FUZZY LOGIC CONTROLLER OF PMSM DRVIES

NUR QAMARINA BINTI MAT RODZI
B011710190

BACHELOR OF ELECTRICAL ENGINEERING WITH HONOURS
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2021

FUZZY LOGIC CONTROLLER OF PMSM DRVIES

NUR QAMARINA BINTI MAT RODZI
B011710190

A report submitted
in partial fulfillment of the requirements for the degree of
Bachelor of Electrical Engineering with Honours

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2021

DECLARATION

I declare that this thesis entitled "FUZZY LOGIC CONTROLLER OF PMSM DRVIES is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not being submitted for any other degree at the same time.

Signature	:	Nur Qamarina
Name	:	NUR QAMARINA BINTI MAT RODZI
Date	:	9 JULY 2021

APPROVAL

I hereby declare that I have checked this report entitled “FUZZY LOGIC CONTROLLER OF PMSM DRVIES” and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature : ....

Supervisor Name : Dr. Jurifa bt Mat Lazi

Date : 9 July 2021

DEDICATIONS

To my beloved mother and father and our respective families, lectures, friends, and faculty members. Thank you for your concern, support, and faith in me.

ACKNOWLEDGEMENTS

I want to articulate my deep gratitude to my supervisor and project guide, Dr. Jurifa binti Mat Lazi. She has always been the source of motivation and firm support for carrying out the project and her invaluable suggestion and constant encouragement throughout the thesis work. I also like to express my heartfelt thanks and obligation to all other faculty members and friends who have assisted and guided me at various times and provided me with many motivation and courageous words. Without the reference and inspiration from the works of others, whose details are list in the references section. This kind of ensemble could never have been created. I acknowledge my gratitude to each one of them. In addition, I like to express my appreciation to my parents, relatives and Allah, who have all encouraged and motivated us in some way during this dissertation.

ABSTRACT

In this project, a Permanent Magnet Synchronous Motor (PMSM) drives is designed by using Fuzzy Logic Controller (FLC). The PI controller's proportional and integral gains are modified using Fuzzy Logic. In this project, the PI controller using 9-rule FLC, and 49-rule FLC are also compared. The Fuzzy Logic Controller (FLC) is built using fuzzy rules to ensure that the systems are essentially stable. For motor tuning, there are 9 and 49 fuzzy rules. There are two inputs on the FLC which are the first input is the difference in motor speed between the reference and actual speed, while the second is the speed change error (speed error derivative). After that, the FLC's output which is the PI controller's parameter is utilised to control the PMSM speed. The performance of a Fuzzy Logic Controller (FLC) based on "if-then" control rules is compared to that of a commonly used Proportional Integral plus Derivative (PID) controller. The FLC is more durable and efficient than the PI controller, according to the study, because it is less susceptible to changes in system parameters and uses less energy. On the basis of the MATLAB simulation result, a comparison was made between the conventional output and the fuzzy self-tuning output. The simulation results show that the developed FLC controller achieves best PMSM dynamic behaviour, perfect speed tracking with shorter rise time, less steady-state error, and superior performance than the typical PI controller.

ABSTRAK

Projek ini berkaitan dengan pemacu *Permanent Magnet Synchronous Motor* (PMSM) dengan menggunakan *Fuzzy Logic Controller* (FLC). Keuntungan proporsional dan integral pengawal PI diubah menggunakan Fuzzy Logic. Dalam projek ini, membandingkan pengawal PI menggunakan FLC *9-rule*, dan FLC *49-rule*. *Fuzzy Logic Controller* (FLC) dibina menggunakan *fuzzy rules* untuk memastikan bahawa sistem pada dasarnya stabil. Untuk penalaan motor, terdapat 9 dan 49 *fuzzy rules*. Terdapat dua input pada FLC iaitu input pertama adalah perbezaan kelajuan motor antara rujukan dan kelajuan sebenar, sementara yang kedua adalah kesalahan perubahan kelajuan (turunan kesalahan kelajuan). Setelah itu, output FLC yang merupakan parameter pengawal PI digunakan untuk mengawal kelajuan PMSM. Prestasi *Fuzzy Logic Controller* (FLC) berdasarkan peraturan "*if-then*" dibandingkan dengan pengawal *Proportional Integral plus Derivative* (PID) yang biasa digunakan. FLC lebih tahan lama dan efisien daripada pengawal PI, menurut kajian, kerana kurang rentan terhadap perubahan parameter sistem dan menggunakan lebih sedikit tenaga. Berdasarkan hasil simulasi MATLAB, perbandingan dibuat antara output konvensional dan *output fuzzy self-tuning*. Hasil simulasi menunjukkan bahawa pengawal FLC yang dikembangkan mencapai tahap dinamik PMSM yang terbaik, penjejakan kelajuan yang sempurna dengan masa kenaikan yang lebih pendek, ralat keadaan stabil, dan prestasi yang lebih tinggi daripada pengawal PI biasa.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Ampere
FLC	-	Fuzzy Logic Control
PI / PID	-	Proportional - Integral / Proportional – Integral - Derivative
FOC	-	Field Oriented Control
AC	-	Alternating Current
DC	-	Direct Current
PMSM	-	Permanent Magnet Synchronous Motor
V	-	Volts
VC	-	Vector Control

CHAPTER 1

INTRODUCTION

1.1 Background

The Permanent Magnet Synchronous Motors (PMSMs) speed industrial drives are becoming more common, and improved motor drives are becoming more important. Rather than windings in the rotor, permanent magnets produce the steady magnetic field in an asynchronous motor. Improvements in permanent magnet (PM) materials, particularly rare earth magnets, have accelerated the development of new applications.

PMSM has a lot of advantages in motion management systems. The advantages are high efficiency, high power density, and broad constant power region. However, the PMSM presents a coupled nonlinear multivariable control structure called an intricate nonlinear design to get good dynamic performance. Moreover, the performances are insensitive to the drive and the variation of load parameters. The vector control technology problem is often referred to as Field Orientated Control (FOC) [7,8].

FOC of PMSM motor drive gives improved performance in terms of faster dynamic response and more efficient operation. The FOC or vector control method improves the dynamic response and performs characteristics similar to the DC machine in the drives desired for specific applications. The high-performance drive system necessitates quick response and robustness to a variety of parameters.

In these applications, to precisely control the motor by giving the desired performance speed controllers, which are designed to control the speed of a PMSM motor to perform many activities, comes in various traditional and numeric controller types. The controllers can be: proportional-integral (PI), proportional integral derivative (PID), Fuzzy Logic Controller (FLC) or the combination between them: Fuzzy-Neural Networks, Fuzzy-Genetic Algorithm, Fuzzy-Ants Colony, Fuzzy-Swarm [13, 14].

Proportional plus integral (PI) controllers are usually preferred, but when the processes need to run with some disturbance or present non-linearities, it causes a disadvantage for returning. With fuzzy logic controller will overcome the complexity of conventional PI controller tuning and high response time [9,10].

The topic of fuzzy control has increased in recent years. Fuzzy logic control (FLC), introduced by L.A. Zadeh in 1973 and used (Mamdani 1974) to control systems architecturally challenging to model structures, is one of the most effective applications of fuzzy set theory. Since then, FLC has grown into a thriving and prolific research field with a wide range of industrial applications. Unlike traditional control, developing an FLC does not require precise knowledge of the system model, such as the poles and zeroes of the system transfer functions. Two inputs for developing a fuzzy control system that replicates human learning are the tracking error and the error rate change [15,16].

1.2 Problem Statement

Permanent Magnet Synchronous Motor (PMSM) drive technologies open up a significant market for electric vehicles and drive systems. However, PMSM drives with traditional controllers struggle to handle various duties such as dynamic speed tracking, parameter fluctuations, and load stress. Because of the complexity of the traditional Proportional and Integral (PI) controller, the modification of parameters and nonlinearities of the PMSM degrade the control performance in a dynamic process, causing torque and speed vibrations. They are unable to resolve the disruption caused by the time-varying system. Modern intelligence control approaches, such as a fuzzy logic controller, are utilized to overcome the traditional PI controller. Fuzzy control with little dependence on the controlled object can alter the control rules based on the control results, resulting in a faster response time and more accuracy. It can control the torque ripple associated with Field-Oriented Control (FOC) to generate a practical selection of the stator voltage vector for smooth torque performance. As a result, when modified the control system parameters, the fuzzy logic controller was found to track the reference control condition better than a PI controller and greater resilience qualities.

1.3 Objectives

The objectives of this project are as follows;

1. To design the Permanent Magnet Synchronous Motor (PMSM) drive using Fuzzy Logic Controller which are using fuzzy logic 9-rule rulebase and 49-rule rulebase.

2. To analyse the performance of fuzzy logic controller compared to PI controller.

3. To verify the effectiveness of the proposed method, PMSM drive using fuzzy logic controller.

1.4 Scope of Project

This project mainly focuses on developing a Fuzzy Logic Controller (FLC) to control the Permanent Magnet Synchronous Motor (PMSM) using MATLAB Simulink software. This project also evaluates the FLC's performance compared to the PI controller using MATLAB Simulink software.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the researcher's previous works based on the project implementation, analyzing the simulation and experimental data of fuzzy logic control for PMSM drives.

2.2 Using Fuzzy Logic Controller for Self-Tuning of PI Speed Controller Gains

Mutasim Nour et al., 2016 in their project [1] which the primary purpose is to overcome the conventional PI controllers that being disadvantage mode when need to return whenever run the processes experiences some disruption or when the process shows complexity. Fuzzy Logic Control (FLC) is the control technique used in this thesis. These techniques are not to replace the conventional methods but are used to aid the conventional method of enhancing output performance. The conventional PI controllers are working well when the system runs with rated speed and rated condition but unable to perform well when the compensation role for such conditions without retuning its parameter. By adding the FLC in the conventional PI controller, the control system optimizes without changing the topology of the conventional system by adding the FLC in the conventional PI controller, the control system optimizes without changing the topology of the conventional system.

For the extraction of the FLC rules, the author uses this method to study the effect of rising time (Tr), maximum overshoot (Mp), and steady-state error (SSE) when varying proportional gain (Kp) and integral gain (Ki) conducted. By using the results of the experiment to develop 25-rules for the FLC of Kp and Ki. Then, varied Kp and Ki's gains to determine the magnitude of the effects on Tr, Mp, and SSE [1].

Table 2.1: Effect of varying Kp ang Ki [1]

Gain		Tr	Mp	SSE
Kp	Increase	Decrease	Increase	Improved
	Decrease	Increase	Decrease	Deteriorated
Ki	Increase	Decrease	Increase	Improved
	Decrease	Increase	Decrease	Deteriorated

Based on Table2.1, the authors used to design the membership function (MF) and manipulated Kp and Ki based on the system's response. When the steady-state error is significant, Kp and Ki's gains will increase and vice versa.

Next, the authors performed a series of tests to choose the most suitable membership function (MF) [1].

Table 2.2: The 25 rules for FLC [1]

K_p

E \ CE	NB	NS	ZE	PS	PB
NB	NB	NS	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PS	PB

K_i

E \ CE	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	PS	PS	PB	PB	PB

Where: NB: Negative Big; NS: Negative Small; ZE: Zero Error; PS: Positive Small; PB: Positive Big.

The author employs input gain (GCE) tuning to tune the FLC's error change (CE) input for the tuning mechanism. The GCE was then fine-tuned for speed changes. GCE optimal values vary depending on the speed response. In terms of rising time, authors that used GCE's value to measure the system's responsiveness performed substantially better.

