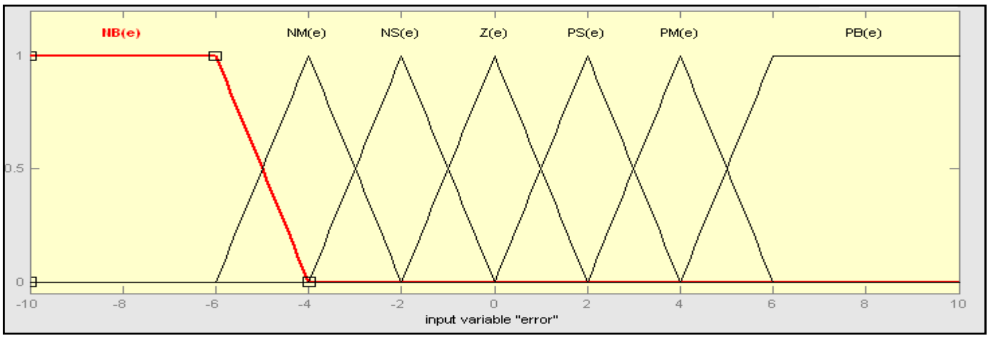
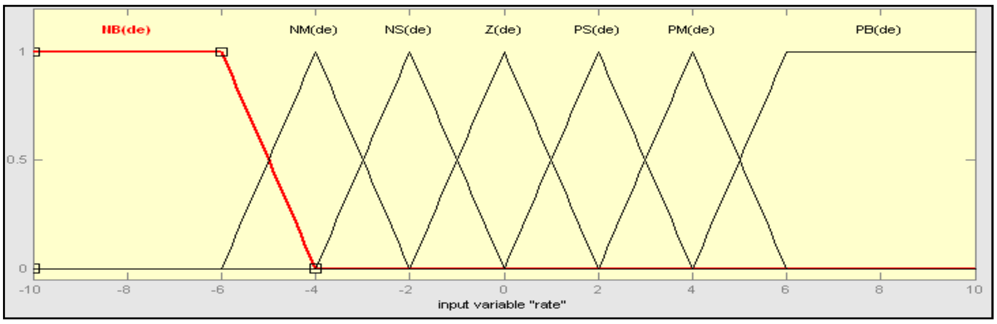


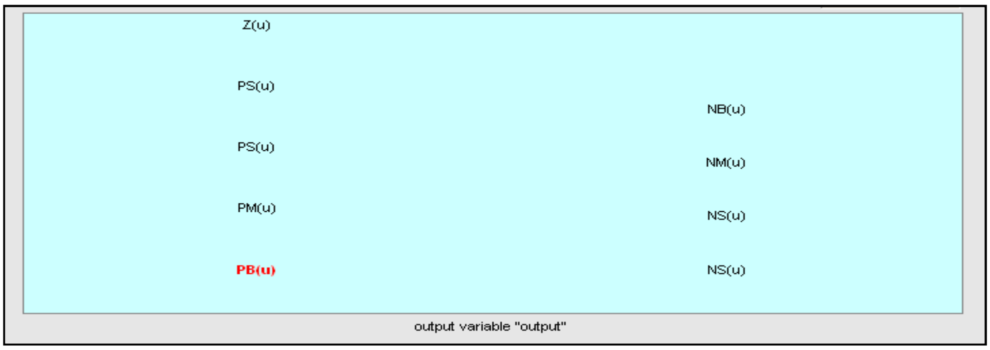
Figure 3.5: Membership function for input and output of fuzzy logic controller



(a) error(e)



(b) rate(de error)



(c) output

Figure 3.6 Membership function for (a) input variable “error” (b) input variable “rate” (c) output variable ”output”

The linguistic variables of the fuzzy sets need to be defined which are represent:

(i) Input variables:

- Error(e)

  Quantized into 3, 5 and 7 membership function: Negative N(e), Negative Small NS(e), Negative Medium NM(e), Negative Big NB(e), Zero Z(e), Positive P(e), Positive Small PS(e), Positive Medium PM(e) and Positive Big PB(e).

- Rate(de error)

  Quantized into 3, 5 and 7 membership function: Negative N(de), Negative Small NS(de), Negative Medium NM(de), Negative Big NB(de), Zero Z(de), Positive P(de), Positive Small PS(de), Positive Medium PM(de) and Positive Big PB(de).

(ii) Output variables:

- Output

  Quantized into 5, 7 and 9 membership function: Negative Small (NS), Negative Medium (NM), Negative Big (NB), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB).

3.5.2 Fuzzy rule

The basic function of the rule based is to represent the expert knowledge in a form of if-then rule structure. The fuzzy logic can be derived into combination of input (3 × 3, 5 × 5 and 7 × 7). The figure 3.9 shows the structure of rule editor. The rule table of fuzzy logic controller as listed in Table 3.2, Table 3.3 and Table 3.4.

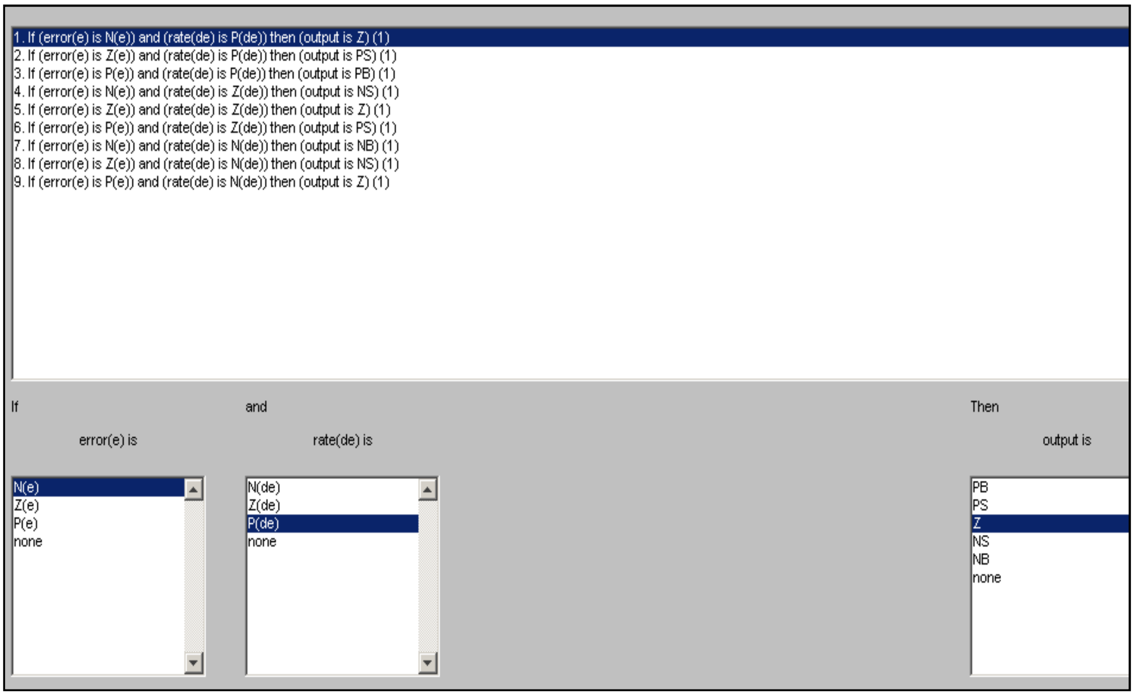


Figure 3.7: Structure of rule editor

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