UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

SIMPLIFIED RULES FUZZY LOGIC SPEED CONTROLLER FOR INDUCTION MOTOR DRIVE

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Bachelor of Electrical Engineering (Honor)

MAY 2018

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A report submitted in partial fulfillment of the requirements for the

Bachelor of Electrical Engineering (Honor)

Faculty of Electrical Engineering

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MAY 2018

DECLARATION

I declare that this report entitled "SIMPLIFIED RULES FUZZY LOGIC SPEED CONTROLLER FOR INDUCTION MOTOR DRIVE**"** is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ……………………………………………

Name : MUHAMMAD FAISAL BIN ZAINUDIN

Date : ……………………………………………..

APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfillment of Bachelor Degree of Electrical Engineering (Honor).

Signature : …………………………………………

Name : DR MD HAIRUL NIZAM BIN TALIB

Date : …………………………………………

DEDICATION

Dedicated to my beloved parents and family members for their love, patience, and support throughout my life

ABSTRACT

Fuzzy Logic Controller (FLC) have been widely used in speed controller due to its superior performance results. Some of the system that have difficulty in modeling mathematically due to its nonlinearity and complexity have been using FLC to solve the problem and it is more suitable. Rule base method that consist of three umber of rule such as 49, 25, and 9 rule has widely use in FLC. However, from the previous research there are more focused on the rules base design and has either 49, 25 and 9 rules to get the maximum potential performance. There are no detail performance compare to the number of rules. By using higher number of rule base will get more accuracy performance result. Thus, this research is to apply the base rule method which is 49, 25 and 9, at induction motor drive. The research will be done using MATLAB/Simulink simulation software to study the result of using different rule base which is 49, 25 and 9 rule towards the performance induction motor drive and analyze the performance result when apply the different of load disturbance. In conclusion, the FLC has successfully implement in control of induction motor drive. The performance will be compare to the characteristic in transient response with various performance that measure from the results such as rise time, overshoot, settling time, speed drop and the recovery time. It will be proven that 49 rules will give the best performance in term of rise time and lower speed drop compare to the 25 and 9 rules.

ABSTRAK

Pengawal Logik Fuzzy (FLC) telah digunakan secara meluas di dalam alat kawalan kelajuan kerana keputusan prestasi yang lebih baik. Sebahagian daripada sistem yang mempunyai kesukaran dalam pemodelan matematik disebabkan oleh ketaklelurusan dan kerumitan telah menggunakan FLC untuk menyelesaikan masalah ini dan ia adalah lebih sesuai. Kaedah asas hukum yang terdiri daripada tiga umber peraturan seperti 49, 25, dan 9 peraturan telah secara meluas digunakan dalam FLC. Walau bagaimanapun, dari penyelidikan sebelumnya terdapat lebih tertumpu kepada reka bentuk kaedah-kaedah asas dan mempunyai sama ada 49, 25 dan 9 kaedah-kaedah untuk mendapat prestasi potensi maksimum. Tidak ada prestasi mendalam dibandingkan dengan jumlah peraturan. Dengan menggunakan nombor yang lebih tinggi asas hukum akan mendapatkan lebih banyak hasil prestasi ketepatan. Oleh itu, kajian ini adalah untuk menggunakan kaedah peraturan asas yang adalah 49, 25 dan 9, di induksi memandu motor. Kajian ini akan dilakukan dengan menggunakan perisian simulasi MATLAB / Simulink untuk mengkaji hasil daripada menggunakan asas hukum yang berbeza iaitu 49, 25 dan 9 peraturan ke arah pemacu motor prestasi. Kesimpulannya, FLC telah berjaya melaksanakan mengawal pemacu motor aruhan. prestasi akan bandingkan dengan ciri dalam sambutan fana dengan pelbagai prestasi yang mengukur dari hasil seperti masa naik, terlajak, masa penetapan, penurunan kelajuan dan masa pemulihan. Ia akan membuktikan bahawa 49 peraturan akan memberikan prestasi terbaik dalam jangka masa kebangkitan dan kejatuhan kelajuan yang lebih rendah berbanding dengan 25 dan 9 peraturan.

ACKNOWLEDGEMENT

In the name of ALLAH, Most Generous and Most Merciful. With the deepest sense of gratitude to ALLAH the Almighty for giving me the strength and motivation to complete this final year report. I would grateful to The Faculty of Electrical Engineering for giving me the opportunity to carry out this project.

I like to express our heartfelt regards and gratitude to my supervisor, Dr. Md Hairul Nizam Bin Talib for being stepping stone and encouragement of my project. Besides that, I express this feeling to my parents, Anidah binti Shahid and Zainudin bin Selamat for their endless support for me to finish this project. In addition, I would like to thanks my partner Liyana Najwa binti Latip and all friends for their help and sharing their knowledge whenever necessary.

Last but not least, I want to acknowledge the contributions to my family members and friends, for their continuous never ending motivation, love, patience and support through the entire progress of this report.

May Allah bless you and Thanks a lot for ALL.

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Motor is a tool that convert electrical energy to mechanical energy while generator is a tool that convert mechanical energy to the electrical energy. Induction motor is an AC electrical motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. Since the day of the invention of high performance induction motor drive, it has become one of the interesting research. Normally induction motor have a constant speed depending on the frequency of supply and the number of pulse[1]. It was not possible to control the speed of the induction motors according to the need without the availability of Thyristors or Silicon Controlled Rectifier (SCR), power transistors and Insulated Bipolar Transistor (IGBT) the variable speed induction motor drives has been invented[2].

There are two type of speed controller that are widely used for induction motor, Proportional Integral Derivative speed controller (PID) and Fuzzy logic speed controller. This project will be using Fuzzy Logic speed control for induction motor drive.

1.2 PROBLEM STATEMENT

The fuzzy logic controller manage to produce various output result compare to other type of speed controller. Those output is affected by various type of tuning factors such as rule base designed, scaling factors, membership function and others. The most important parameters in Fuzzy Logic controller is rule base design. There is lack of performance comparison investigation between 49, 25 and 9 rules size for the speed controller of Induction Motor drives[3]. Therefore, it is difficult to study the effect of the rules size towards the motor performance. But, by refer to other research, it has proven that by using higher number of rules in design of Fuzzy Logic controller, it will increase the computation time and the effectiveness of the control process. The defect of using higher of rule base number, it will require larger memory space with powerful processor to perform the base rule design[4].

1.3 OBJECTIVE

The objective of the project are:

1. To develop the mathematical model of field oriented control method for induction motor drive.
2. To design the fuzzy logic speed controller with variation of fuzzy logic rules based for the input and output.
3. To compare the speed performance of induction motor based on 49, 25 and 9 rules based during load and unload condition.

1.4 PROJECT SCOPE

The scope of the project are:

1. This project is focused on the literature review which includes a DC motor, Induction Motor drives, based rule design and speed controller.

2. To develop indirect field oriented control of induction motor drive fed by hysteresis current controller using MATLAB/SIMULINK. The approach of FLSC, fuzzy rules and membership functions are included in this project.
3. The comparison of FLSC using different based rule of FLSC such as 49, 25 and 9 rules to the performance of induction motor drive.

CHAPTER 2

LITERATURE RIVIEW

2.1 Electrical Machine

This days, many electrical machine or appliances consist of electric motor generator and etc. There are numerous type of electric motor to choose in the industry. Nowadays, the electrical motor are divided into two category AC motor and DC motor. Because of the economic cost consideration, AC type motor has been widely used in the industry[5]. AC motor come in variety of type such as induction motor, permanent magnet synchronous motor and reluctance motor.

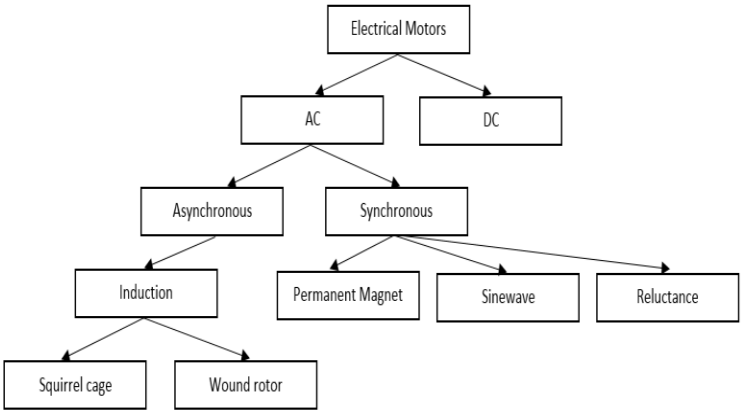


Figure 2.1: Diagram of electrical motor classification.

2.1.1 AC Motors

AC motor is powered with alternating current and it change electrical energy into mechanical energy. AC motor consists of rotor that rotate by magnetic field that induced by the current that produce by the stator and AC motor produce magnetic field[6].

AC motor can be divided into two categories:

1. Asynchronous motor
2. Synchronous motor

Table 2.1 show the category of the AC motor differentiate between their type of motor and characteristic of the motor.

Table 2.1: Table of comparison AC motor

	Asynchronous	Synchronous		
Description	Induction motor	Brush DC	Brush Less DC	PMSM
Torque ripple	Low	High	High	Low
Controllability	Low	Good	Good	Good
Cost	Cheap	Expensive	Expensive	Expensive
Heat Dissipation	Good	Low	Good	Low

Usually, because of good overloading capabilities and high torque-to-current ratio which can lead to smaller inverter and compact construction, PMSM is used instead of induction motor. But, in the industry Induction Motor are the most selected motor and it has received widespread research interest. The induction motor characteristic such as good self-starting capability, rugged structure, reliable and low cost, make the induction motor popular among the researcher. Most of the application that using induction motor is because the constant speed of induction motor produced.

Table 2.2 shows characteristic of the advantages and disadvantages of PMSM and Induction Motor drive.

Table 2.2: Different criteria for PMSM and induction motor

Criteria	Induction motor	PMSM
Speed	Less than synchronous speed	Motor run at synchronous speed
Starting torque	Has self-starting torque	No self-starting torque
Excitation	Single excited machine	Double excited machine
Efficiency	Less efficient	More efficient
Cost	Expensive	Cheap

2.1.2 Squirrel cage induction motor

Rotor core: closed slot either rectangular or circular shapes are equipped in the lamination (stamping). The shaft of the rotor is installed after stacking of laminations[7]. Due to the 'skew' added, the rotor bars are lightly willing to the shaft axis while stacking the rotor laminations. Skewing need to be done because:

a) It reduce locking tendency of the rotor.

b) It helps the motor run softly (quietly) by decreasing magnetic hum.

Stator winding: It is done on the stator core with the three phase stator winding. One starting and one finishing end for each phase winding. It is brought out for an interconnection in delta or star. Double layer lap windings is for medium sized machines and single layer mesh winding is used for smaller capacity machine. Large capacity motor used single layer concentric winding.

Rotor winding/cage: for slip ring motor, rotor winding is on the rotor cage and it is called the wound rotor motors[8]. The winding is usually connected in Y and the resultant three terminals are linked to the three slip rings that produce on one end of the shaft. The number of poles in the rotor is same as stator.

2.2 Control methods

A Variable Frequency Drive (VFD) is used to control the speed of three phase AC Induction motor. VFD are divided into two category, Scalar control and Vector control. Vector control consist of Field Oriented Control (FOC) and Direct Torque Current (DTC) technique.

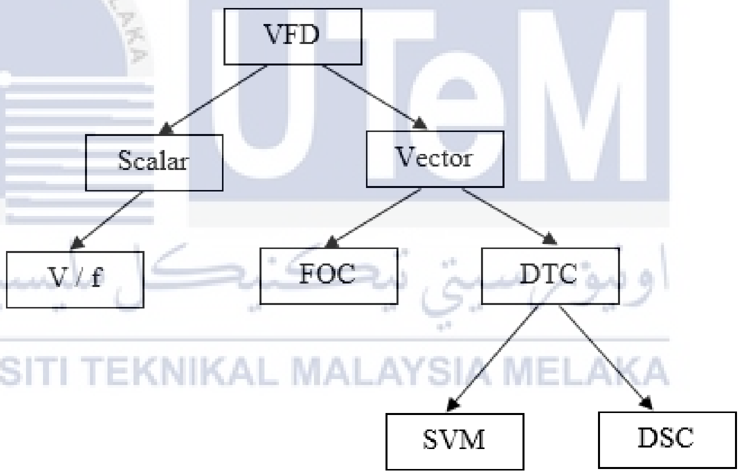


Figure 2.2: Overview of available control method

2.2.1 Scalar Control

In the motor speed range, voltage, current and frequency are constant. Scalar control is a technique to control the magnitude of the chosen control quantities followed the synchronous speed desired. The magnitude of voltage or the magnitude of current is altered to hold the ratio between the constant and frequency is set based on desired synchronous speed. There is no angles in the scalar control[9]. Open-loop control are the technique that without having feedback from the motor. The advantage of the technique is easy to implement with low desired on computational power.

One of the weaknesses is the instability of drive after certain applied frequency, to overcome the problem, the rotor is need to be implemented with the damper windings[3]. Furthermore, open-loop control method does not control the torque, so that the desired torque is only accessible at the nominal operating point. Different with the close-loop control method that the technique can control the torque. Close-loop control method consist of slip control loop because the slip is proportional to the torque.

2.2.2 Vector Control

One of the vector control that popular among the electrical machine is Field Oriented Control (FOC). There are also various type of methods such as Direct Torque Control (DTC) and direct self-control that work with the vector[10]. FOC is widely use in the industry because of the good and robust control in case of transient. To get a two-dimensional rotating reference frame (d-q) it required FOC to convert the reference frame from three dimensional stationary reference frame[11]. Component “d” is represent the flux while component “q” represent the torque. There are several type of switching pattern method that implement by using modulation technique such as PWM, SVPWM and Hysteresis current control. This method is apply at the separately excited DC motor and as the result, it produce excellent torque-speed curve. Under the control with the reference to a specific flux linkage space vector (rotor flux linkage, rotor flux linkage or magnetizing flux linkage), the transformation from the stationary reference to the rotating reference frame is possible.