Mutasim Nour et al., 2016 in [1] use the data serve as an on-line adjustment mechanism for various speeds. As a result, the author looks for gain scheduling or the look-up table strategy. Different GCE values are input into a software, and the interpolation method is used to calculate the other values in between. Interpolation is a technique for estimating values between two known data points.

To reduce the maximum overshoot, the rise time must be reduced. The maximum overshoot for GCE values has been eliminated, however the system's rise time has greatly increased. This method was utilised by the author to avoid any system harm caused by a large overshoot. Because of the higher inertia in a high-performance motor system, the delayed rising time cannot be tolerated.

Then, to improve the rise time for the smoother and faster response for certain speeds, the author tuned the I/O Gains as a function of inertia and speed, and fixing GCE tuning. Also, to overcome high overshoot and slow response as a result of increased inertia [1].

In conclusion, the self-tuning Fuzzy Logic Controller (FLC) that tunes PI controller gains improves the traditional PI controller in zero steady-state error and fast recovery from load variations. It also increased inertia and response smoothness.

2.3 Self-Tuning Fuzzy PID Control Application for PMSM Simulation of Drive System

Hui Hang and Bingyi Zhang, 2017 in [2], suggests the controller outperforms the classic fuzzy PID controller, and the quantification item self-tuning fuzzy PID controller in terms of dynamic balance overall performance and pace monitoring energy that has strong robustness to outside disturbance. Nonlinearities, uncertainties, and outside disturbances must be considered in the design of control laws for a Permanent Magnet Synchronous Motor (PMSM) power manage device for power gadget equipment. The use of assessment the deficiencies and qualities of traditional PID controller and the limitations of conventional fuzzy PID controller is typically advocated for a quantification thing self-tuning fuzzy PID controller for power gadget. The simulation outputs show that the controller can map the error to a bushy region within the entire speed reference range and slow the device down when the error is minor. Each hasty and sluggish procedure has almost no overshoot.

The conventional fuzzy PID controller and the quantitative item self-tuning fuzzy PID controller were designed by the author, with the traditional PID controller's parameters designed using the engineering approach and the trial and errors approach used to determine the final manage parameters. Conventional PID controllers are proportional, fundamental, and differential proportional. Even if the parameters are set to the correct values, the servo system will not achieve its requirements since there are numerous unknown elements within the permanent magnet synchronous motor feeding system, such as unexpected load disturbances and others.

The authors also increase the fuzzy PID controller's adaptive ability Traditional fuzzy controllers have a fuzzy design with fixed de-fuzzy quantization factors. A controller with a fixed factor cannot correctly transform the continuous input to a fuzzy domain over the speed range. The system's adaptive capabilities will be reduced as a result of the fuzzy controller's incorrect judgement [2].

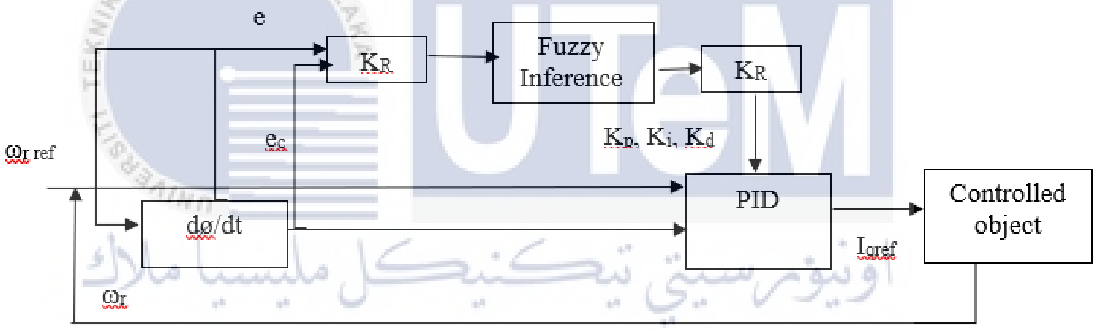


Figure 2.1: Block of Fuzzy PID Controller [2]

With quantification factor, K_a fixed the conventional fuzzy PID the controller, so it is not able to map the error in correct value in the fuzzy domain, and it will cause the fuzzy PID not adaptive to varying command.

The authors obtain the parameter of PID controller through trial and error by using the principle of tuning to adjust the proportional coefficient to make the system respond fast and little overshoot. Then, the integral is increase coefficient when error eliminates quickly [2].

Finally, a quantification factor self-tuning fuzzy PID controller is constructed by merging PID control and fuzzy controllers make it robust, stable, and insensitive to changes in parameters and operating conditions. Their rising times are nearly equal since the controller's current limiting effect has the same acceleration. However, the adjustment time of quantification factor self-tuning fuzzy PID control is much shorter than the conventional fuzzy PID controller, an overshoot of the proposed controller is also much smaller than the fuzzy PID controller.

2.4 Field Oriented Control of Permanent Magnet Synchronous Motor (PMSM) using Fuzzy Logic Based

P. Jeevananthan et al., 2012 in [5] employs area vector modulation to simulate a velocity manipulate device based on fuzzy common-sense technology for an oblique vector managed everlasting magnet synchronous force. With the use of a Fuzzy controller, the complexity of PI controller tuning and excessive reaction time can be overcome. With no mathematical calculation, it has a far shorter reaction time and a high level of accuracy. However, the fuzzy controller's performance compared to the PI controller is superior only under transient conditions. The authors proposed a gain scheduled PI speed controller with variable controller gains based on the input error signal. This controller has the disadvantage of poor performance, the controller gains' limits, and the inability to choose the rate at which they change.

2.5 The Permanent Magnet Linear Synchronous Motor Fuzzy PID Control Research

Ying Wu et al., 2012 in [17] purpose mathematical mode of the everlasting magnet linear synchronous motor (PMLSM), 3-closed- loop manage gadget in this paper by the authors. A fixed of adaptive fuzzy PID manage gadget is designed for the velocity loop of the proposed manage gadget, moreover, fuzzy inference regulations is mounted to recognise the Fuzzy PID controlling of the velocity loop, combining the benefits of conventional PID manage set of rules and fuzzy manage set of rules, in accordance with the characteristics of linear motor and the possible elements of uncertainty. Because of its simple set of principles and high reliability, traditional PID control is widely used in movement control. However, in fact, a number of the managed items lack a mathematical equivalent, resulting in a complex collection of PID parameters; also, the parameters often have poor overall performance.

Linguistic values used by the author are the following 7 linguistic variables: NB (Negative Big), NM (Negative Middle), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Middle), PB (Positive Big). When the control rules are defined, it is vital to eliminate overshoot as well as increase the response speed and stability of the entire system in order to meet the requirements of control precision and response speed. [18]. According to the expertise, the fuzzy rules about ΔK_p, *i* ΔK, *d* ΔK of the fuzzy controller can be obtained as shown in the following tables:

Table 2.3: Fuzzy rules ΔK_p [17]

ce/e	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PM	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NM
ZE	PM	PS	NS	ZO	ZO	NS	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	PS	NS	NM	NM	NB	NB
PB	NS	ZO	NM	NM	NB	NB	NB

Table 2.4: Fuzzy rules *i* ΔK [17]

ce/e	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NM	NM	NS	NS	ZO
NM	NB	NB	NM	NS	NS	NS	ZO
NS	NB	NM	NS	NS	ZO	PS	PM
ZE	NM	NM	NS	ZO	ZO	PS	PM
PS	NM	NS	ZO	PS	PM	PM	PB
PM	ZO	ZO	ZO	PS	PM	PM	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 2.5: Fuzzy rules $d\ \Delta K$ [17]

ce/e	NB	NM	NS	ZE	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NS	NS	ZO
NS	ZO	NS	NM	NM	NS	ZO	ZO
ZE	ZO	ZO	NS	NS	NS	NS	ZO
PS	NS	NS	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PM	PB
PB	PB	PB	PM	PM	PS	PS	PB

In comparison to conventional PID controllers, fuzzy PID controllers provide better static and dynamic features, as well as anti-jamming capability. As for the PMLSM, the velocity close-loop employing the fuzzy PID controller would make the electric motor response fast and operate stably, achieving the control goals well without any changes in other close-loops [17].

2.6 Comparison of all research paper

Table 2.6: Comparison of all research paper

No.	Title	Author	Method
1	Using Fuzzy Logic Controller for Self-Tuning of PI Speed Controller Gains	Mutasim Nour et al., 2016	A two input and two output FLC is used
2	Self-Tuning Fuzzy PID Control Application for PMSM Simulation of Drive System	Hui Hang and Bingyi Zhang, 2017	Combination the advantage of PID controller and fuzzt controller a quantification factor self-tuning fuzzy PID controller
3	Field Oriented Control of Permanent Magnet Synchronous Motor	P. Jeevananthan et al., 2012	Fuzzy based gain scheduling of PI controller

	(PMSM) using Fuzzy Logic Based		
4	The Permanent Magnet Linear Synchronous Motor Fuzzy PID Control Research	Ying Wu et al., 2012	Using fuzzy 49-rule base with 3 output

After a thorough observation, most of the researchers used fuzzy logic controller techniques to improve the conventional PI controller. As a result of techniques, the PMSM improves in reducing steady-state error, rising time, maximum overshoot of the speedy response with less oscillation. To control the motor speed at different speeds and parameters variation are robust when applied it. It is because fuzzy controllers are more robust to plant parameter changes than conventional PI or PID controllers. Therefore, this current study propose to use FLC in PMSM drives in order to improves the steady-state error, rising time, maximum overshoot of the speedy response and can control the motor speed at different speeds.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the method that used for this project. This project has two part which are for the first part is the development of Permanent Magnet Synchronous Motor (PMSM) drives system and establish the Field-Oriented Control (FOC) simulation. The second part is an intelligent control system that used a Fuzzy Logic Controller (FLC). Both developments based on MATLAB Simulink.

3.2 Flowchart of the process

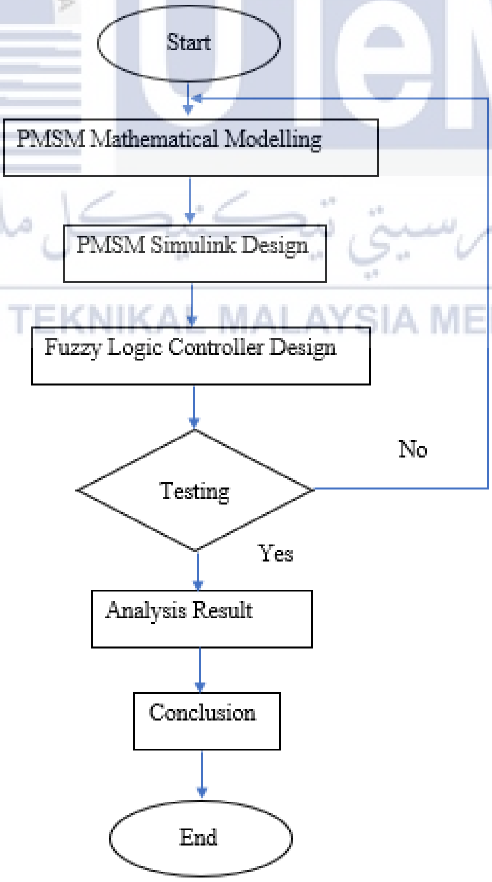


Figure 3.1: Flowchart of the project

3.3 Mathematical Modelling of PMSM

The mathematical model starts with the voltage equations then substitute into the flux equations.

Voltage equations from the model are given by,

$$V_q = R_S i_q + \omega_r \lambda_d + \rho \lambda_q \quad (3\text{-}1)$$

$$V_d = R_S i_d - \omega_r \lambda_q + \rho \lambda_d \quad (3\text{-}2)$$

Flux linkages are given by,

$$\lambda_q = L_q i_q \quad (3\text{-}3)$$

$$\lambda_q = L_q i_q + \lambda_f \quad (3\text{-}4)$$

Substituting Eq. (3-3) and Eq. (3-4) into Eq. (3-1) and Eq. (3-2) form of the voltage obtain as shown in (3-5) and (3-6).

$$V_q = R_S i_q + \omega_r (L_d i_d + \lambda_f) + \rho L_d i_d \quad (3\text{-}5)$$

$$V_d = R_S i_d - \omega_r L_q i_q + \rho (L_d i_d + \lambda_f) \quad (3\text{-}6)$$

The developed torque motor is being given by,

$$T_e = \frac{3}{2} (\frac{P}{2}) (\lambda_d i_q - \lambda_q i_d) \quad (3\text{-}7)$$

3.3.1 Architecture of the system

The figures below show the overall block diagram and simulation circuit of the PMSM drives.

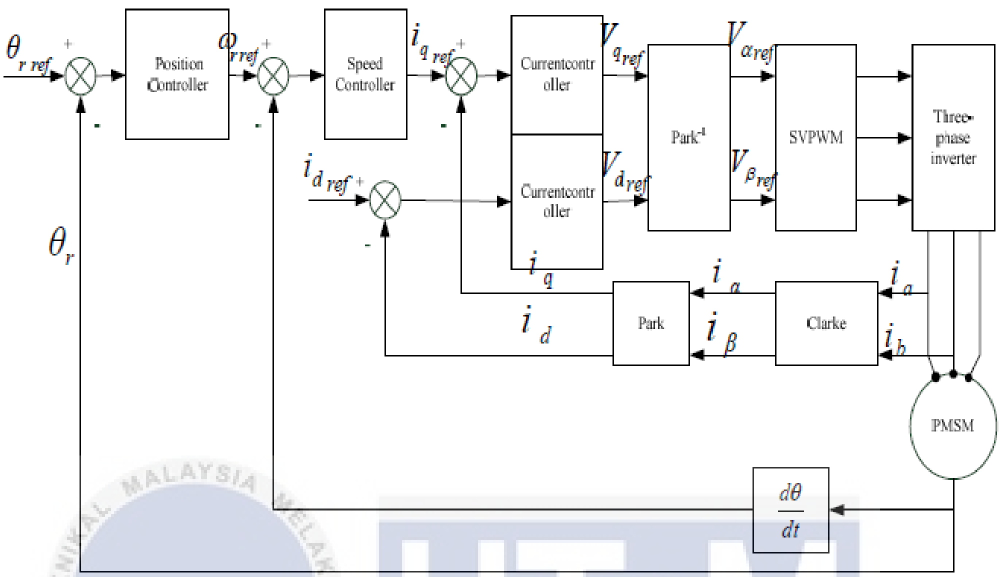


Figure 3.2: Block diagram of purpose system

Figure 3.2 shows the overall block diagram of PMSM drives. The system starts with the input which is the speed use. The position controller which is Fuzzy Logic Controller (FLC) is the mechanism to tune the PMSM drives. FLC executes the rule base, receiving the input and giving the output, where the input is speed error and change in speed error. Next, the speed controller generates a reference torque that is proportional to the current component of the quadrature-axis stator I_{sq} and current controller creates the stator current quadrature axis reference, I_{sq}, by comparing the speed set point with the measured mechanical speed of the rotor.

Then, the Space Vector Pulse Width Modulation (SVPWM) will impressed the new stator voltage vector to the three-phase inverter to converts a three-phase time and speed-dependent system into a two-coordinate time-invariant system (*d* and *q* coordinates). After that, the output current controller is sent to the Clark to modifies a three-phase system to a two-phase and go through the inverse Park transform to determine the rotor flux position. Lastly, the output of the motor such as speed and current are feedback to the FLC to execute the rule base and giving the desired output.

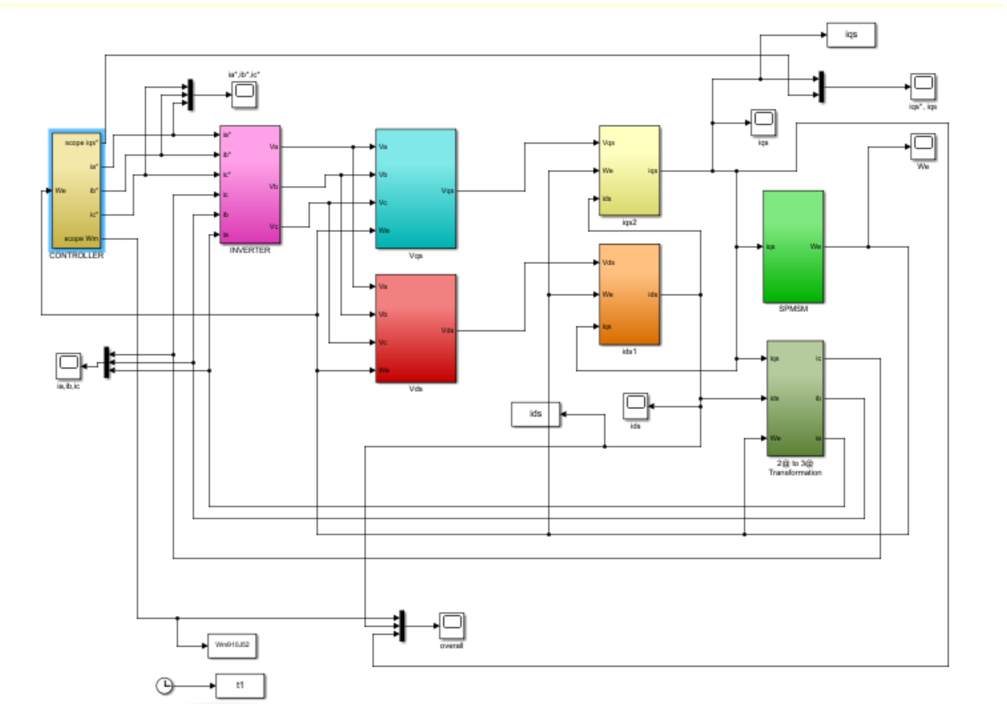


Figure 3.3: PMSM circuit design using Matlab Simulink

Figure 3.3 show the simulink diagram circuit of the PMSM drives using the Matlab Simulink software. Start with the step input in the controller subsystem. In controller subsystem has the FLC to tune the PMSM motor by receive the input form the feedback in form of speed and current from the PMSM motor. The inverter converts three-phase time and speed-dependent system into a two-coordinate time-invariant system. The output SVPWM will impressed the new stator voltage vector. Then, the rule base in FLC execute the feedback and give the desired output.

3.3.1.1 Vector Control Principle

Vector control allows an induction motor to be controlled by a separately excited DC motor, increasing the efficiency of AC drives. Both asynchronous and synchronous motor drives can benefit from vector control [5].

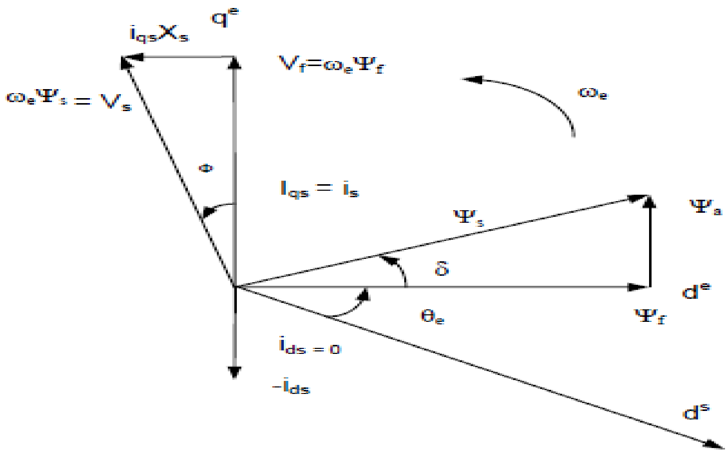


Figure 3.4: Vector Control Phasor Diagram [5]

L_s, the synchronous inductance, and L_s, the equivalent armature flux, are very small. We can set id_s=0 and $I_s = iq_s$ for maximal torque sensitivity with the stator current by ignoring the stator resistance, R_s, as illustrated in the phasor figure for simplicity. This situation also results in a low inverter power rating. To quickly derive the torque expression that has been developed:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\Psi_f i_{qs} \qquad (3\text{-}8)$$

Where Ψ_f is the space vector magnitude, the equation indicates that the torque is proportional to iq_s and the power factor angle φ equals the torque angle δ. The stator command current, iq_s is derived from the speed control loop.

3.3.1.2 Field Orientated Control (FOC)

The Field-Oriented Control (FOC) technique is utilised for the synchronous motor to evaluate the DC motor for PM motor control. An inverter feeds the stator windings of the motor, generating a variable frequency variable voltage scheme. Instead of manipulating the inverter frequency separately, it can use a position sensor to control the output wave frequency and phase. To regulate this, use the projection, which converts a three-phase time and speed-dependent system into a two-coordinate time-invariant system (*d* and *q* coordinates). These projections result in a framework that resembles the control structure of a DC machine. Field orientated controlled machines consist of two constants as input references: the torque component, *q* coordinate and the flux component, *d* coordinate [4].

3.1.1.2.1 Clarke Transformation

The Clarke transformation is a mathematical transformation used to simplify the three-phase currents i_a, i_b, i_c. It is also known as the alpha-beta transformation. Clarke's mathematical transformation modifies a three-phase system to a two-phase orthogonal stator axis: the i_α and i_β [11].

$$i_{s_\alpha} = i_a \tag{3-9}$$

$$i_{s_\beta} = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \tag{3-10}$$

3.1.1.2.2 Park Transformation

The Park's transformation rotates the reference frame of three-phase systems by a mathematical transformation. The three different sinusoidal phase quantities are projected onto two axes that rotate at the same angular velocity. The two axes are called the direct axis and the quadrature axis, where the q axis is at an angle of 90 degrees from the direct axis, as shown in Figure 3.4.

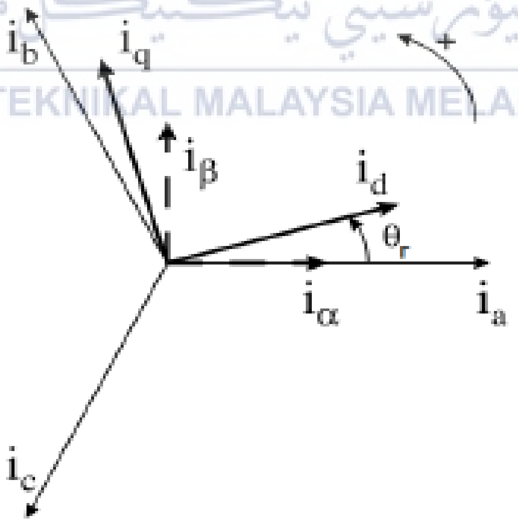


Figure 3.5: Representation of stator currents in the three different reference frames [11]

The flux and the torque components of the current vector can be determined using the following equations:

$$i_{Sd} = i_{S\alpha}\cos\theta + i_{S\beta}\, sin\theta \qquad (3\text{-}11)$$

$$i_{Sq} = -i_{S\alpha}\sin\theta + i_{S\beta}\, cos\theta \qquad (3\text{-}12)$$

By using these equations, the rotor flux position can be determined. These components depend on the current vector (a,b) components and the rotor flux position.