Generally vector control can be divide into two categories, direct and indirect. Direct, will be using the Hall device to capture the flux measurement but as the result will be not accurate and the hardware cost will be increase[9]. Mostly, in electrical machine, Indirect vector control technique will be more preferred because the present of sensor the result of the flux angle will be more accurate. The method that usually use for estimating the rotor flux is slip relation. By using the methods the performance over the speed range is quite well. Some of the advantage of FOC are good torque response, accurate speed control, and full torque at zero speed. The disadvantage of the FOC is it will be more expensive as addition of feedback device and the modulator into the system. The reason of using FOC in this project is because induction motor advantage to DC machine with respect to size, weight, inertia, cost and speed. But, in the terms of control and the performance of the motor, DC machine is winner[8]. FOC responsible to transform the dynamics of induction motor to become similar DC motor.

2.2.3 Direct Torque Control (DTC)

The first model of DTC for induction motor is introduced by Takahashi and Noguchi [13] and Direct Self Control by Depenbrock [14]. This technique was characterized as simplicity, robustness and good performance. Unlike FOC, DTC worked without external measurement of rotor mechanical position. To ensure the right rotational direction, rotor position must be known at motor start up. For DTC, any current regulator is not required. DTC produced high torque ripple, high current, high noise level and difficult to control torque at low speed[12]. There are some suggestions on improving the characteristic of DTC, such as: Improving switching tables, using multilevel hysteresis comparators.

2.3 Pulse Width Modulation methods

Pulse-Width Modulation (PWM) is a modulation technique used to encode a massage into a pulsing signal. The average value of voltage and current fed to the load by turning the switch between supply and load on and off. The longer the switch is on compared to the off periods, the higher the total supply to the load.

2.3.1 Hysteresis current control

In the hysteresis current control method, the inverter output current is forced to follow current reference in each phase. There is limitation of upper and lower by the deviation between the two quantities. The leg of inverter will be switch off for the decreasing of current if the actual current reach upper limit of hysteresis band[13]. The current will drop until it reach the lower band and the inverter will quickly switch on again and the actual current will reach the upper band. Magnitude of ripple is determine by the gap wide between the upper band and the lower band. Hysteresis-current control advantages are low cost, fast transient, excellent dynamic response and easy to be implement. But, there are some weaknesses in this method such as there was a large current ripple at the steady state, variation of switching frequency and no intercommunication between each hysteresis controller of three phases[14].

2.3.2 Sinusoidal Pulse Width Modulation (SPWM) Three-Phase Inverter

SPWM modulation can be used for three phase inverter and single phase inverter. Basically the circuit of PWM three phase inverter is same with Six Step Inverter but SPWM requires a triangular waveform which is carrier signal and comparator [15]. The advantages of SPWM inverter are reduced filter requirement for harmonic reduction and controllability of the amplitude of the fundamental frequency[16]. The disadvantage are too many modulation index for reference and carrier and that SCRs are costly as they should carry low turn-on and turn-off times.

2.4 Speed Controller

2.4.1 PI controller

PI controller is the most common and widely used because of simple and practical which is produce an output signal that is proportional to the input signal. Moreover, PI controller enhance the steady state accuracy, relative stability and disturbance rejection. By using the PI controller, the sensitivity of the system and the parameters variations is minimizes. The two elements of the output signal that produce by PI controller that is one proportional input and one proportional integral of the input signal[17]. The weaknesses of this controller is the gain tuning, it required many trial and error process. It also reduce the steady state error. There is more than 95% control application that using PI type and widely use in the industry.

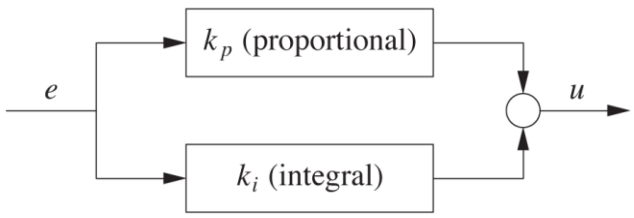


Figure 2.3: Block diagram for PI controller

2.4.2 Fuzzy Logic Controller

Fuzzy logic was introduced by Lotfi A. Zadeh, represent human-like logic. Fuzzy controller uses a mode of approximate reasoning resembling the conclusion, making path of user. The procedure apply to infer a decision about what they understand.

It has been firstly implement to the control of processes through a set of fuzzy linguistic if-then rules by membership functions[3]. Fuzzy logic is a superset of Boolean logic which has been continuing to manipulate the concept of partial truth-truth values between "completely false" and "completely true". In many motor control implementations, fuzzy logic has a growing interest due to its independence of modeling and non-linearity handling. Fuzzy logic duplicates human knowledge into control logic.

The essential characteristic of fuzzy logic is as follows:

- The exact mathematical model are not required.
- Any logical system can be fuzzified.
- Fuzzy constraint on a collection of variables and knowledge is interpreted as a collection of elastic.

Crisp variable: A physical variable that can be measured through equipment and can be assigned a discrete value, such as an output voltage of 10V, a temperature of 20°C etc.

Linguistic variable: To partition X into some fuzzy sets whose MFs cover X in a more or less uniform manner. These fuzzy sets mostly carry names that emerge in our daily linguistic usage, equally like "large", "medium", and "small", are labeled linguistic values. Universe of discourse X is called the linguistic variable.

The advantages of Fuzzy Logic Controller are high speed response and less overshoot[18]. Moreover, linear and nonlinear system can work effectively. It also can collaborate human intelligence in control algorithm. In addition, Linguistic variables operate in place of numerical variable and it simple to design. Any membership functions characterizes the fuzzy set. A blunt and convenient way to describe an MF is to set it as a mathematical function. In form to explain fuzzy membership function, programmer chooses many other shapes based on their know-how and preference. Membership functions [7] have different classes of parameter that are commonly used such as Triangular MFs, Trapezoidal MFs, Gaussian MFs and Generalized bell MFs.

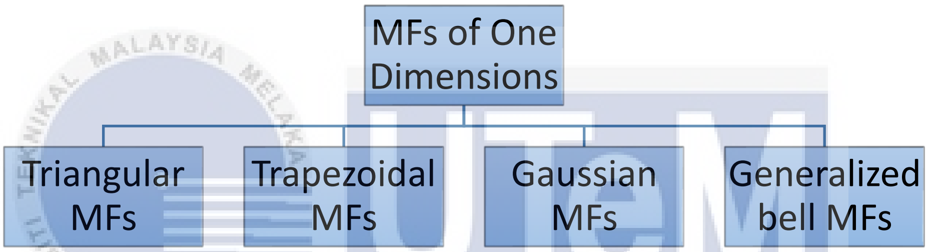


Figure 2.4: Diagram of membership function

The most favorite MFs used are triangular and trapezoidal because require low computation time and easy to represent the programmer’s idea. It also easy in calculations.

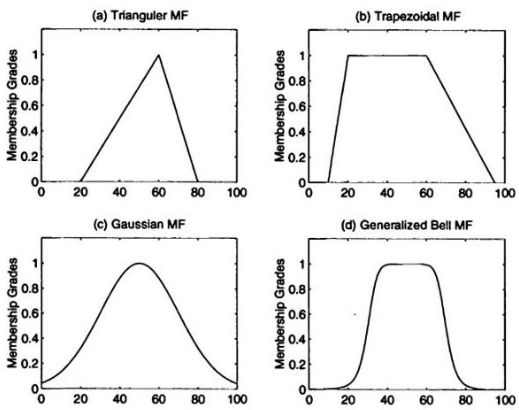


Figure 2.5: Example of four classes of MFs: (a) Triangle; (b) Trapezoid; (c) Gaussian; (d) Generalized bell.

The advantages of polygonal MFs are easy of modification parameters of MFs, need a small amount of data to define MF, and possibility of obtaining input. The disadvantages are that these functions much harder to identification and also not continuously differentiable.

CHAPTER 3

METHODOLOGY

3.1 Mathematical modeling of induction motor

Induction motor operation is built to acknowledge the dynamic behavior of FOC. The purpose of the equation is to get the d-q axis form of current by changing the state-space variable into space vector variable to denote the induction motor[19]. The stator voltage equation in stationary reference frame is shown as:

$$\overline{V}_s = \mathrm{R}_s\overline{I}_s + \frac{\mathrm{d}\overline{\varphi}_s}{\mathrm{dt}}$$

$$\overline{V}_r = R_r I_r + \frac{d\overline{\varphi}_r}{dt} - j\omega_r\overline{\varphi}_r$$

$$\overline{\varphi}_s = L_s\overline{I}_s + L_m\overline{I}_r$$

$$\overline{\varphi}_r = L_r\overline{I}_r + L_m\overline{I}_r$$

Sub (3) and (4) into (1) and (2):

$$\overline{V}_s = \mathrm{R}_s\overline{I}_s + \frac{d}{dt}L_s\overline{I}_s + \frac{d}{dt}L_m\overline{I}_r$$

$$\overline{V}_s = \mathrm{R}_s\overline{I}_s + \frac{d}{dt}L_s\overline{I}_s + \frac{d}{dt}L_m\overline{I}_r - j\omega_r(L_r\overline{I}_r + L_m\overline{I}_r)$$

The equation above are written into stator stationary reference frame. Where $\overline{V}_s, \overline{V}_r, \overline{I}_s, \overline{I}_r$ are the instantaneous value of voltage and current, while R_r and R_s are the resistance of rotor winding and resistance of stator winding. For flux linkages, $\overline{\varphi}_s$and $\overline{\varphi}_r$ are the stator and rotor space phasor flux linkages are defined in terms of motor inductance. Then, the equation (3) and (4) will be substitute into (1) and (2) to express equation (5) and (6) in order to set the equation of phase variable turn into state space in matrix by the terms of $\bar{x} = Ax + Bu$.

These equation (5) and (6) can be also be written into matrix form:

$$\begin{bmatrix} \overline{V}_s \\ \overline{V}_r \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix} - j\omega_r \begin{bmatrix} 0 & 0 \\ L_m & L_r \end{bmatrix} \begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix}$$

Rearrange equation (7) as follow:

$$\begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix} = \begin{bmatrix} -R_s & 0 \\ j\omega_r L_m & j\omega_r L_r - R_r \end{bmatrix} \begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix} + \begin{bmatrix} \overline{V}_s \\ \overline{V}_r \end{bmatrix}$$

Then applying inverse matrix to equation (8) to express equation (9) into state space form where stator and rotor current are sets as state variables:

$$\begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix} = \frac{1}{L_s L_r - {L_m}^2} \begin{bmatrix} -R_s & 0 \\ j\omega_r L_m & j\omega_r L_r - R_r \end{bmatrix} \begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix} + \begin{bmatrix} L_s & -L_m \\ -L_m & L_r \end{bmatrix} \begin{bmatrix} \overline{V}_s \\ \overline{V}_r \end{bmatrix}$$

$$\begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix} = \frac{1}{{L_m}^2 - L_s L_r} \begin{bmatrix} R_s L_r + j\omega_r {L_m}^2 & -R_r L_m + j\omega_r L_r L_m \\ -R_s L_m + j\omega_r L_m L_s & R_s L_s + j\omega_r L_r L_s \end{bmatrix} \begin{bmatrix} \overline{I}_s \\ \overline{I}_r \end{bmatrix} + \frac{1}{{L_m}^2 - L_s L_r} \begin{bmatrix} \overline{V}_s \\ \overline{V}_r \end{bmatrix}$$

The state space form equation (10) is converted to its equivalent d-q axis form (11):

$$\begin{bmatrix}\dot{i}_{sd}\\ \dot{i}_{sq}\\ \dot{i}_{rd}\\ \dot{i}_{rd}\end{bmatrix} = \frac{1}{{L_m}^2 - L_s L_r}\begin{bmatrix} R_s L_r & -\omega_r {L_m}^2 & -R_r L_m & -\omega_r L_r L_m \\ \omega_r {L_m}^2 & R_s L_r & \omega_r L_m L_r & -R_r L_m \\ -R_s L_m & \omega_r L_m L_s & R_r L_s & \omega_r L_r L_s \\ -\omega_r L_m L_s & -R_s L_m & -\omega_r L_r L_s & R_r L_s \end{bmatrix}\begin{bmatrix}\dot{i}_{sd}\\ \dot{i}_{sq}\\ \dot{i}_{rd}\\ \dot{i}_{rd}\end{bmatrix} + \frac{1}{{L_m}^2 - L_s L_r}\begin{bmatrix} -L_r & 0 \\ 0 & -L_r \\ L_m & 0 \\ 0 & L_m \end{bmatrix}\begin{bmatrix}\overline{V}_{sd}\\ \overline{V}_{rd}\end{bmatrix}$$

$\overline{x} = A_x + B_u$

Stator Flux Equations:

$$\varphi_{sd} = L_s i_{sd} + L_m i_{rd}$$

$$\varphi_{sq} = L_s i_{sq} + L_m i_{rq}$$

Rotor Flux equations:

$$\varphi_{rd} = L_m i_{sd} + L_r i_{rd}$$

$$\varphi_{rq} = L_m i_{sq} + L_r i_{rq}$$

Electrical and Mechanical torque equations:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left({\varphi_{rq}}^s . {i_{sq}}^s - {\varphi_{rd}}^s . {i_{sd}}^s\right)$$

$$T_e = J\frac{dw_m}{dt} + Bw_m + T_L$$

Where P, B, T_L and J denote the number of poles, friction, external load and inertia of IM.