3.3.1.3 Space Vector Pusle Width Modulation Insert

The switching sequence of the upper switches of a three-phase voltage source inverter is determined using the Space Vector Pulse Width Modulation approach (VSI). The eight-phase voltage configurations are determined by the different combinations of ‘on’ and ‘off’ states. This PWM approach uses switching space voltage vectors to drive the motor and create an approximate circular rotary magnetic field. By integrating the eight switching patterns (V0–V7), it approximates the reference voltage V_{ref}. The plane is divided into six sectors which each sector is 60 degrees. Two neighbouring non-zero vectors and two zero vectors are used to form V_{ref} [6].

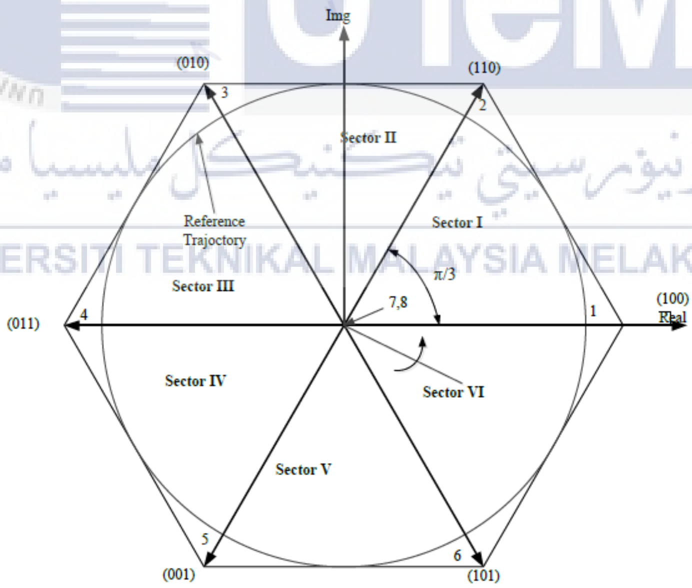


Figure 3.6: Voltage space vector switching states. [6]

Table 3.1: Switching Vectors. [6]

Vector	A+	B+	C+	A-	B-	C-	VAB	VBC	VCA
V0={000}	OFF	OFF	OFF	ON	ON	ON	0	0	0
V1={100}	ON	OFF	OFF	OFF	ON	ON	+Vdc	0	-Vdc
V2={110}	ON	ON	OFF	OFF	OFF	ON	0	+Vdc	-Vdc
V3={010}	OFF	ON	OFF	ON	OFF	ON	-Vdc	+Vdc	0
V4={011}	OFF	ON	ON	ON	OFF	OFF	-Vdc	0	+Vdc
V5={001}	OFF	OFF	ON	ON	ON	OFF	0	-Vdc	+Vdc
V6={101}	ON	OFF	ON	OFF	ON	OFF	+Vdc	-Vdc	0
V7={111}	ON	ON	ON	OFF	OFF	OFF	0	0	0

3.3.1.4 Proportional plus Intergral plus Derivative Controller

PID controllers is used in closed-loop processes in PMSM drives. It can be tuned by operators without an extensive background in controls.

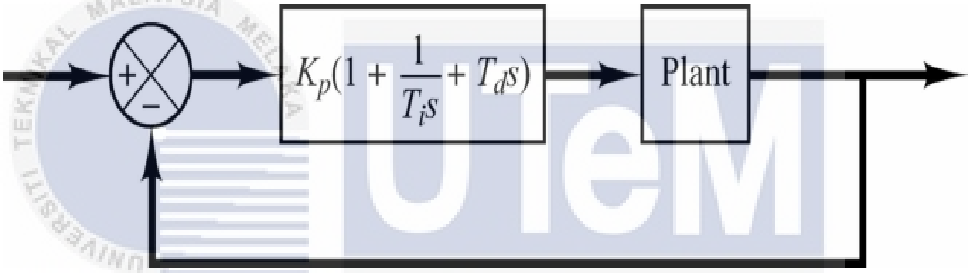


Figure 3.7: PID controller block diagram

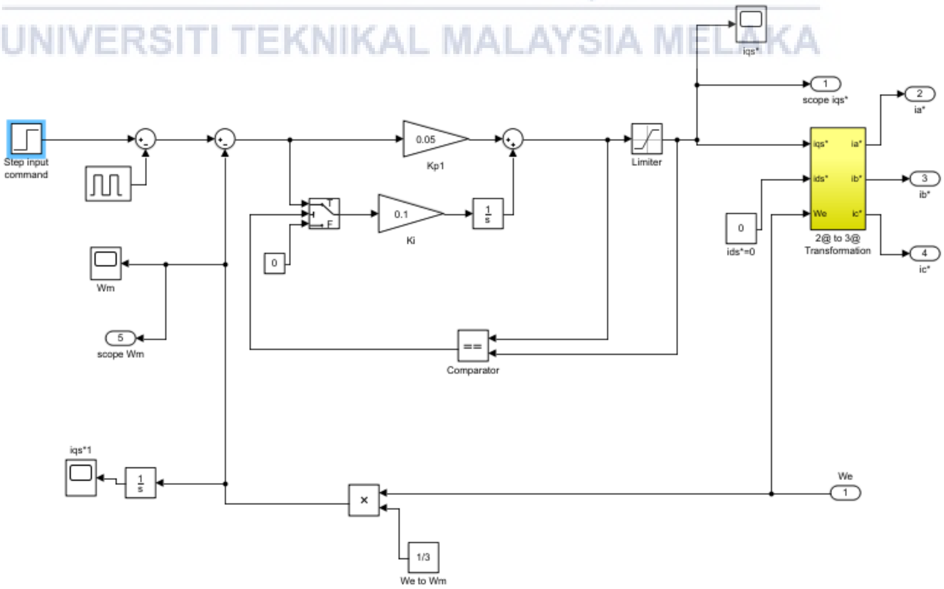


Figure 3.8: PI circuit design using Matlab Simulink

$$\frac{U(s)}{E(s)} = G_{PID}(s) = K_P K_I \frac{1}{s} + K_D s = K_P\left(1 + \frac{2}{T_I s} + T_D s\right) \qquad (3\text{-}13)$$

K_p, K_i, and K_d are the parameter used to determine the system's characteristic need to be improved. K_p is used to decrease the rise time, K_i used to reduce the overshoot and settling time, and K_d is for eliminate the steady-state error.

3.4 Fuzzy Logic Controller (FLC)

FLC's basic concept is to utilize a human operator's expert knowledge and experience for designing a controller and application processes whose input-output relationship is given by a collection of fuzzy control rules using linguistic variables instead of a complicated dynamic model [6].

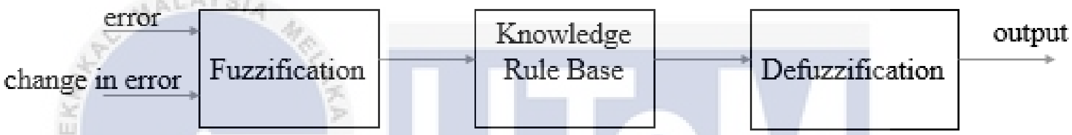


Figure 3.9: Block diagram of fuzzy logic [3]

An FLC's operation is based on a qualitative understanding of the system under control. It does not necessitate any complex mathematical calculations, as do other control systems. While other control systems rely on complicated mathematical calculations to create a model of the controlled plant, this one relies solely on simple mathematical calculations to replicate the expert knowledge.

The use of an FLC emerges most often in scenarios where [17]:

- The description of the technological process is available only in word form, not in analytical form.
- It is impossible to precisely identify the parameters of the process.
- The process description is complicated, and it would be more appropriate to state it in plain language phrases.
- The technologically regulated procedure has a "fuzzy" quality to it.
- It is not possible to precisely define these conditions.

A fuzzy logic controller has four main components as shown in listed below:

a) Fuzzification

b) Data Base

c) Rule base

d) Defuzzification

3.4.1 Fuzziticzation

The first step in creating a fuzzy controller is determining which state variables indicate the system's dynamic performance and should be used as the controller's input signal. Instead of numerical variables, fuzzy logic employs linguistic variables. Fuzzification transforms a numerical variable into a linguistic variable (a fuzzy number) [3]. The fuzzified types used for the fuzzification process in this project are trapezoidal and triangular fuzzifier.

The fuzzification interface consists of the following operations [17]:

1. Determine the input variables (crisp values of error and change of error).
2. Perform a scale mapping (quantization/normalization) to convert the input variable ranges into a comparable universe of discourse.
3. Use a fuzzification approach to transform crisp input data into useful linguistic variables, which can be thought of as labels for fuzzy sets.

The fuzzification strategy converts the crisp input data into fuzzy sets (linguistic variables). Table 3.2 shows the linguistic variables for fuzzy with 49 rulebase and 9 rulebase.

Table 3.2: The crisp input data into fuzzy sets (linguistic variables)

49-Rule Rulebase	9-Rule Rulebase
Positive Large (PL), Negative Large (NL), Positive small (PS), Negative Small (NS), Zero (ZE), Positive Medium (PM) and Negative Medium (NM)	Positive (P), Negative (N) and Zero (ZE)

3.4.2 Membership Functions

The 'rule and data base' is the second portion, which keeps the necessary data for setting the expert decision-making logic that interconnects fuzzy control action from knowledge of control rules and language variable definitions, simulating the engineer's control technique or judicial procedure. The rules are written in an “If”, “Then” structure, with the "If" side referred to as the conditions and the "Then" side as the conclusion [10].

An inference engine is software that processes rules, cases, objects, or other sorts of knowledge and expertise depending on the facts of a given scenario. To handle problems that demand reasoning rather than fencing abilities, we use several inference processes such as deduction, association, recognition, and decision making.

The inference mechanism involves the following two functions:

1. Determine which rules apply to any fuzzy controller input (error and change of error).
2. Using fuzzy reasoning, determine the fuzzy control action.

Based on the measured input error (e) and change in error, the computer can execute the rules and compute a control signal (de). The control strategy is stored in a rule-based controller in a more or less natural language. For a non-specialist end user, a rule-based controller is simple to comprehend and maintain, and an equivalent controller might be developed using traditional techniques.

3.4.3 Defuzification

The final part is the ‘defuzzification’ to convert the fuzzy variable to an easy understanding variable. The reverse of Fuzzification is called Defuzzification. The use of the Fuzzy Logic Controller (FLC) produces the required output in a linguistic variable (fuzzy number). According to real-world requirements, the linguistic variables have to be transformed to crisp output. The defuzzification method used in this project is the Center Of Gravity (COG) or centroid method.

For COG is called Center Of Gravity for singletons (COGS) where the crisp control value is the abscissa of the center of gravity of the fuzzy set is calculated as follows:

$$u_{COGS} = \frac{\sum_i \mu_c(x_i) x_i}{\sum_i \mu_c(x_i)} \quad (3\text{-}14)$$

Where *xi* is a point in the universe of the conclusion (i=1, 2, 3…) and μ*c* (*x*i) is the membership value of the resulting conclusion set. For continuous sets summations are replaced by integrals [12].