There are more equation that involve of phase transformation of three phase voltage. The equation is to transform the three phase voltage to the two phase voltage in terms of a, b, and c phase into two phase direct and quadrant axis.

$$i_{sd} = \frac{2}{3} i_a - \frac{1}{3} i_b - \frac{1}{3} i_c$$

$$i_{sd} = \frac{2}{\sqrt{3}} (i_b - i_c)$$

3.2 Principle of indirect field oriented control

One of the vector control branch is FOC that control the stator current. FOC transform three phase into two phase which are direct and quadrant frame time invariant. These transformation lead a structure that similar to separately excited DC machine where flux and torque can directly control by their respective current producing element in order to gain high performance control of AC drive[20]. It popular due to its easy of control. Field flux produced by the current i_f perpendicular to the armature flux φ_a, which is produce by armature current i_a. There are the relationship of torque and flux to the current:

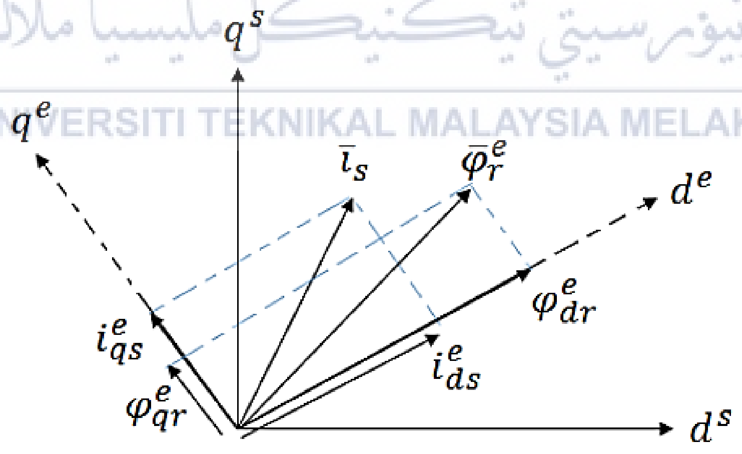


Figure 3.1: Diagram of q-d

$$T_e \propto i_{qs}^e$$

$$\varphi_r \propto i_{qs}^e$$

The rectangular coordinates, i_{ds}^{e} and i_{qs}^{e} , of $\bar{i}_s$ in a excitation frame attached to the rotor flux axis. The flux is proportional to direct current excitation reference frame while torque is propotional to the quadrant current.

3.2.1 Field orientation control

The excitation reference frame are oriented so that the d-q axis is aligned with the rotor flux vector $\bar{\varphi}_{r}^{e}$. If the excitation frame is locked to $\bar{\varphi}_{r}^{e}$ then:

$$\varphi_{qr}^{e} = 0$$

$$\frac{d\varphi_{qr}^{e}}{dt} = 0$$

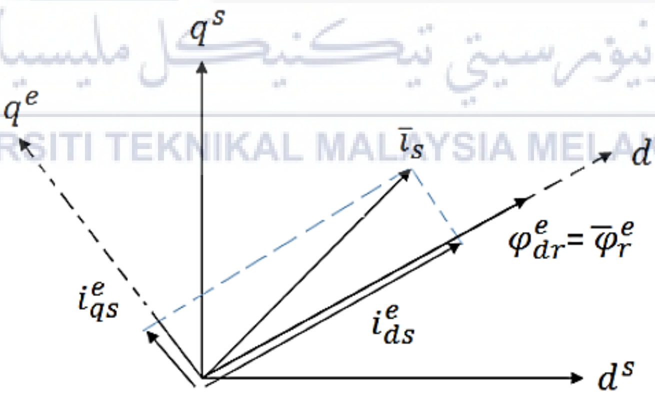


Figure 3.2: Magnitude and vector components on excitation frame

Simplify formula after substitution. Therefore:

$$\frac{d\varphi_{qr}^{e}}{dt} = -\frac{1}{T_r}\varphi_{dr}^{e} + \frac{L_m}{T_r}\ i_{ds}^{e}$$

$$(\omega_e - \omega_r)\varphi_{dr}^{e} = \frac{L_m}{T_r}\ i_{qs}^{e}$$

Apply the field orientation constraints at torque equation in term d and q components of stator current and rotor flux written in excitation frame:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(i_{qs}^{e}.\varphi_{dr}^{e})$$

The magnitude of the rotor flux φ_{dr}^{e} is controlled by i_{ds}^{e} at equation has a first order lag response. Since:

$$\frac{d\varphi_{qr}^{e}}{dt} = 0$$

$$\varphi_{dr}^{e} = L_m i_{ds}^{e}$$

The torque in equation is proportional to the product of φ_{dr}^{e} and i_{qs}^{e} as has been suggested earlier. The rotor flux is regulated with i_{ds}^{e} and the torque is a simple product of φ_{dr}^{e}andi_{qs}^{e}. If φ_{dr}^{e} is allowed to settle to a constant steady state value then T_e response is as fast asi_{qs}^{e}.

For field orientation, the angle θ_e must be known. Rearrange equation (27):

$$\omega_e = \omega_r + \frac{L_m}{T_r}\frac{i_{qs}^{e}}{\varphi_{dr}^{e}}$$

$\frac{d\theta_e}{dt} = \frac{d\theta_r}{dt} + \frac{L_m}{T_r}\frac{i_{qs}^{e}}{\varphi_{dr}^{e}}$, integrate respected to time

Thus,

$$\theta_e = \theta_r + \int \frac{L_m}{T_r} \frac{i_{qs}^e}{\varphi_{dr}^e} \, .\mathrm{dt} = \theta_f$$

By using the equation (33) can be used to find the position of the rotor flux θ_f. Can be obtain by:

1. Motor parameter L_m and T_r.
2. Rotor position θ_r that can be obtain from resolver.
3. Knowledge of φ_{dr}^e and i_{qs}^e.

3.2.2 Phase Transformation

Clarke transformation is use to simplify the analysis of three phase circuit. It does transform a magnitude from three phases into two orthogonal forms. This can be proof by using the vector diagram. From the diagram, each three phase components has offset to120°. Clarke transform convert the three phase current into two phase stationary reference frame current[21].

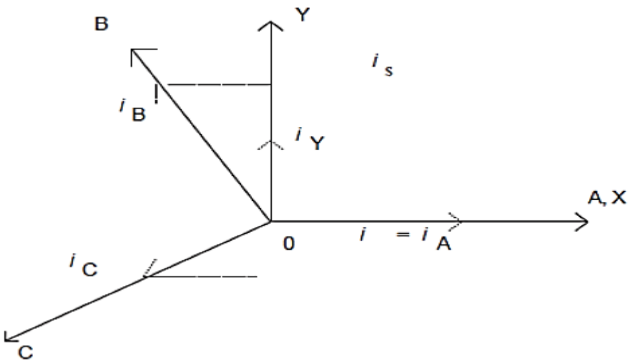


Figure3.3: Clarke Transformation

$$\begin{bmatrix} I_{sd}^{s} \\ I_{sq}^{s} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{2}{\sqrt{3}} & -\frac{2}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$I_{sd}^{s} = \frac{2}{3} i_a - \frac{1}{3}(i_b - i_c)$$

$$I_{sq}^{s} = \frac{2}{\sqrt{3}}(i_b - i_c)$$

Park transformation is a vector rotation that rotate at specified angle. Two phase frame calculated with Clarke transform then fed to a vector rotation block where it rotate over an angle to follow the two trigonometric calculation attached to rotor flux. Park transform convert two phase stationary frame into two phase excitation frame.

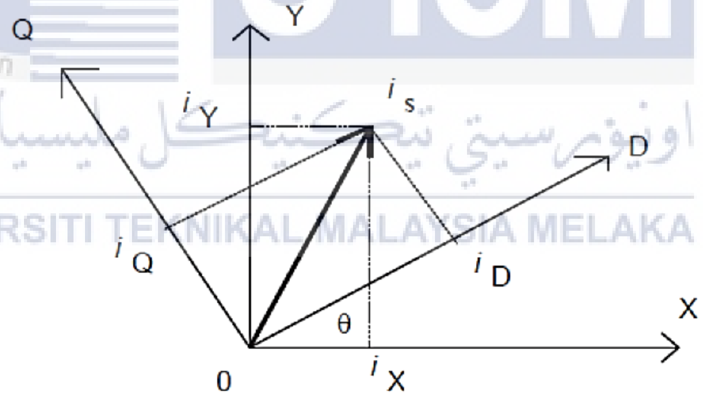


Figure 3.4: Park transformation

$$\begin{bmatrix} I_{sd}^{e} \\ I_{sq}^{e} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} I_{sd}^{s} \\ I_{sq}^{s} \end{bmatrix}$$

$$I_{sd}^{e} = I_{sd}^{s}\cos\theta_e + I_{sq}^{s}\sin\theta_e$$

$$I_{sq}^{e} = -I_{sd}^{s}\sin\theta_e + I_{sq}^{s}\cos\theta_e$$

3.3 Hysteresis current control

The basic implementation of hysteresis current is based on deriving the switching signals from the comparison of the current error with fixed tolerance band. To control three phase current, it can be done by applying 3 sets of 2 level hysteresis comparator. The use of hysteresis current controller is to make sure that the actual current flow in the circuit are same or close as possible to the reference current.

The bandwidth of the hysteresis current controller can be control that affected the current ripple. As the result of decrease the hysteresis bandwidth, the current ripple is reduced. However, it can cause switching frequency as well as switching losses increases[22]. To overcome the problem, the switching frequency should be increasing exceed to the limitation of switching device.

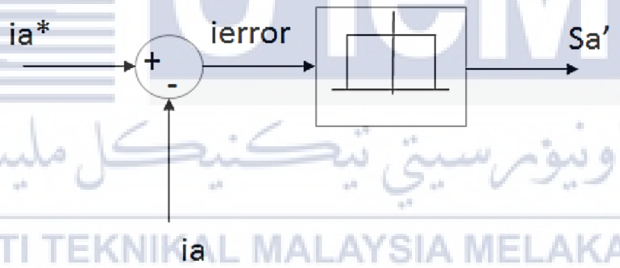


Figure3.5: Example of current control in a phase

The bandwidth of hysteresis is related to the peak to peak current ripple and the switching frequency. The relationship between the width of hysteresis and current ripple is when the width of hysteresis band is increases, the ripple current also increasing but the switching frequency will decreasing. While the width of hysteresis band is decreasing, the result of the waveform becomes better[22]. This is because there is low amount of harmonic content. To overcome the problem of unbalanced between harmonic ripple and the inverter switching loses, the width of hysteresis band selection must be carried out.

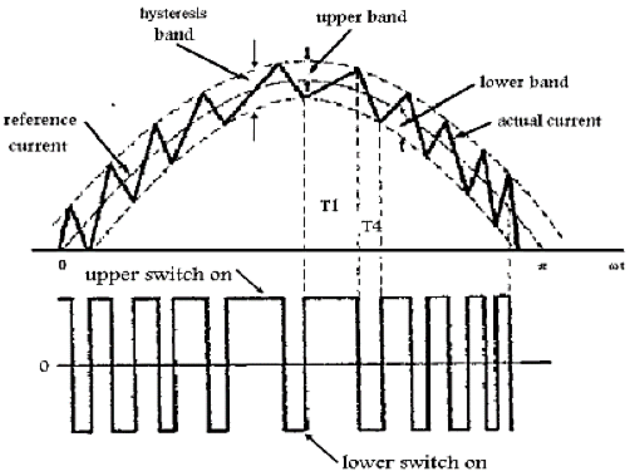


Figure 3.6: Hysteresis current band

3.4 Fuzzy Logic Controller Design

In the Fuzzy Logic, Membership Function (MF's) is one of the important parameters that the fuzzy logic depend on. MF's is important in the fuzzy logic because it almost cover overall part in fuzzy logic. The MF's setting should be neatly taken care because it overlap each other. the step must be done carefully in order to prevent any kind of interruption if any changes in the input. The membership function that near to the zero should be made narrow to get the best control system. Spacious membership functions away from zero produce faster response to the system[4]. Thus the rule base must be created after pick the relevant membership function. It will be decide the behavior of the system.

3.4.1 Fuzzy logic controller

The logical resemblance to human operator is the main reasons for the popularity of fuzzy logic controller. The different rule base that has been set by the user, it make the output or the result similar to the human logic[17]. The mathematical use in the fuzzy logic does not complex, thus make it simple from tee others. That knowledge is more focus on the qualitative so that the controller are simple to use and mere to the design.

3.4.2 Components of fuzzy logic controller

The fuzzy logic controller input are the mechanism with the support of linguistic variables which are represented with the backup of membership functions. The membership function is very important because its cover all the design result. To prevent the minor changes in the input, the all the component must work to getter to get the good result.

Three of the important components that helps the membership functions in the fuzzy logic controller:

1. Fuzzier or fuzzification block
2. Inference system
3. Defuzzifier or defuzzyfication

3.4.3 Fuzzifier or Fuzzification

In the design, the input that given to the fuzzy logic controller is in numeric form. Fuzzifier will transform the numerical number to the linguistic variable. Thus, the work can be continue. Another task that happen in fuzzifier is choosing the proper membership function for the variable.