3.4.4 Fuzzy Design with Matlab Simulation

Figure 3.10 shows the fuzzy logic circuit design using Matlab Simulation. Set of rule base is in the FLC using the Fuzzy Inference System (FIS) editor. The step input as the input data of the desired speed. The gains which is PI controller use to control the rise time and the overshoot of the speed input.

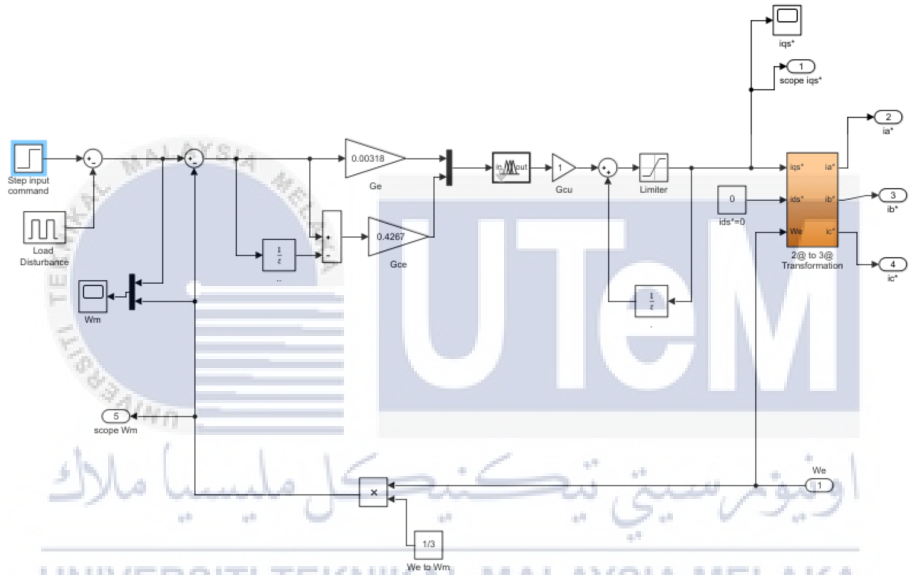


Figure 3.10: Simulink Model for Fuzzy Logic Control

3.4.4.1 Fuzzy Logic Design for Fuzzy 9-rule

Figure 3.11 shows Fuzzy Inference System (FIS) for the Fuzzy 9-rule based on L.A. Zadeh in 1973 and used (Mamdani 1974) [15] to control PMSM drives by define the rule with desired input which is the speed error and change of speed error and the desired output variables.

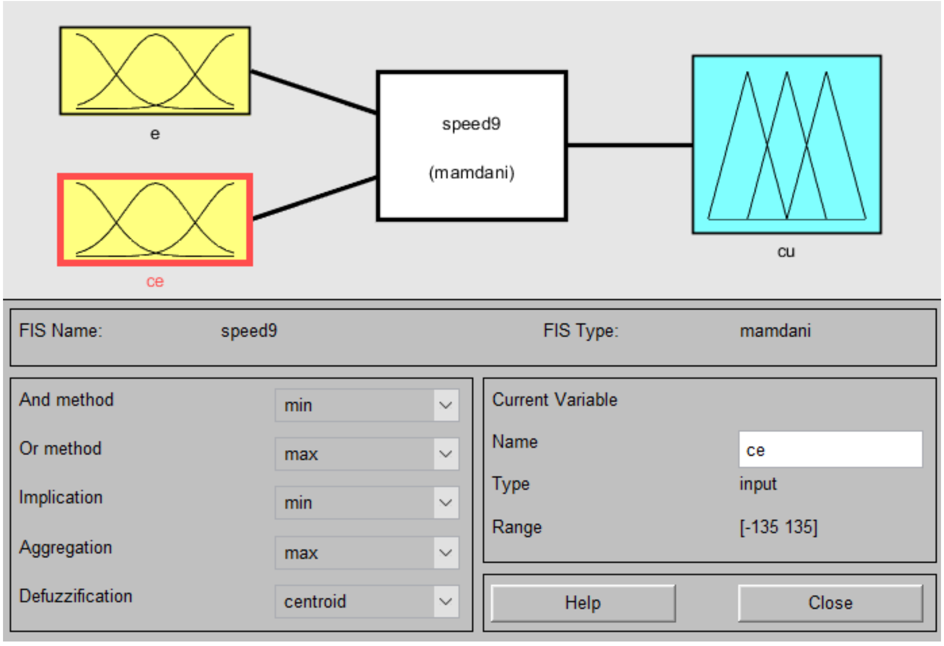


Figure 3.11: FIS editor for fuzzy 9-rule

Figure 3.12 and 3.13 are the Membership Function (MF) for the inputs variable which is the speed error 'e' and change of speed error 'ce' plots. Figure 3.14 show the MF desired output plots.

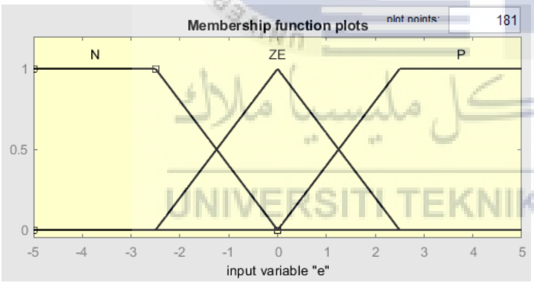


Figure 3.12: MF of e

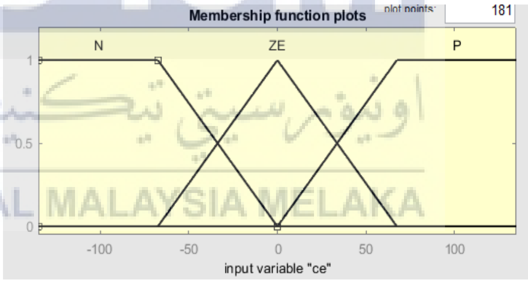


Figure 3.13: MF of ce

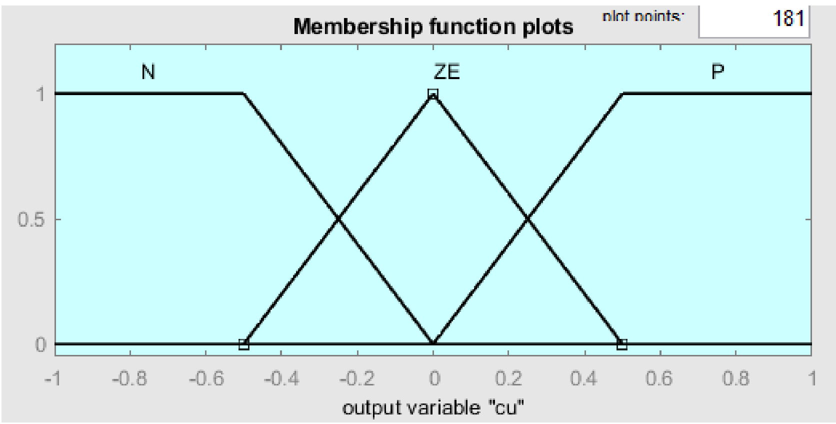


Figure 3.14: MF of cu

3.4.4.2 Fuzzy Logic Design for Fuzzy 49-rule

Figure 3.15 shows Fuzzy Inference System (FIS) for the Fuzzy 49-rule based on L.A. Zadeh in 1973 and used (Mamdani 1974) [15] to control PMSM drives by define the rule with desired input which is the speed error and change of speed error and the desired output variables.

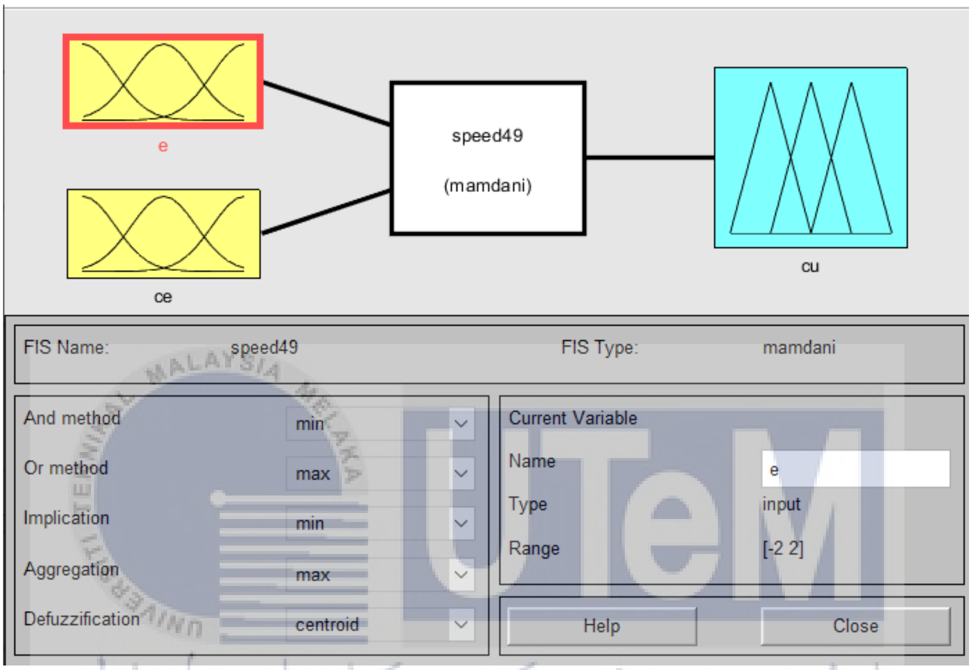


Figure 3.15: FIS editor for fuzzy 49-rule

Figure 3.16 and 3.17 are the Membership Function (MF) for the inputs variable which is the speed error 'e' and change of speed error 'ce' plots. Figure 3.18 show the MF desired output plots.

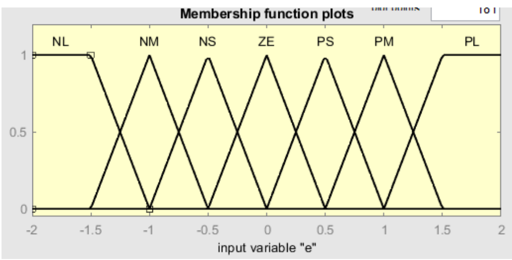


Figure 3.16: MF of e

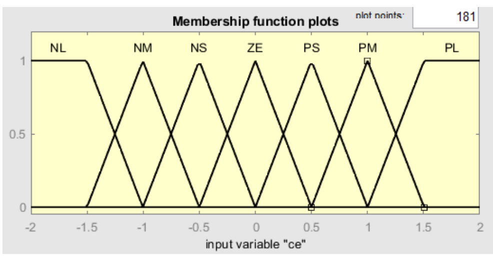


Figure 3.17: MF of ce

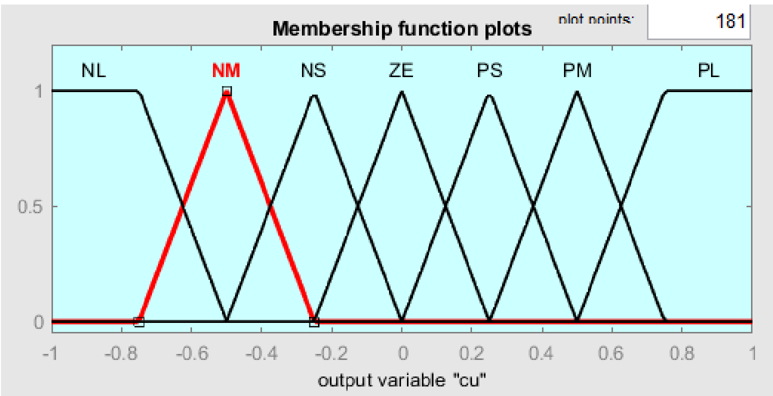


Figure 3.18: MF of cu

3.4.5 Design of Membership Functions (MF)

FLC's rules and membership operations have been altered to improve its performance. The membership functions need to be changed to achieve the finer control resolution by narrowing the membership functions near the ZE region. Making the area further from the ZE zone wider, on the other hand, results in a speedier control reaction. Changing the harshness of regulations can also help increase performance [19].

3.4.5.1 Input Variable for Fuzzy 9-rule Rulebase

The input variable for Fuzzy 9-rule consist of two input, speed error and change of speed error shows in Table 3.3 and 3.4. It can divide by 3 fuzzy set which is Negative (N), Zero (ZE) and Positive (P). The range for speed error is between -5 to 5 while the range for change of speed error is -135 to 135 and the shape of MF use for both inputs is trapezoidal and triangular.

a) Fuzzy sets of speed error (e) variable

Table 3.3: Membership function of speed error

Fuzzy Set (Label)	Description	Numerical Range	Shape of Membership Function
Negative (N)	Speed difference in negative direction	-5 to -5 -5 to -2.5 -2.5 to 0	Trapezoidal
Zero (ZE)	Speed difference is zero	-2.5 to 0 0 to 2.5	Triangular

Positive (P)	Speed difference in positive direction	0 to 2.5 2.5 to 5 5 to 5	Trapezoidal

b) Fuzzy sets of change in speed error (de) variable

Table 3.4: Membership function of change in speed of error

Fuzzy Set (Label)	Description	Numerical Range	Shape of Membership Function
Negative (N)	Speed error difference in negative direction	-135 to -135 -135 to -67.5 -67.5 to 0	Trapezoidal
Zero (ZE)	Speed error difference is zero	-67.5 to 0 0 to 67.5	Triangular
Positive (P)	Speed error difference in positive direction	0 to 67.5 67.5 to 135 135 to 135	Trapezoidal

3.4.5.2 Output Variable for Fuzzy 9-rule Rulebase

The output variable for Fuzzy 9-rule shows in Table 3.5. It can divide by 3 fuzzy set which is Negative (N), Zero (ZE) and Positive (P). The range for the output is between -1 to 1 and the shape of MF use is trapezoidal and triangular.

Table 3.5: Membership function for cu

Fuzzy Set (Label)	Numerical Range	Shape of Membership Function
Negative (N)	-1 to -1 -1 to -0.5 -0.5 to 0	Trapezoidal
Zero (ZE)	-0.5 to 0 0 to 0.5	Triangular
Positive (P)	0 to 0.5 0.5 to 1 1 to 1	Trapezoidal

3.4.5.3 Input Variable for Fuzzy 49-rule Rulebase

The input variable for Fuzzy 49-rule consist of two input, speed error and change of speed error shows in Table 3.6 and 3.7. It can divide by 7 fuzzy set which is Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). The range for speed error is between -2 to 2 while the range for change of speed error is -2 to 2 and the shape of MF use for both inputs is trapezoidal and triangular.

a) Fuzzy sets of speed error (e) variable

Table 3.6: Membership function of speed error

Fuzzy Set (Label)	Description	Numerical Range	Shape of Membership Function
Negative Large (NL)	Large Speed difference in negative direction	-2 to -2 -2 to -1.501 -1.501 to -1	Trapezoidal
Negative Medium (NM)	Medium Speed difference in negative direction	-1.501 to -1 -1 to -0.5	Triangular
Negative Small (NS)	Small Speed difference in negative direction	-1 to -0.5 -0.5 to 0	Triangular
Zero (ZE)	Speed difference is zero	-0.5 to 0 0 to 0.5	Triangular
Positive Small (PS)	Small Speed difference in positive direction	0 to 0.5 0.5 to 1	Triangular
Positive Medium (PM)	Medium Speed difference in positive direction	0.5 to 1 1 to 1.501	Triangular
Positive Large (PL)	Large Speed difference in positive direction	1 to 1.501 1.501 to 2 2 to 2	Trapezoidal

b) Fuzzy sets of change in speed error (de) variable

Table 3.7: Membership function of change in speed of error

Fuzzy Set (Label)	Description	Numerical Range	Shape of Membership Function
Negative Large (NL)	Large Speed error difference in negative direction	-2 to -2 -2 to -1.501 -1.501 to -1.003	Trapezoidal
Negative Medium (NM)	Medium Speed error difference in negative direction	-1.501 to -1.003 -1.003 to -0.5	Triangular
Negative Small (NS)	Small Speed error difference in negative direction	-1.003 to -0.5 -0.5 to 0	Triangular
Zero (ZE)	Speed error difference is zero	-0.5 to 0 0 to 0.5	Triangular
Positive Small (PS)	Small Speed error difference in positive direction	0 to 0.5 0.5 to 1	Triangular
Positive Medium (PM)	Medium Speed error difference in positive direction	0.5 to 1 1 to 1.504	Triangular
Positive Large (PL)	Large Speed error difference in positive direction	1 to 1.504 1.504 to 2 2 to 2	Trapezoidal

3.4.5.4 Output Variable for Fuzzy 49-rule Rulebase

The output variable for Fuzzy 49-rule shows in Table 3.8. It can divide by 7 fuzzy set which is Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). The range for the output is between -1 to 1 and the shape of MF use is trapezoidal and triangular.

Table 3.8: Membership function for cu

Fuzzy Set (Label)	Numerical Range	Shape of Membership Function
Negative Large (NL)	-1 to -1 -1 to -0.75 -0.75 to -0.5	Trapezoidal

Negative Medium (NM)	-0.75 to -0.5 -0.5 to -0.25	Triangular
Negative Small (NS)	-0.5 to -0.25 -0.25 to 0	Triangular
Zero (ZE)	-0.25 to 0 0 to 0.25	Triangular
Positive Small (PS)	0 to 0.25 0.25 to 0.5	Triangular
Positive Medium (PM)	0.25 to 0.5 0.5 to 0.75	Triangular
Positive Large (PL)	0.5 to 0.75 0.75 to 1 1 to 1	Trapezoidal

3.4.6 Design of Fuzzy Rules

Tabel 3.9 and 3.10 shows the fuzzy rules for rule base 9-rule and 49-rule after adjusting the range and parameter of input and output.

Table 3.9: Fuzzy rule table for rule base 9-rule

ce/e	**N**	**ZE**	**P**
N	N	N	ZE
ZE	N	ZE	P
P	ZE	P	P

Table 3.10: Fuzzy rule table for rule base 49-rule

ce/e	**NL**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	PL	ZE	PS	PM	PL	PL	PL

3.5 Ghant Chart FYP 2

The implementation of the project is planned based on the milestone show in the Table 3.11 below.

Table 3.11: The milestone for Final Year Project 2

Task	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Design the PMSM Circuit using Matlab Simulink														
Design the Fuzzy Logic Controller														
Result analysis														
Slide presentation and video														
Seminar presentation and Q&A														
Report writing														

3.6 Summary

From above explanation, the process involved for the designing fuzzy logic control of PMSM drives is presented. The MATLAB Simulink is used to simulate the project by implement all the processes involved for this system it will improve the conventional PI controller by using Fuzzy Logic Control (FLC).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Results and Discussions

This chapter presents the about the results and the discussion regarding this project. This project has three type of results for two different speeds by using three difference type of controllers which are PI controller, Fuzzy Logic Controller (FLC) with Fuzzy 9-rule base and Fuzzy 49-rule base. All developments of the controller are based on MATLAB Simulink

4.1.1 Speed at 500rpm condition

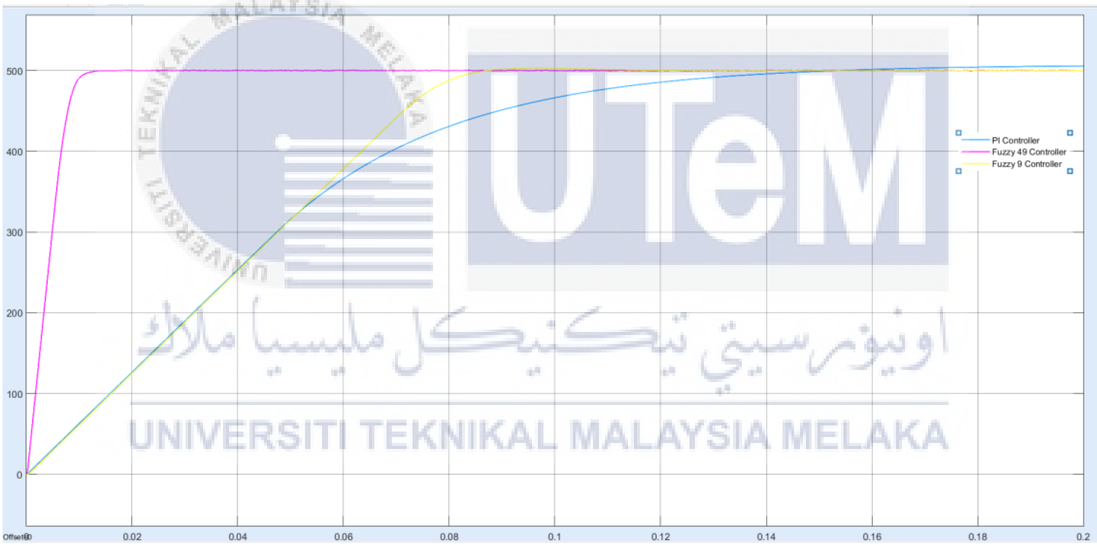
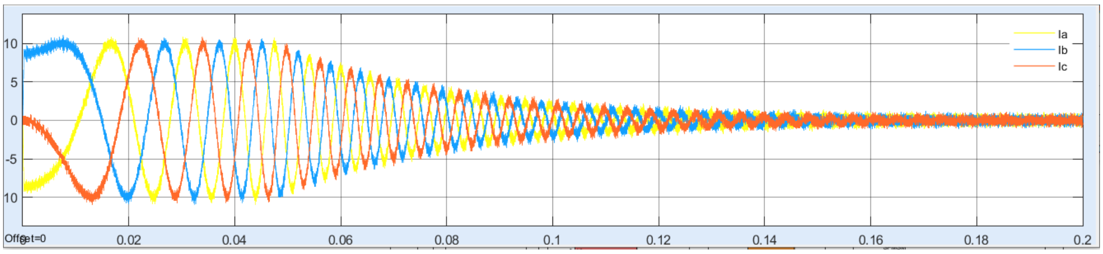
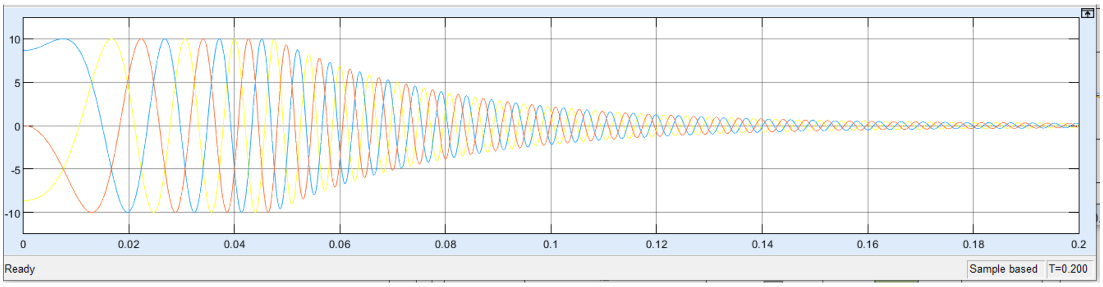


Figure 4.1: The speed response of PMSM drives at 500rpm condition for PI Controller, FLC; Fuzzy 9-rule and Fuzzy 49-rule

Figure 4.1 show the graph for PMSM drives respond based on speed at 500rpm for PI controller and Fuzzy Logic Control (FLC) for Fuzzy 9-rule and Fuzzy 49-rule as the control mechanism.