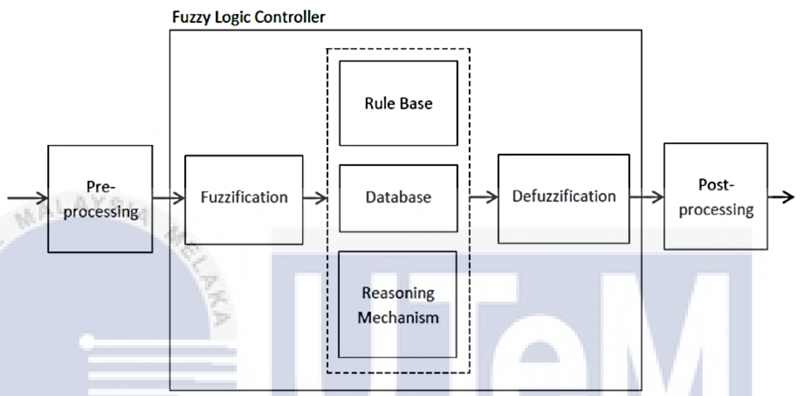


Figure 3.7: Fuzzy logic controller structure

3.4.4 Inference system

Consist of three paradigms that is rule base, data base and reasoning mechanism.

1. Rule base: -Consists of a number of If-Then rules. If side is called the antecedent and Then side is called the consequence. The process is almost similar to the human logical thinking and using the linguistic variable developed after fuzzification.
2. Data base: - Consists of all describe membership functions that are already to be used by the rule.

3. Reasoning mechanism: - Perform inference operation on the rules and data to produce a reasonable output. The code of the software which are developed the rules and the knowledge based on the appropriate situation.

3.4.5 Defuzzifier or defuzzification block

The function of the defuzzifier is to change the linguistic variable that has been finished process into crisp value. The crisp value can only be seized as inputs to the other system. A defuzziefier is commonly recommended only when the Mamdani fuzzy model for designing a controller.

Mamdani model is more likely use because it ensure the Compositional Rule of Inference in fuzzy reasoning mechanism. There are some different type of defuzzification technique admit for defuzzification.

3.4.6 Forming rule decision table

Fuzzy logic controller has different number of input. Inside all the input consist of membership function and rule. The rule is design to give the direction or command of the output. Therefore, the rule design is related to the input and output control. There are three different sets of fuzzy logic membership function, therefore there are three different fuzzy rule is develop to complete the fuzzy logic controller. The rules are develop using Mamdani-type fuzzy inference. Appropriated rules are interpreted based on the decision tables for the rule design using fuzzy Logic Tools MATLAB. The design of the fuzzy rule for the 9, 25 and 49 rules are set up follow in the table.

Table 3.1: Fuzzy rule (9)

E & Ve	NL	ZE	PL
NL	NL	NL	ZE
ZE	NL	ZE	PL
PL	ZE	PL	PL

Table 3.2: Fuzzy rule (25)

E & Ve	NL	NS	ZE	PS	PL
NL	NL	NL	PS	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NL	NS	NS	PS	PL
PS	NS	ZE	ZE	PS	PL
PL	ZE	PS	PS	PL	PL

Table 3.3: Fuzzy Rule (49)

E & Ve	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	ZE	PS	PM	NL	PL	PL	PL

3.4.7 Membership function design

The membership function in the fuzzy logic controller is divided into three section, error (e) , change of error (ve) and incremental output gain (cu). For this experiment, there are three type of membership function used which are 3, 5 and 9. All the shape and MFs applied for the input and output variable which is triangular and trapezoid membership function shape with normalized value of -1 to 1 domain. The shape of Membership Function are set to be equally overlapped between the next membership function to gain the best performance. The membership function is shown at figure below.

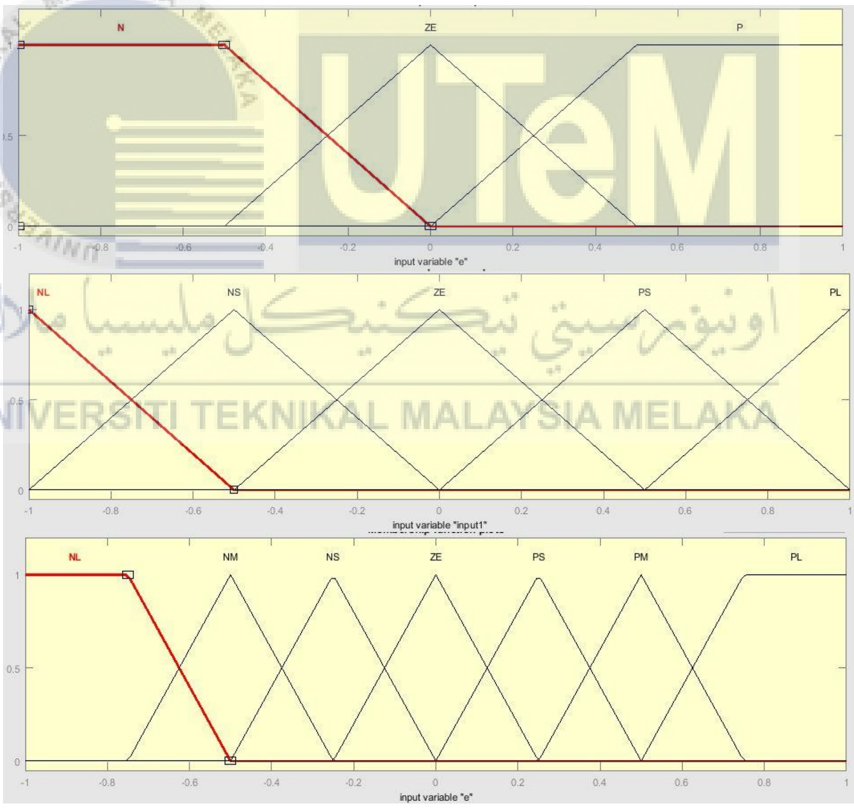


Figure 3.8: Membership function of Fuzzy logic

3.4.8 Design FLC using MATLAB

- To design Fuzzy Logic controller in MATLAB, firstly need to open FIS EDITOR.

  Open the command window of MATLAB, then type to open FIS editor.

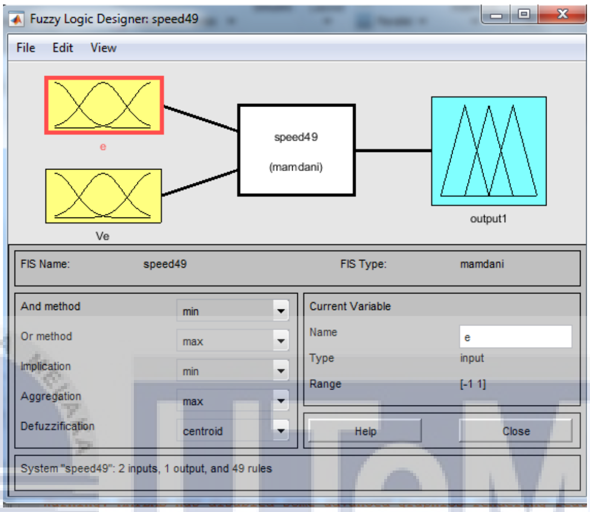


Figure 3.9: Fuzzy logic Fis editor

- The input variation can be created for E and CE. For input 1 change to error (e) and input 2 change to change of error (Ve).
- Next click edit to choose the membership function.

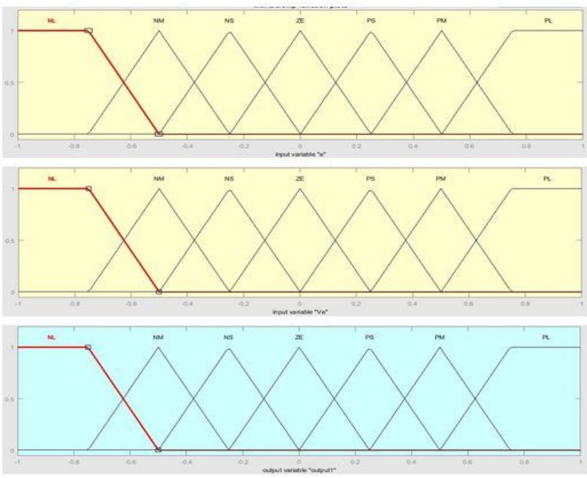


Figure 3.10: Membership function editor

- From the membership function able, change all the name at fuzzy sets for each input and output.
- Set the range for each fuzzy set.

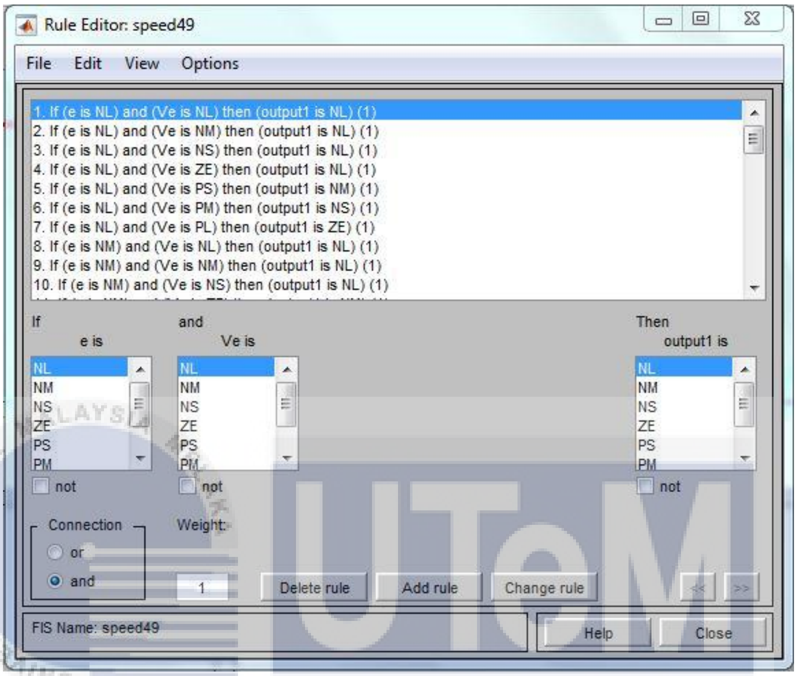


Figure 3.11: Rule viewer editor

- Develop the fuzzy rule for each fuzzy set.
- At FIS editor, it will show the rules and surface for input and output of the Fuzzy logic controller.
- From the surface viewer, it will show the surface following by its different rule. The higher the rule is, the smoother the surface will be.

•

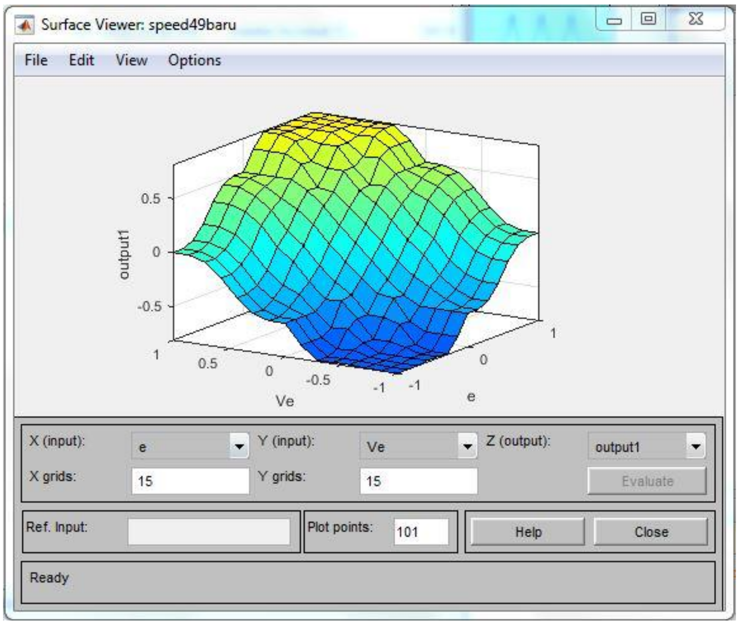


Figure 3.12: Dimensional plot of the surface

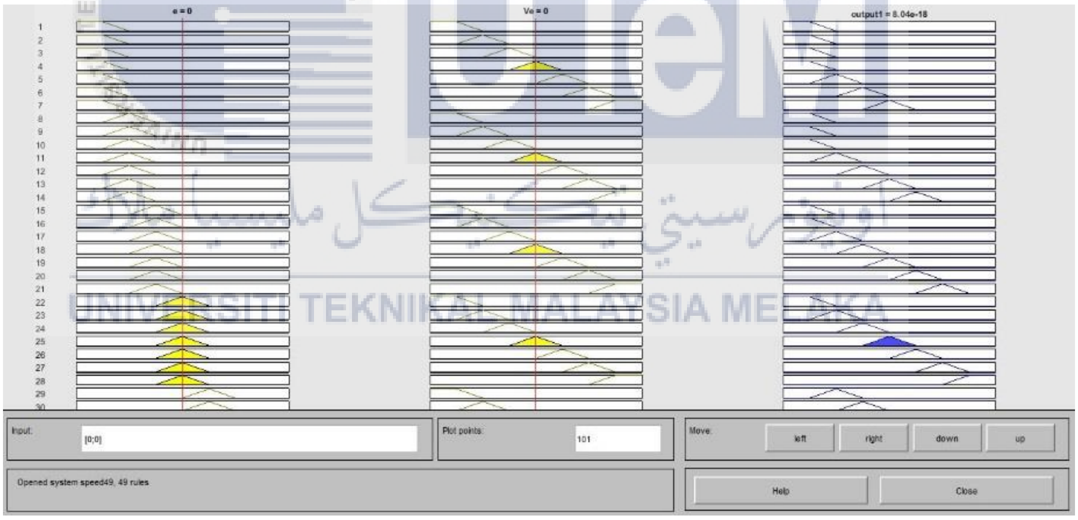


Figure 3.13: Rule viewer

3.5 Overall Schematic Diagram

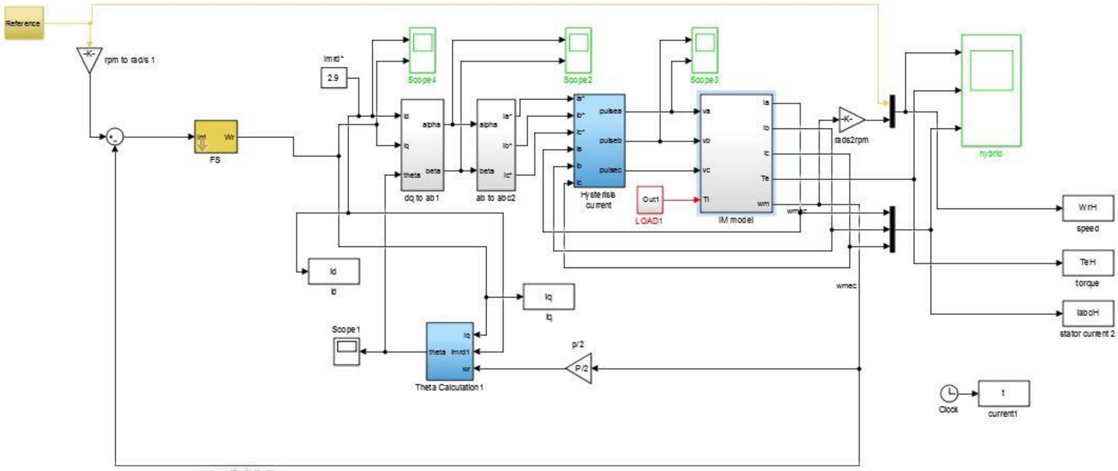


Figure 3.14: Indirect FOC induction motor drives of FLC schematic diagram

Fuzzy logic speed controller of an induction motor schematic diagram is shown in Figure 3.14. Vector control method is employed. The input of the vector control is speed, torque and reference current. In the FOC method, the stators currents are controlled which is represented by two orthogonal current component vector. This controls based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system. These projections lead to a structure similar to that of a DC machine control.