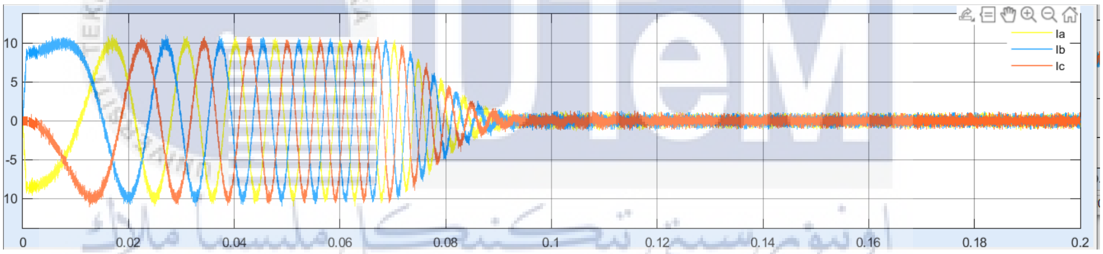


(a)

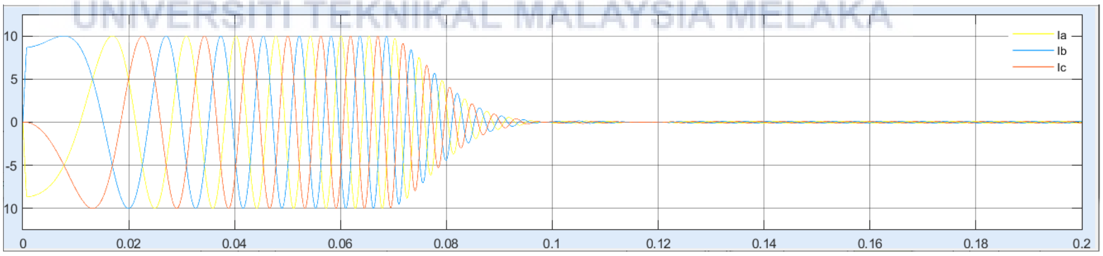


(b)

Figure 4.2 : The stator current (a) FOC and (b) MPC at 500rpm for PI Controller of PMSM drives

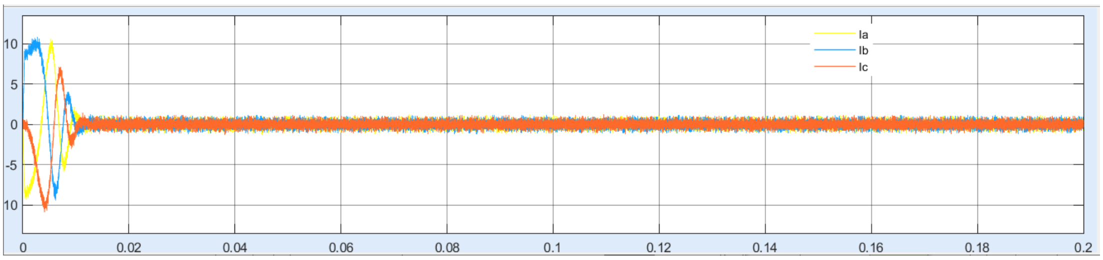


(a)

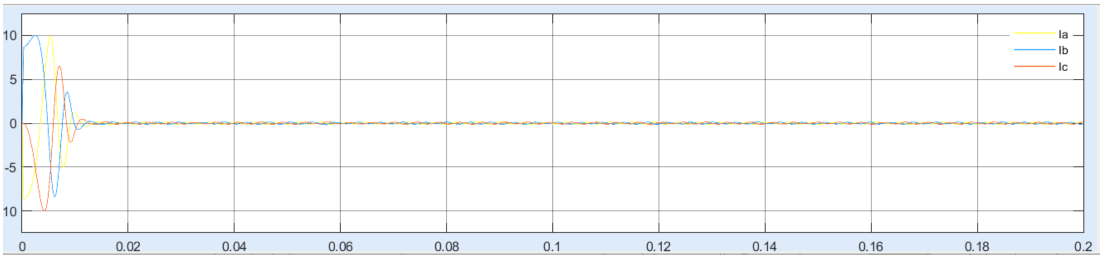


(b)

Figure 4.3: The The stator current (a) FOC and (b) MPC at 500rpm for FLC Fuzzy 9-rule of PMSM drives



(a)



(b)

Figure 4.4: The stator current (a) FOC and (b) MPC at 500rpm for FLC Fuzzy 49-rule of PMSM drives

Figure 4.2-4.4 shows the graph for stator current at 500rpm for PI controller and Fuzzy Logic Control (FLC) for Fuzzy 9-rule and Fuzzy 49-rule for PMSM drives.

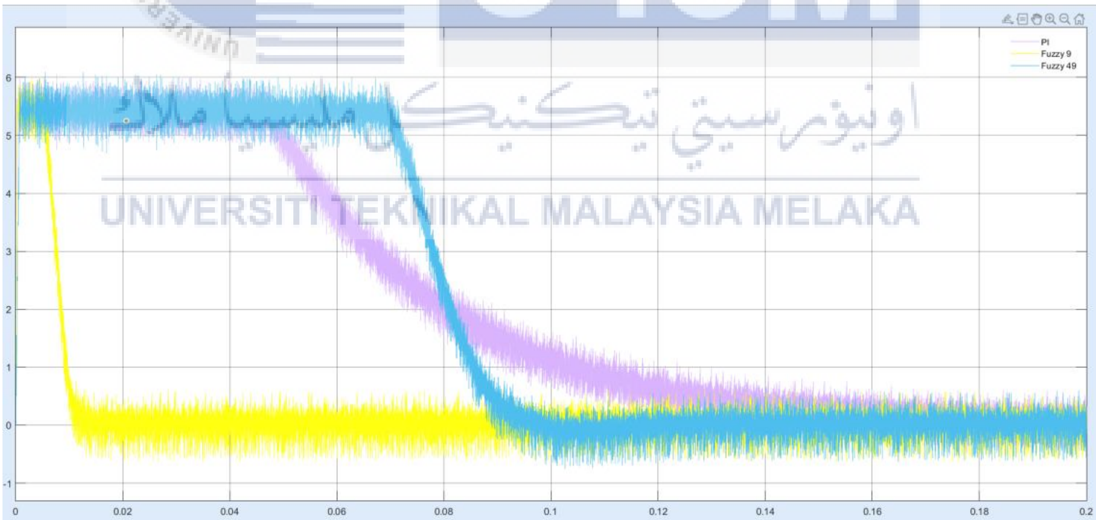


Figure 4.5: The torque response of PMSM drives at 500rpm for PI Controller and FLC; Fuzzy 9-rule and Fuzzy-49

Figure 4.5 show the graph for PMSM drive based on torque respond at 500rpm for PI controller and Fuzzy Logic Control (FLC) for Fuzzy 9-rule and Fuzzy 49-rule.

Table 4.1: Performance comparison for speed 500rpm

Controller	PI	Fuzzy 9-rule	Fuzzy 49-rule
Tr (msec)	83.776	64.66	6.96
OS (%)	9.018	8.07	10.356

Figure 4.1, shows that conventional PI control system and Fuzzy Logic Controller (FLC) for Fuzzy 9-rule and Fuzzy 49-rule. The current overshoot is 9.018% and stability time is 0.18s and he rise time is 83.776ms. For FLC 9-rule, the current overshoot is 8.070% and stability time is 0.1s and the rise time is 64.66ms. Compared to when PI controller speed is 500rpm, the overshoot is lower but the rise time is faster and the steady state error is low compared to 500rpm PI controller.

Next, when using 49-rule for fuzzy rule base the current overshoot is 10.356% and stability time is 0.014s and the rise time is 6.960ms. Compared to when PI controller and 9-rule FLC speed is 500rpm, the overshoot is higher but the responses is faster and the steady state error is zero.

4.1.2 Speed at 1000rpm condition

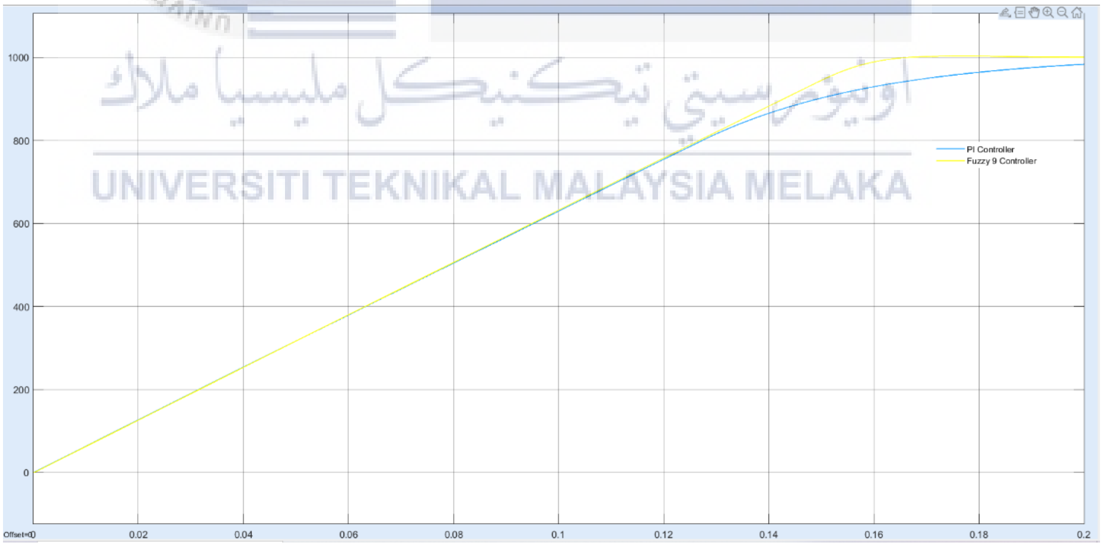
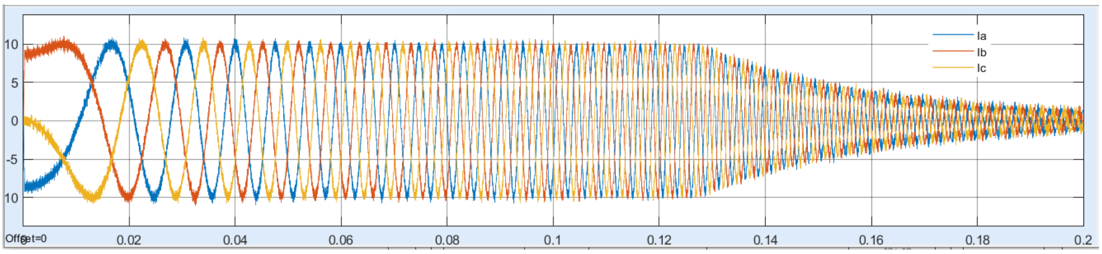
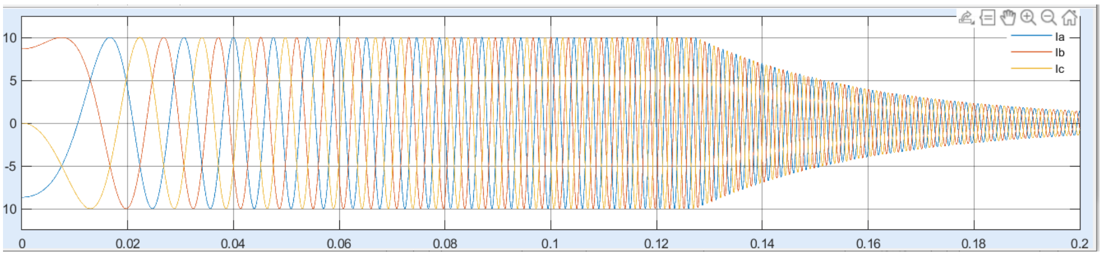