Field orientated controlled machines need two constants as input references: the torque current component (aligned with the co-ordinate) and the flux current component (aligned with d co-ordinate). As FOC is simply based on projections, the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient).

The block diagram presents the FOC of induction motor with hysteresis current control in which the system includes the induction motor model, inverter, phase transformations, theta calculation, hysteresis current controller and speed (FLC) controller.

The speed reference is compared with the actual speed produced from the motor. The error signal is fed into the fuzzy logic controller, which produced the torque current, iq reference. The iq and id currents component is converted into three phase current reference to be compared with actual three phase currents in the hysteresis current block and produce the control signals for the inverter.

CHAPTER 4

RESULT

4.0 Induction motor

From chapter 3 using previous research, the induction motor has been modelled. To study this model, the induction motor model is created in Simulink and the equation that has been mentioned is used. Figure 4.1 shows the block diagram of the induction motor with three phase input voltage (V_a, V_b and V_c). The speed of the induction motor (ω_m) and the output are three phase current (i_a, i_b and i_c).

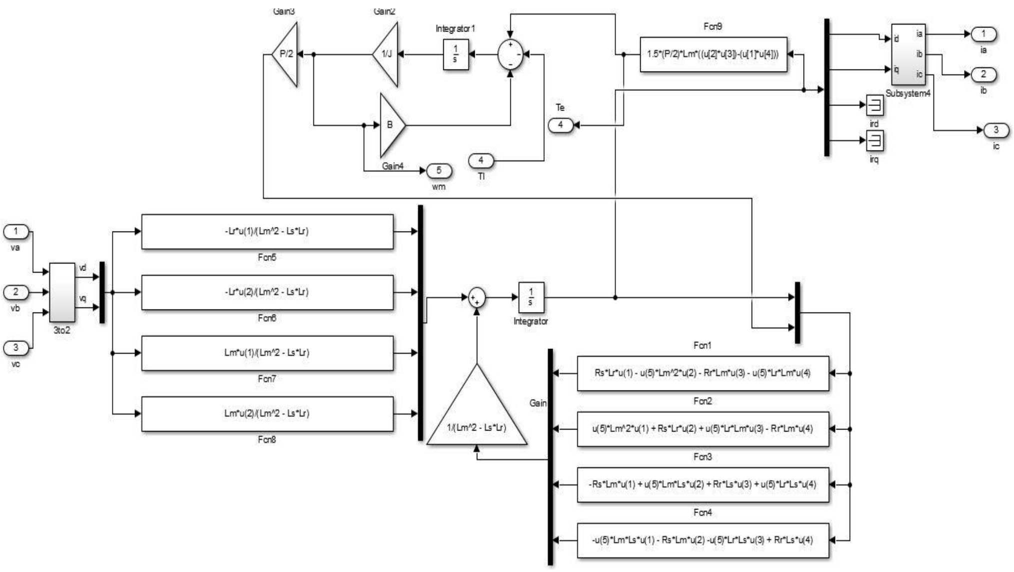


Figure 4.1: Block diagram for induction motor model

4.1 Indirect field oriented control of induction motor

For a learning purpose, the block diagram of indirect field oriented control of induction motor is designed in MATLAB/SIMULINK. The equation from chapter 3 for indirect FOC is implemented. Figure 4.2 shows the block diagram of indirect FOC of induction motor.

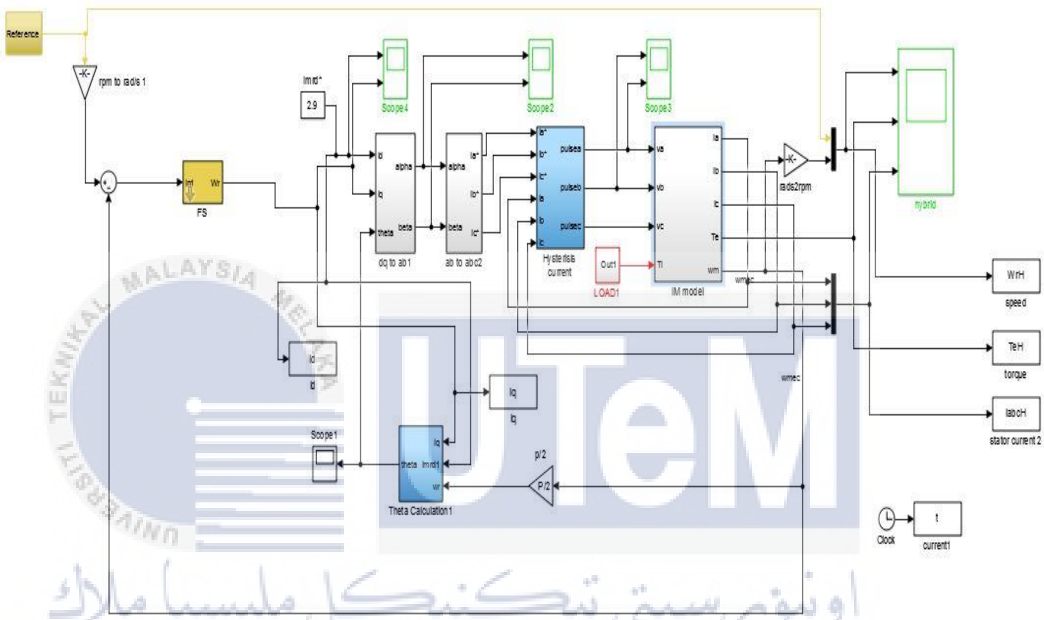


Figure 4.2: block diagram of indirect FOC of induction motor

For the hysteresis current control, the Figure 4.3 shows the hysteresis current control block diagram.

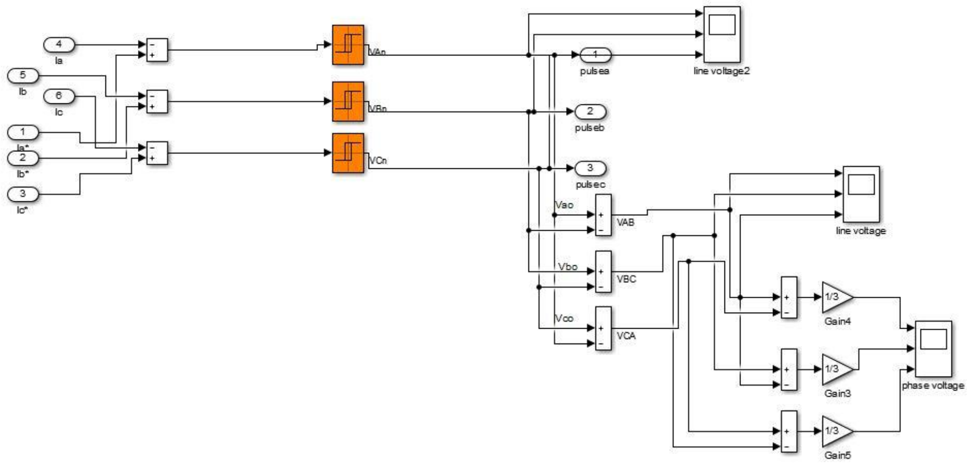


Figure 4.3: Block diagram for hysteresis current control

4.2 Fuzzy logic speed controller

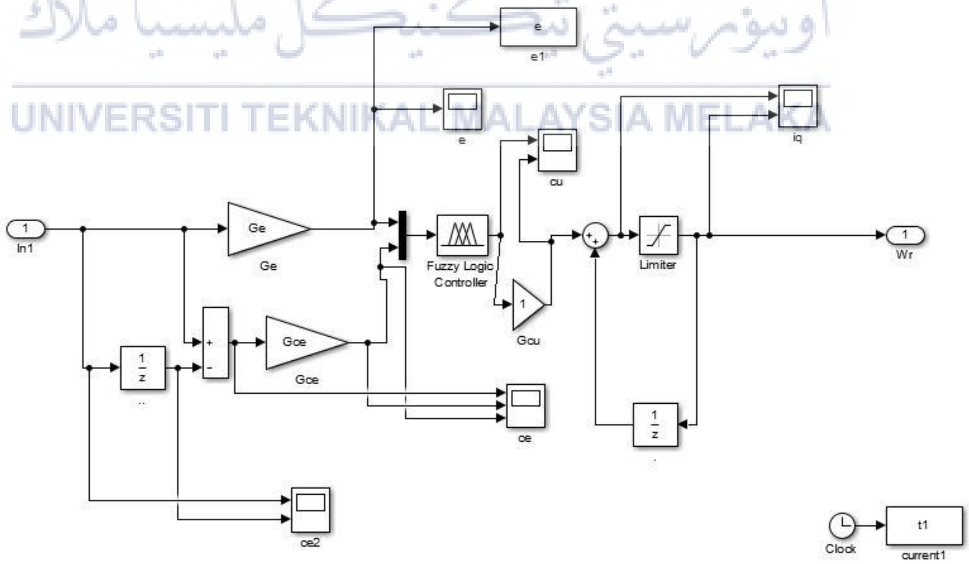


Figure 4.4: Block diagram of fuzzy logic tool box block diagram

4.3 Parameter setting for 49, 25 and 9 rules

Each of the membership function is set up following the parameter. Table 4.1 shows the parameter for set up the Fuzzy rule speed controller.

Table 4.1: 49, 25 and 9 FLSC rules parameter

Number of rules	Input membership function	Output membership function	Input scaling factors	Output scaling factors
49	Speed error -7 membership function (NL, NM, NS, ZE, PS, PM, PL) -50% symmetrical overlap Change of speed error -7 membership function (NL, NM, NS, ZE, PS, PM, PL) -50% symmetrical overlap	i_{sq} -7 membership function (NL, NM, NS, ZE, PS, PM, PL) -50% symmetrical overlap	$G_e = 0.00334$ $G_e = 1$	$G_{cu} = 1$

25	Speed error -5 membership function (NL, NS, ZE, PS, PL) -50% symmetrical overlap Change of speed error -5 membership function (NL, NS, ZE, PS, PL) -50% symmetrical overlap	i_{sq} -5 membership function (NL, NS, ZE, PS, PL) -50% symmetrical overlap	$G_e = 0.00334$ $G_e = 1$	$G_{cu} = 1$
9	Speed error -3 membership function (NL, ZE, P) -50% symmetrical overlap Change of speed error -3 membership function (NL, ZE, P) -50% symmetrical overlap	i_{sq} -3 membership function (NL, ZE, P) -50% symmetrical overlap	$G_e = 0.00334$ $G_e = 1$	$G_{cu} = 1$

4.3 Result and discussion

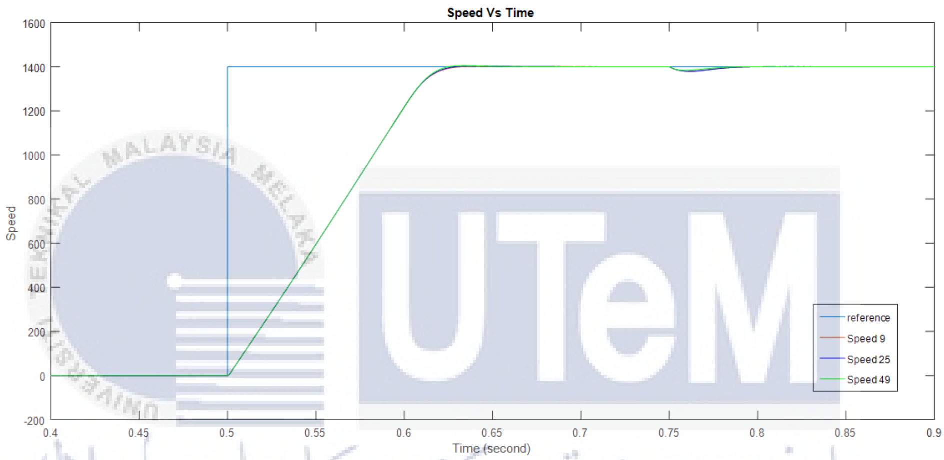
Based on fuzzy logic with indirect field oriented control induction motor drive, the study has been investigated which it will be stimulate with different change in command speed and step in load disturbance. The parameters of induction motor that will be used is shown in Table 4.2.

Table 4.2: Motor parameter and control system

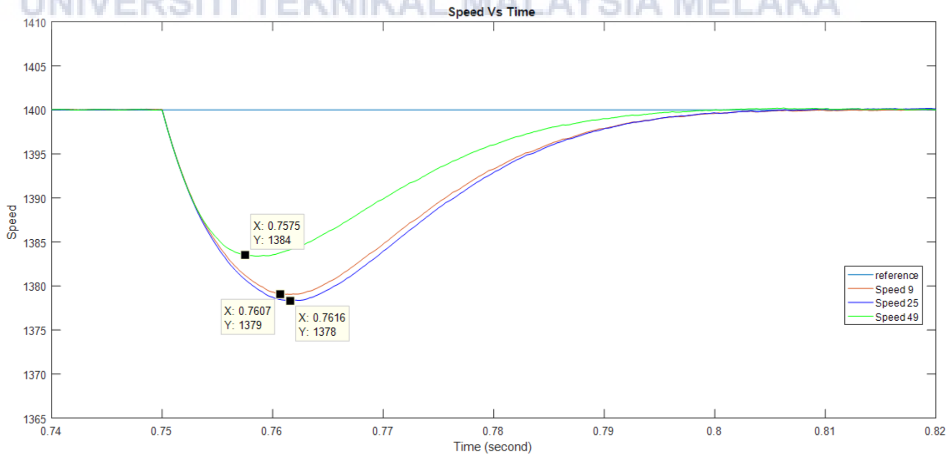
Parameters	**Value**
Rated speed, ω	1430 rpm
Rotor resistance, R_r	3.161Ω
Stator Resistance, R_s	3.45Ω
Stator self-inductance,L_s	0.3264 H
Rotor self-inductance, L_r	0.3252 H
Mutual inductance, L_m	0.3117 H
Number of pole, p	4
Number of pair poles, P	2
Moment of inertia, J	0.02 Kgm^2
Viscous friction, B	0.001 Nm/(rad/s)
DC voltage, , V_{dc}	537.4 V
Hysteresis band, HB	0.1

4.4.1 Performance comparison between 49, 25 and 9 FLSC

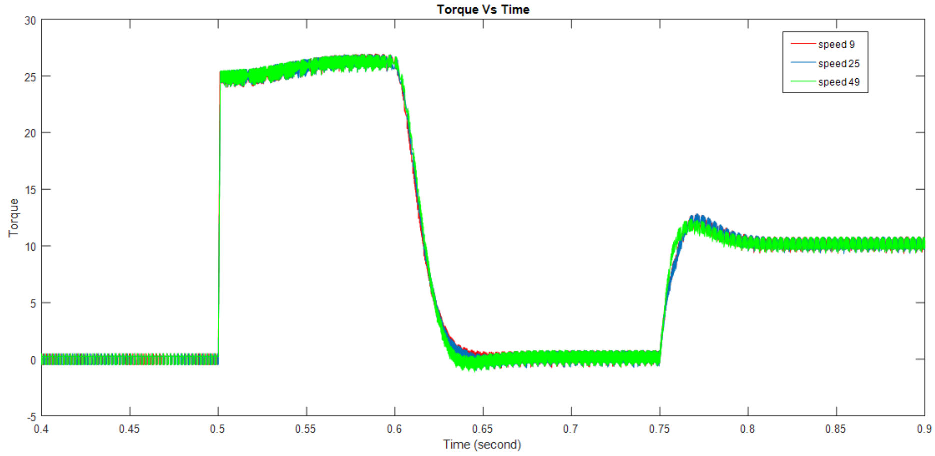
The speed performance of 9, 25 and 49 rules are investigated. The induction motor drive system is tested with load applied. The speed command test from standstill to a rated speed of 1400 rpm and with load applied of 10 Nm at t = 0.75 s. The speed response with load disturbance is shown as Figure 4.5. 9 rules obtain the slowest rise time and it improve when 25 rules is applied and the fastest rise time is 49 rules.



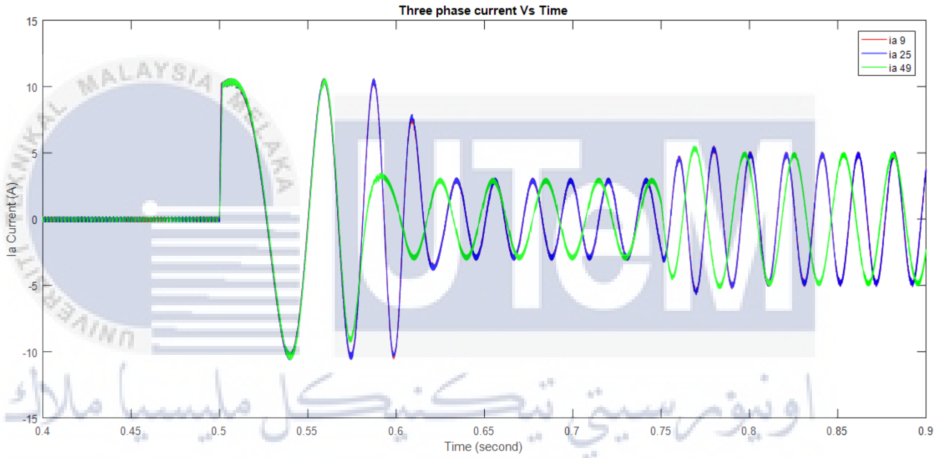
(a)



(b)



(c)



(d)

Figure 4.5: Speed response obtain for 49, 25 and 9 rules for rated speed 1400 rpm; (a) Overall response; (b) Closed-up view during load disturbance; (c) Torque and flux; (d) Overall three phase Current (ia)

Table 4.3: Forward operation at rated speed

Numbers of Rules	Overshoot (%)	Rise time (s)
49	0	0.0911
25	0	0.0912
9	0	0.0912

Table 4.4: Load disturbance during forward operation at rated speed.

Number of rule	Speed drop (rpm)	Recovery time (s)
49	17	0.0439
25	22	0.0485
9	21	0.0485

All the rule produce overshoot when operating. For the load rejection, the motor operated with rated torque at t=s as described in Figure 4.5 and Table 4.3 until Table 4.4. All the rules shown fast recovery time. 49 rules obtain the smallest speed drop among all three rules during the operation. However, 25 rules has obtained the highest undershoot but it settles almost the same with 9 rules. Lastly, 49 rules obtained the fastest rise time and the smallest speed drop.

With 49 rules obtained the optimum performance, it related with the membership functions. For better understanding, the relationship between fuzzy set and speed error were observed.

There are seven fuzzy sets which are:

i. Fuzzy set ZE covered the ranges of ±0.25

ii. Fuzzy set PS covered the ranges between 0.0 and 0.5

iii. Fuzzy set PM covered the ranges between 0.25 and 0.75

iv. Fuzzy set PL covered the ranges between 0.5 and 1.0

v. Fuzzy set NS covered the ranges between -0.5 and 0.0

vi. Fuzzy set NM covered the ranges between -0.75 and -0.25

vii. Fuzzy set NL covered the ranges between -1.0 and -0.5

When the motor starts to accelerate, the speed error which activates the fuzzy set PS. Then, the fuzzy set ZE is activated when the response reaches the steady state. In order to obtain the stability, the fuzzy set ZE remains activated. During the load torque application, the speed error activates fuzzy set PS for a while until the system is stable. Therefore, the speed error activates the fuzzy sets of PS and ZE.

The fuzzy set NL is activated when the motor starts to decelerate from the steady state. Then, fuzzy set NS is activated followed by the fuzzy set ZE when the motor settled down. Hence, the fuzzy sets of NL, NS and ZE are activated by the speed error. Meanwhile, the fuzzy sets of NS, ZE and PS remain activated by the change of speed error, to obtain the stability of the system.

Figure 4.6 until Figure 4.8 shows waveform of three phase current (ia, ib, and ic) and the torque for 49, 25 and 9 rules with rated speed of 1400 rpm and 0.1 hysteresis band. As we know, equation (20) and (21) from chapter 3 is proved that flux, φr is proportional to id and torque (Te) is proportional to iq. The two phase current $\alpha\beta$ are the components produced that known as inverse Park transformation, while three phase current is produced from two to three transformation which is call as inverse Clarke transformation.

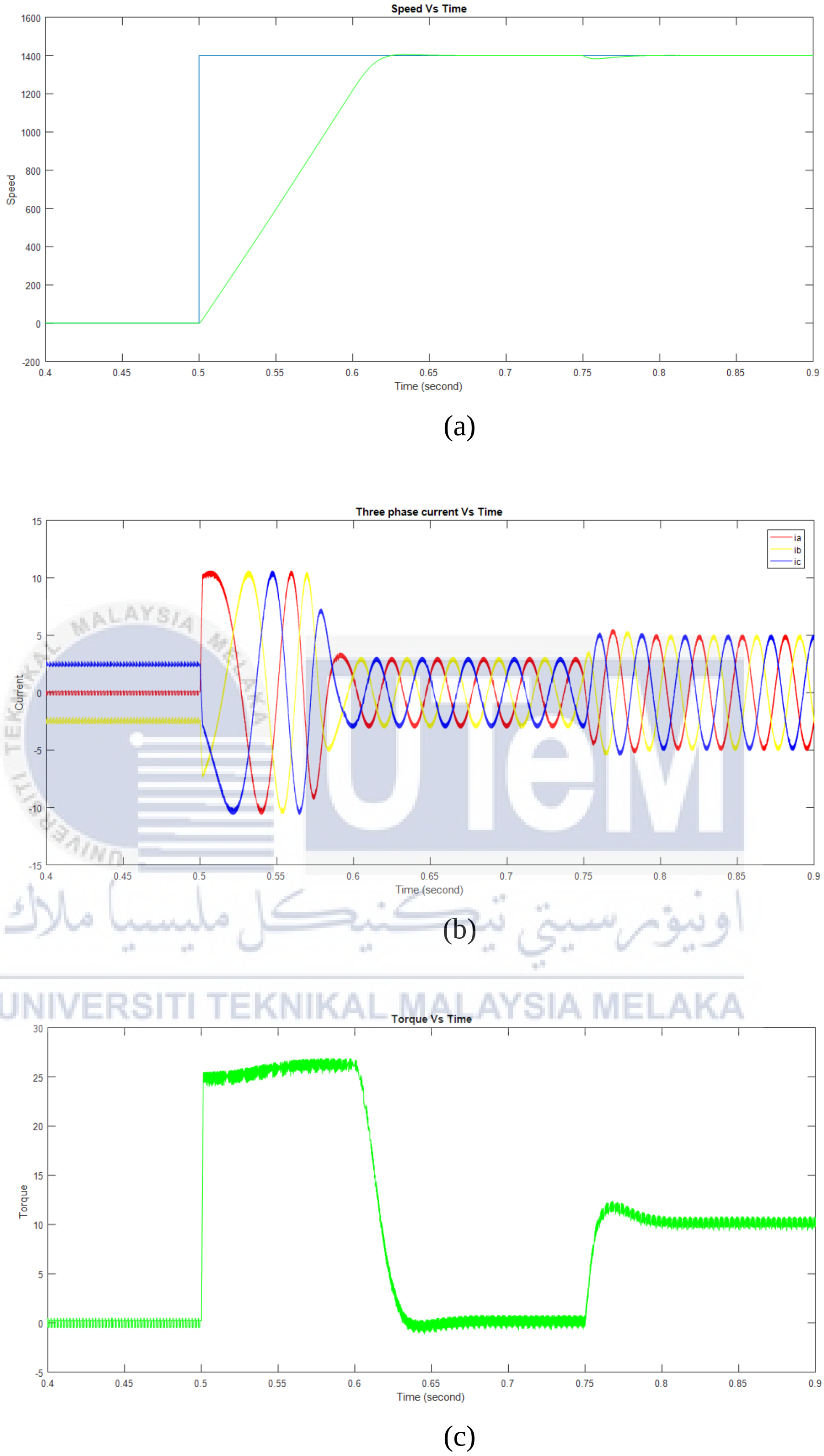
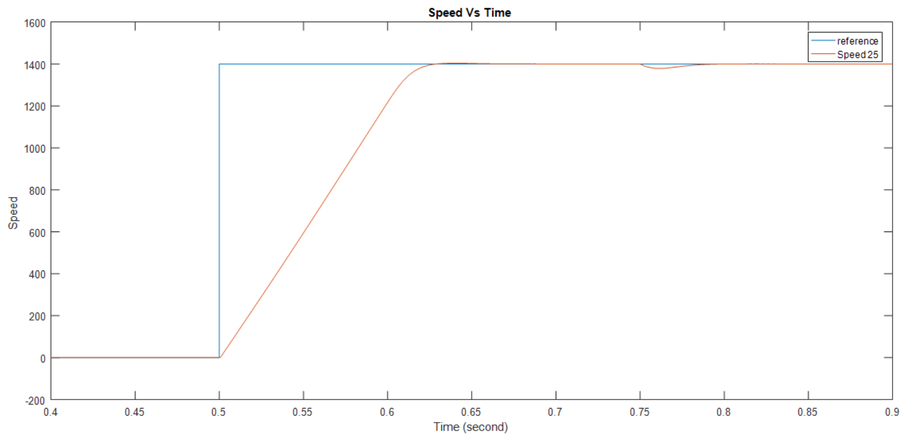
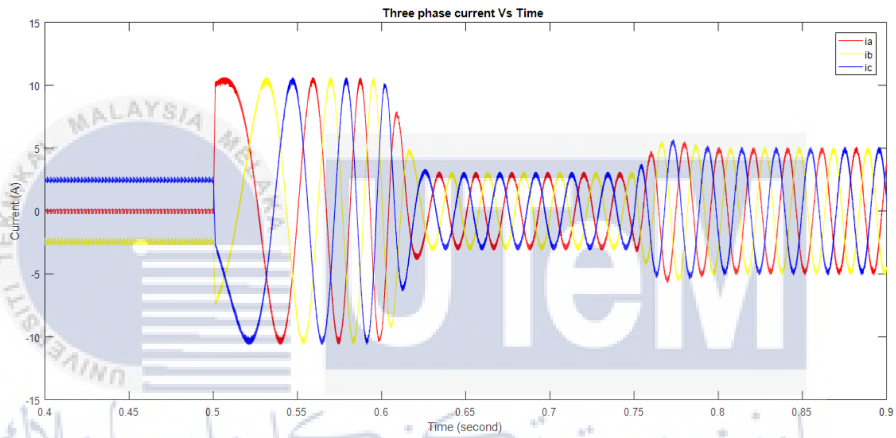