Figure 4.6: The speed response of PMSM drives at 1000rpm condition for PI Controller, FLC; Fuzzy 9-rule and Fuzzy 49-rule

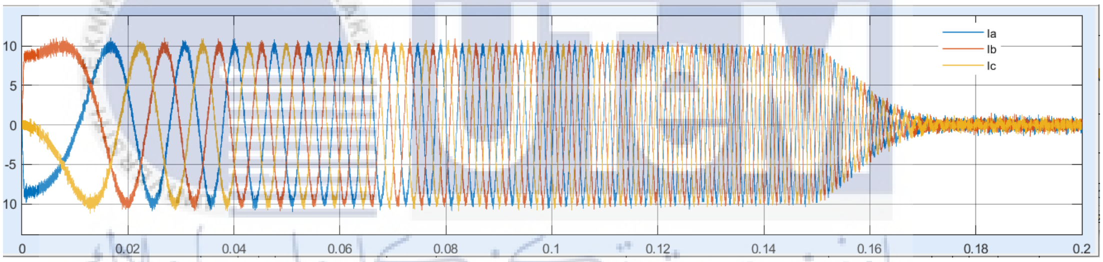


(a)

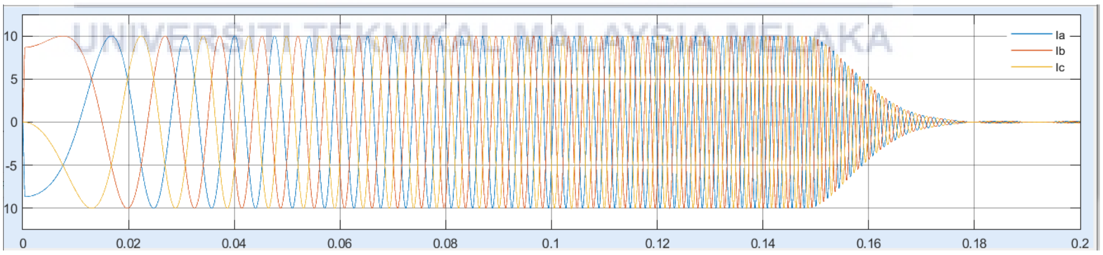


(b)

Figure 4.7 : The stator current (a) FOC and (b) MPC at 1000rpm for PI Controller of PMSM drives



(a)



(b)

Figure 4.8 : The stator current (a) FOC and (b) MPC at 1000rpm for FLC Fuzzy 49-rule Controller of PMSM drives

Figure 4.7 and 4.8 shows the graph for stator current at 1000rpm for PI controller and Fuzzy Logic Control (FLC) for Fuzzy 9-rule of PMSM drives.

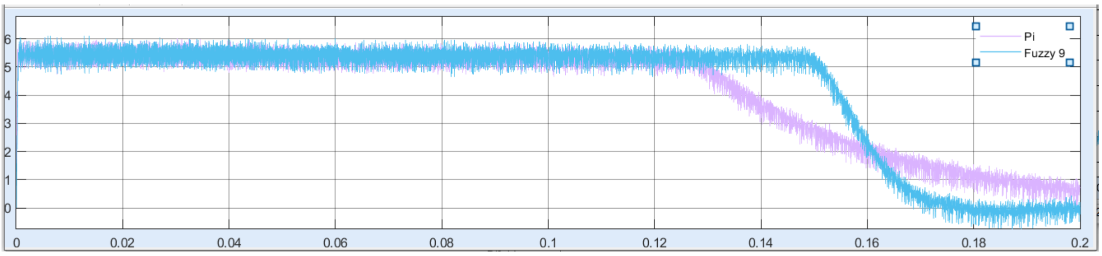


Figure 4.9: The torque response of PMSM drives at 1000rpm for PI Controller and FLC Fuzzy 9-rule

Figure 4.9 show the graph for PMSM drive based on torque respond at 1000rpm for PI controller and Fuzzy Logic Control (FLC) for Fuzzy 9-rule.

Table 4.2: Performance comparison for speed 1000rpm

Controller	PI	Fuzzy 9-rule
Tr (msec)	127.85	126.088
OS (%)	8.865	10.927

Figure 4.1, shows that conventional PI control system and Fuzzy Logic Controller (FLC) for Fuzzy 9-rule. Thr speed 1000rpm when using PI controller as control mechanism the current overshoot is 8.865% and stability time is 0.2s and the rise time is 127.846ms. While the current for 9-rule FLC overshoot is 10.927% and stability time is 0.177s and the rise time for the controller is 126.088ms. The steady state error is low compared to 1000rpm PI controller. For the 49-rule FLC, when speed is 1000rpm the motor cannot process and it reached it limit.

CHAPTER 5

CONCLUSION

5.1 Conclusion

A fuzzy rule-base design of Fuzzy Logic Controller (FLC) speed control has been studied for speed control of PMSM Drive. A set of fuzzy decision rules are formulated based of the literature review of the controller's design. The FLC is found to have better tracking of the reference control state as well as superior resilience features when the parameters of the system under control were modified than a comparable tuned PI controller. The FLC has the advantage of not requiring a mathematical model of the plant or measurements of plant response, which are essential for satisfactory PI controller tuning. Simulation study comparing the performance of the traditional PI controller with the FLC reveals that the FLC outperforms the conventional PI controller. 49-rule FLC is able to perform better than the conventional PI controller and 9-rule FLC. With 49-rule FL controller improve in terms of zero steady-state error. The results show that, despite without knowing the details of the control plants, we were able to create a well-performing fuzzy logic controller based on our position controller knowledge. 49-Rule FL controller also make the motor stable run and fast response, which can achieve the purposes of control well. When compared to a typical PI controller, the self-tuning FLC has a better dynamic response curve, shorter response time, small steady state error (SSE), and excellent steady accuracy.

REFERENCES

[1] Nour, Mutasim & Bouketir, Omrane & Yong, Ch'ng. (2009). *Self-Tuning of PI Speed Controller Gains Using Fuzzy Logic Controller*. Modern Applied Science. 2. 10.5539/mas.v2n6p55.

[2] Hang, Hui & Zhang, Bingyi. (2017). *Simulation of Drive System with Self-Tuning Fuzzy PID Control Application to PMSM*. 10.2991/eame-17.2017.25.

[3] Pewmaikam C., Srisertpol J., and Khajorntraidet C. *Adaptive Fuzzy Logic Compensator for Permanent Magnet Synchronous Motor Torque Control System*, International Journal of Modeling and Optimization, Vol. 2, No. 2, April 2012.

[4] LIU QINGHUA (2005-09-09). *Analysis, design and control of permanent magnet synchronous motors for wide-speed operation*. ScholarBank@NUS Repository.

[5] P.Jeevananthan, C.Sathish Kumar, R.K.Nithya. International Journal of *Advanced Research in Electrical, Electronics and Instrumentation Engineering* Vol. 1, Issue 5, November 2012/ ISSN 2278 - 8875

[6] Balashanmugham, Adhavan & Maheswaran, Mockaisamy. (2019). *Permanent-Magnet Synchronous Machine Drives*. 10.5772/intechopen.88597.

[7] Bhim Singh, Senior Member, IEEE, B.P. Singh, Senior Member, IEEE and Sanjeet Dwivedi, *DSP based implementation of Hybrid Speed Controller for Vector Controlled Permanent Magnet Synchronous Motor Drive*. Emerging electric power system vol.8,no 2,pp1-22 2007.

[8] J. Qian and M.A. Rahman, "*Analysis of Field Oriented Control for Permanent Magnet Hysteresis Synchronous Motors*", IEEE Trans. on Industrial Applications, Vol. IA-29, NO. 6, NOV. 1993, p 1156.

[9] Amit Vilas Sant and K. R. Rajagopal *PM Synchronous Motor Speed Control Using Hybrid Fuzzy-PI With Novel Switching functions IEEE transactions on magnetic*, vol. 45, no. 10, October 2009 pp 4672-4675

[10] Siti Noormiza Mat Isa, Zulkifilie Ibrahim, Fazlli *Patkar Comparative Study of Fuzzy Logic Speed Controller in vector Controlled PMSM Drive: Minimum Number of Fuzzy Rule-Base 2009 Conference on Innovative Technologies in Intelligent Systems and Industrial Applications* (CITISIA 2009) Monash University, Sunway campus, Malaysia, 25th & 26th July 2009.

[11] R. Di Gabriele, F. Parasiliti, M. Tursini, "*Digital Field Oriented Control for induction motors: implementation and experimental results*", Universities Power Engineering Conference (UPEC"97)

[12] Houmei CUI, Xijin GUO, Kelin LIU, "*Fuzzy-Adaptive PID Control in the Speed Control System*," Techniques of Automation & Applications,vol.28, no.9, pp.101-104, 2009.

[13] J. Zhang, N. Wang and S. Wang, "*A developed method of tuning PID controllers with fuzzy rules for integrating process*," Proceedings of the American Control Conference,Boston, 2004, pp. 1109-1114.

[14] K.H. Ang, G. Chong and Y. Li, "*PID control system analysis, design and technology*," IEEE transaction on Control System Technology, Vol.13, No.4, 2005, pp. 559-576

[15] Thana Pattaradej, Guanrong Chen and PitikhateSooraksa, "*Design and Implementation of Fuzzy PID Control of a bicycle robot*", Integrated computer-aided engineering, Vol.9, No.4, 2002.

[16] Weiming Tang, Guanrong Chen and Rongde Lu, "*A Modified Fuzzy PI Controller for a Flexible-joint Robot Arm with Uncertainties*", Fuzzy Set and System, 118 (2001) 109-119.

[17] Wu, Y., Jiang, H., & Zou, M. (1970, January 1). *The Research on Fuzzy PID Control of the Permanent Magnet Linear Synchronous Motor*. CORE. https://core.ac.uk/display/82122726.

[18] Caihua Lu, Yuewen Xu, and Weiming Yang. *Permanent magnet linear synchronous motor feed system for fuzzy PID control[J]*. Journal of Electrotechnics, 2007, 22 (9): 59-63.

[19] M.Chow and A. Menozzi ,"*on the comparison of emerging and conventional techniques for DC motor control*" proc.IECON ,PP.1008-1013,1992.