Figure 4.6: Speed response obtain for 49 rule based; (a) Speed response;(b) Three phase current; (c) Torque



(a)



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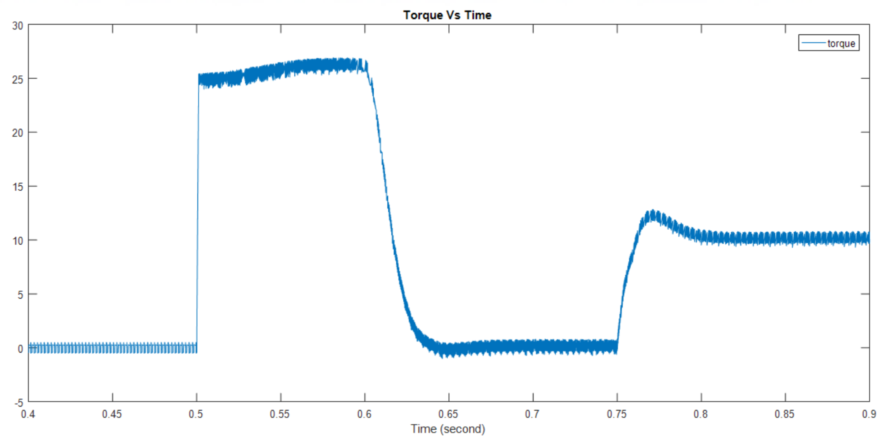
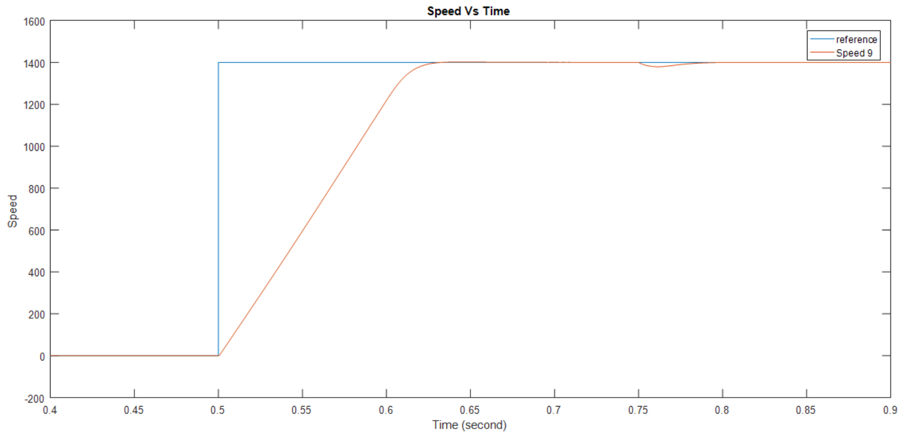
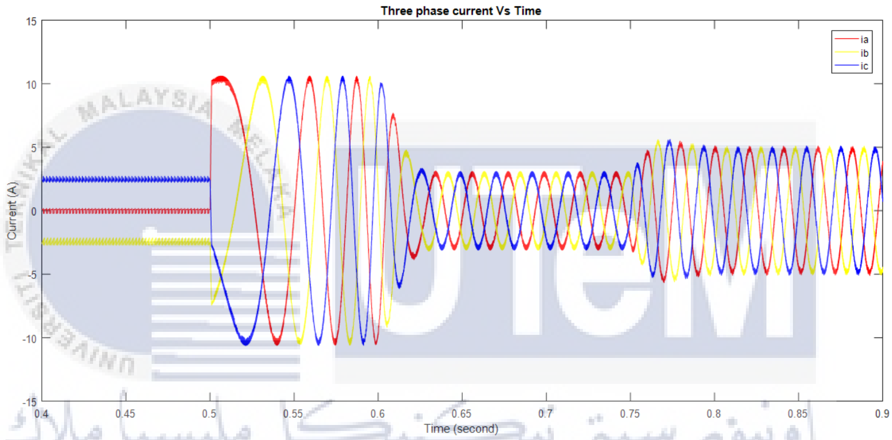


(c)

Figure 4.7: Speed response obtain for 25 rule based; (a) Speed response;(b) Three phase current; (c) Torque



(a)



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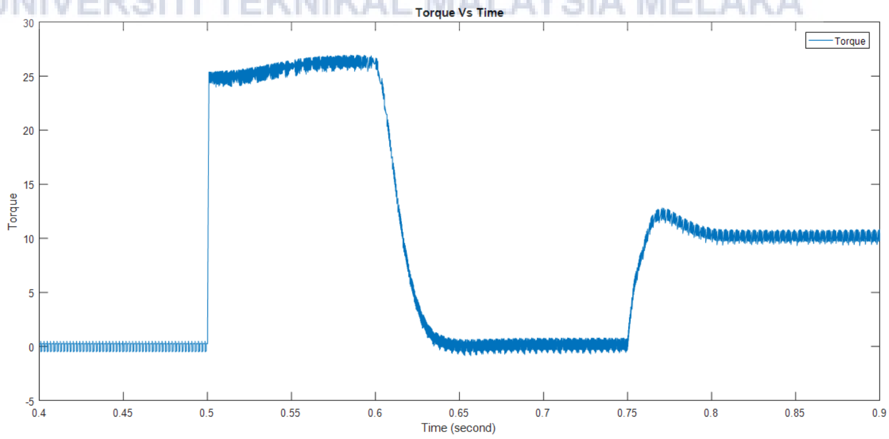
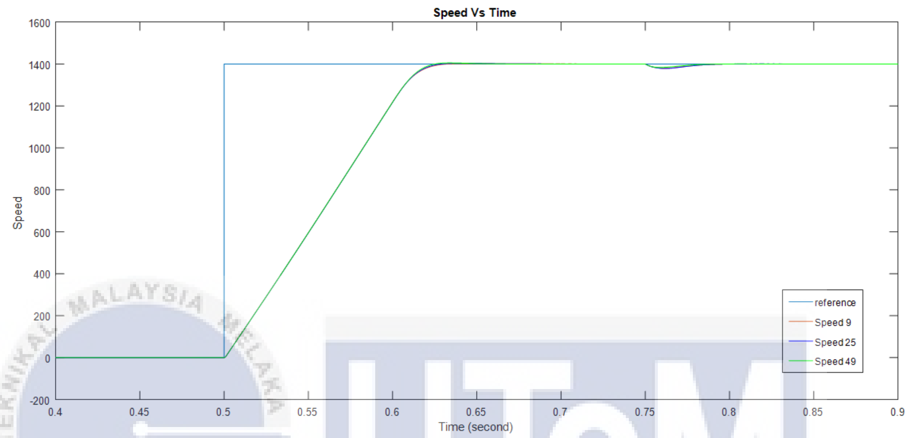


(c)

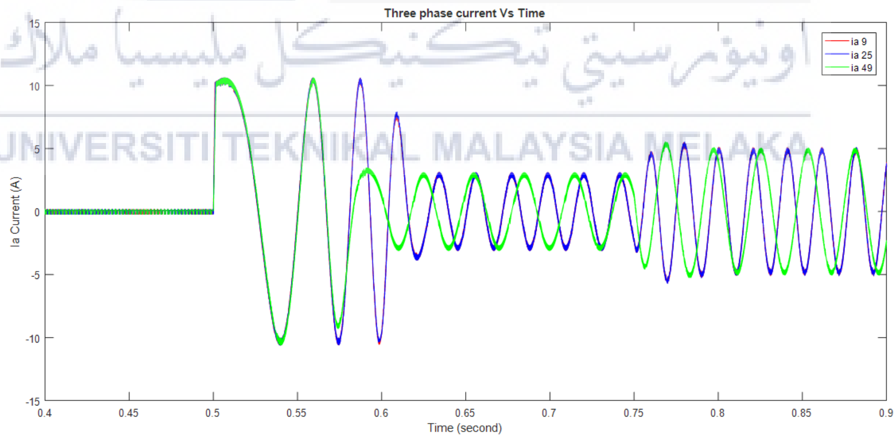
Figure 4.8: Speed response obtain for 9 rule based; (a) Speed response; (b) Three phase current; (c) Torque

4.4.2 Differential initial performance

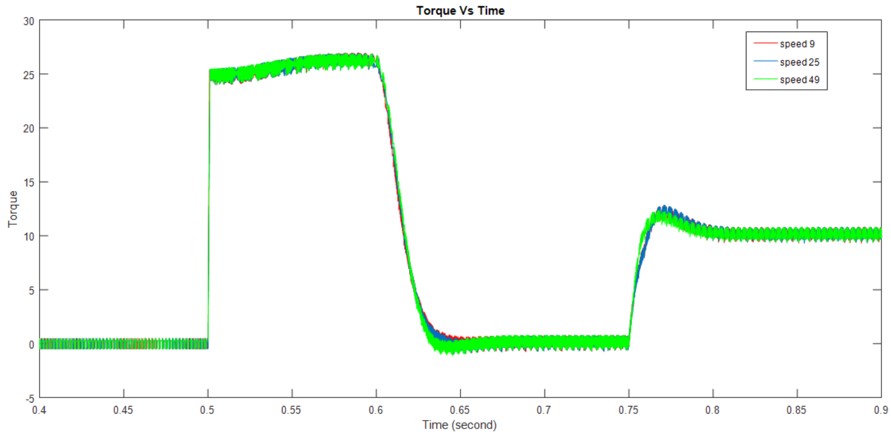
From Figure 4.9 until Figure 4.11 and Table 4.5 until Table 4.10 describe that all three rules obtain performance at transient state with load disturbance 10Nm at t=0.75 with changes in speed command. From rated speed 1400 rpm, it changes to 1000 rpm and 500 rpm.



(a)



(b)



(c)

Figure 4.9: Rated speed response of 1400rpm for 49, 25 and 9 rules with load disturbance 10Nm at t= 0.75; (a) Speed response; (b) Ia Three phase current; (c) Torque

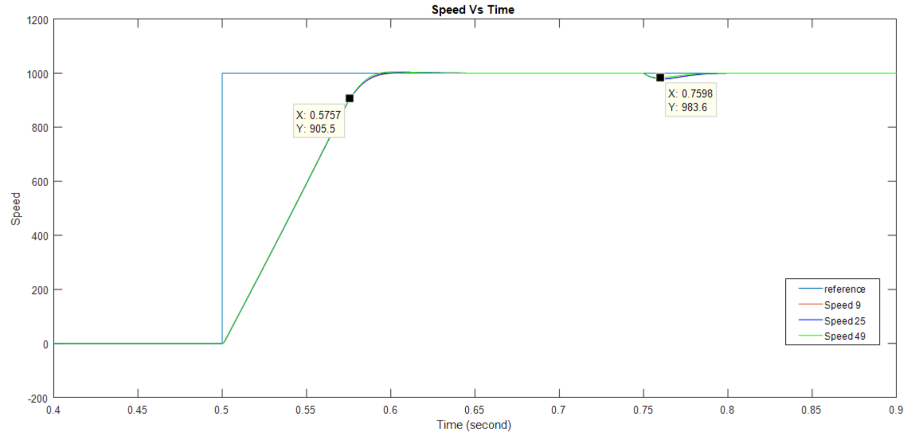
. Table 4.5: Forward operation at rated speed

Numbers of Rules	Overshoot (%)	Rise time (s)	Settling time (s)
49	0	0.0911	0.0911
25	0	0.0912	0.0912
9	0	0.0912	0.0912

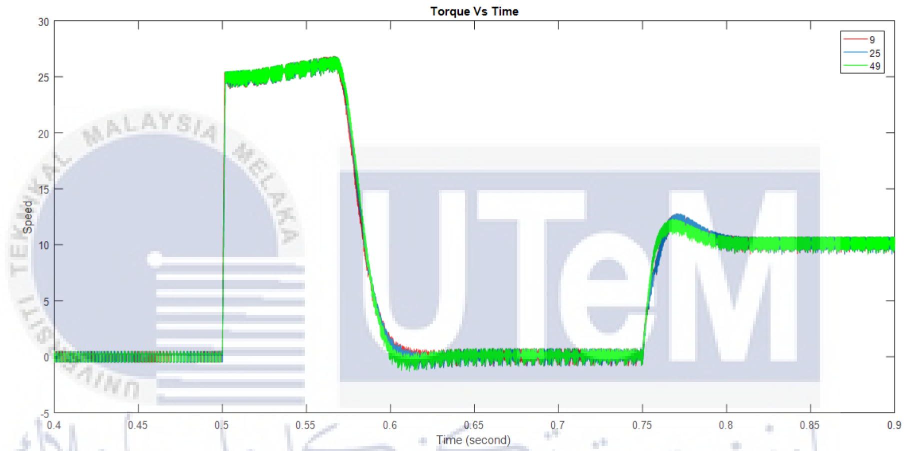
Table 4.6: Load disturbance during forward operation at rated speed

Number of rule	Speed drop (rpm)	Recovery time (s)
49	17	0.0439
25	22	0.0485
9	21	0.0485

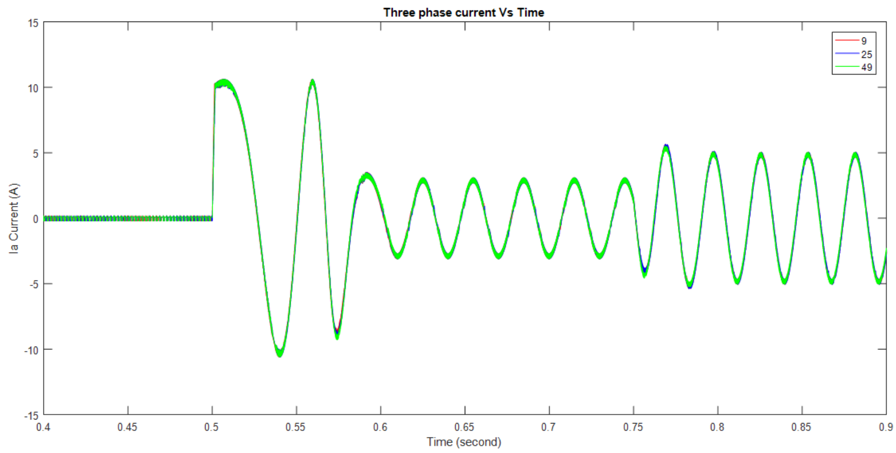
As mention above, all the rule does not produce overshoot when operating. All the rules shown fast recovery time. 49 rules obtain the smallest speed drop among all three rules during the operation. However, 25 rules has obtained the highest undershoot but it settles almost the same with 9 rules


Speed Vs Time
Speed
Time (second)
X: 0.5757
Y: 905.5
X: 0.7598
Y: 983.6
reference
Speed 9
Speed 25
Speed 49

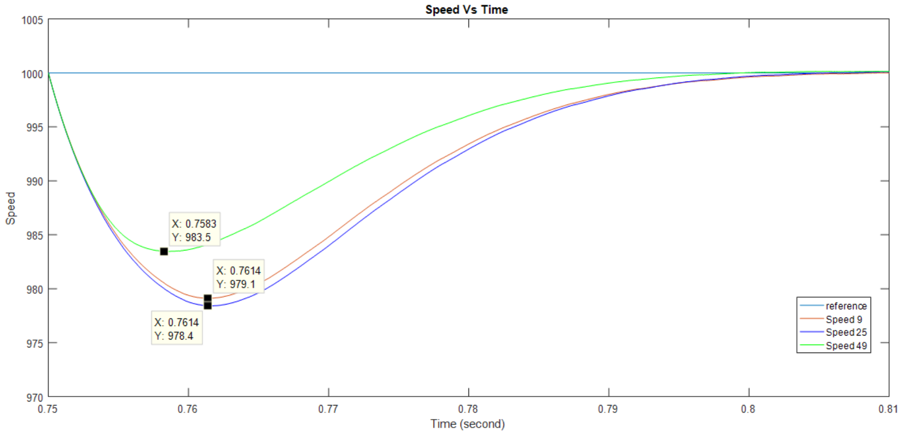
(a)


Torque Vs Time
Speed
Time (second)
9
25
49

(b)


Three phase current Vs Time
Ia Current (A)
Time (second)
9
25
49

(c)



(d)

Figure 4.10: Rated speed response of 100rpm for 49, 25 and 9 rules with load disturbance 10Nm at t= 0.75; ; (a) Speed response; (b) Torque ; (c) Ia Three phase current; (d) Closed-view load disturbance

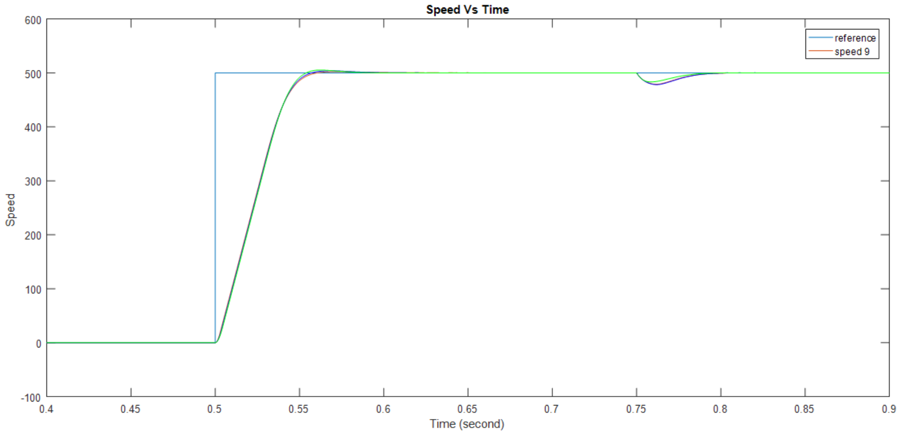
. Table 4.7: Forward operation at rated speed

Numbers of Rules	Overshoot (%)	Rise time (s)	Settling time (s)
49	0.5	0.1300	0.0661
25	0.3	0.1357	0.0662
9	0.2	0.1384	0.0662

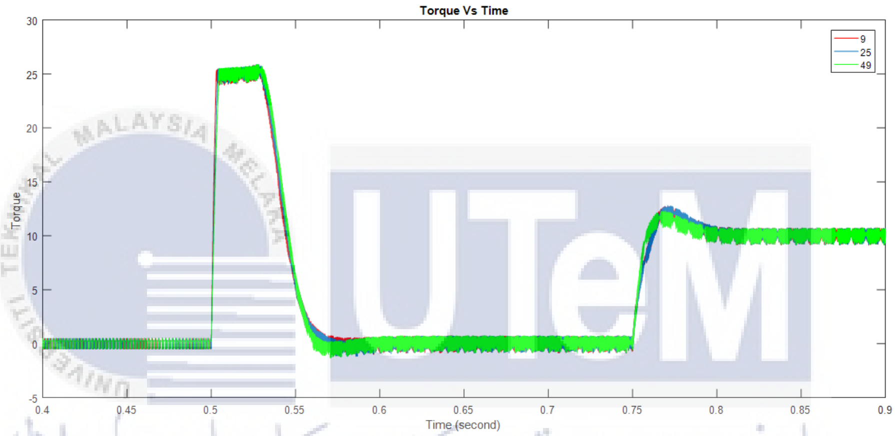
Table 4.8: Load disturbance during forward operation at rated speed

Number of rule	Speed drop (rpm)	Recovery time (s)
49	17	0.0491
25	22	0.0574
9	21	0.0598

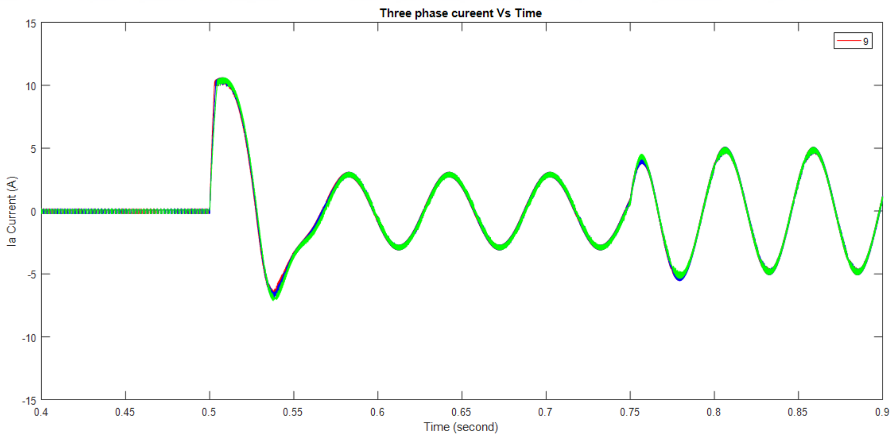
All the rule produce overshoot when operating. For the load rejection, the motor operated with rated torque at t=0.75s. The result show that 49 rule has the less overshoot follow by the 25 rules and lastly 9 rules. All the rules shown fast recovery time. 49 rules obtain the smallest speed drop while 25 rules has obtained the highest undershoot but it settles almost the same with 9 rules.


Speed Vs Time
reference
speed 9
Speed
Time (second)

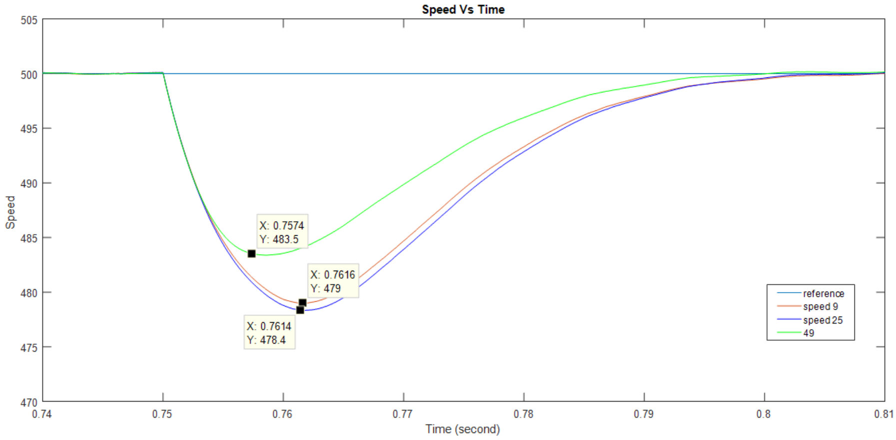
(a)


Torque Vs Time
9
25
49
Torque
Time (second)

(b)


Three phase cureent Vs Time
9
Ia Current (A)
Time (second)

(c)



(d)

Figure 4.11: Rated speed response of 500rpm for 49, 25 and 9 rules with load disturbance 10Nm at t= 0.75; (a) Speed response; (b) Torque ; (c) Ia Three phase current; (d) Closed-view load disturbance

. Table 4.9: Forward operation at rated speed

Numbers of Rules	Overshoot (%)	Rise time (s)	Settling time (s)
49	0.5	0.1081	0.0353
25	0.3	0.1170	0.0358
9	0.2	0.1201	0.0362

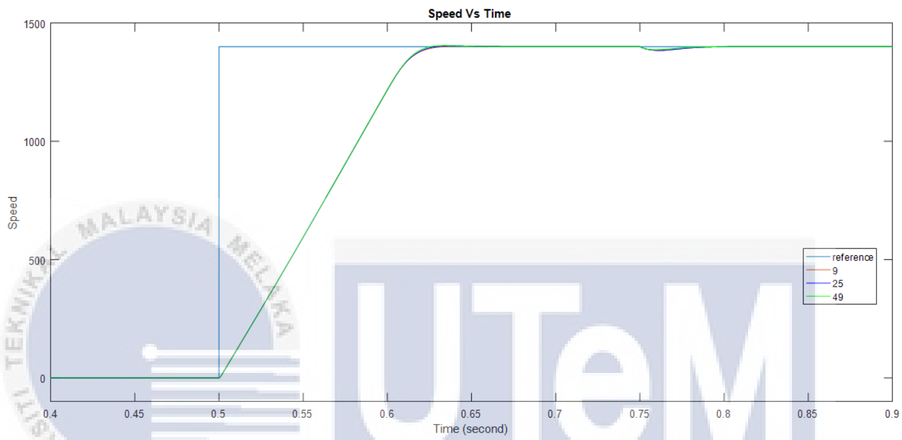
Table 4.10: Load disturbance during forward operation at rated speed

Number of rule	Speed drop (rpm)	Recovery time (s)
49	17	0.0505
25	22	0.0576
9	21	0.0587

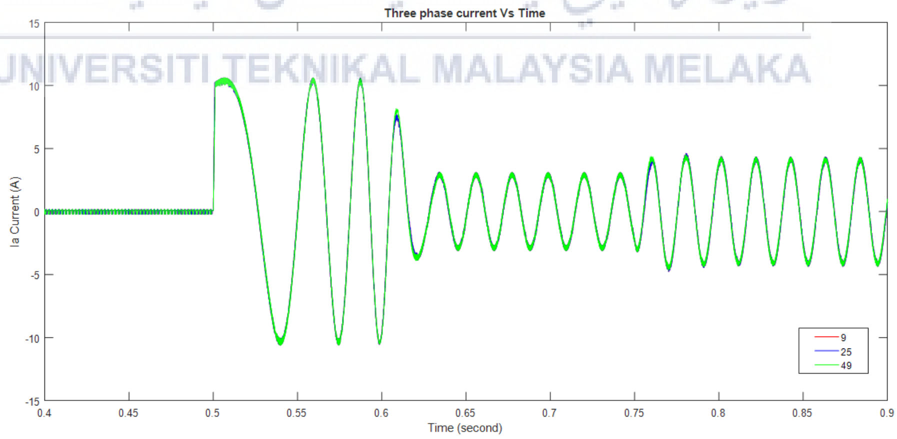
All the rule produce overshoot when operating. For the load rejection, the motor operated with rated torque at t=0.75s. The result show that all the rule has same settling time and slightly difference at rise time. All the rules shown fast recovery time. 49 rules obtain the smallest speed drop while 25 rules has obtained the highest undershoot but it settles almost the same with 9 rules.

4.4.3 Different initial load with rated speed 1400rpm

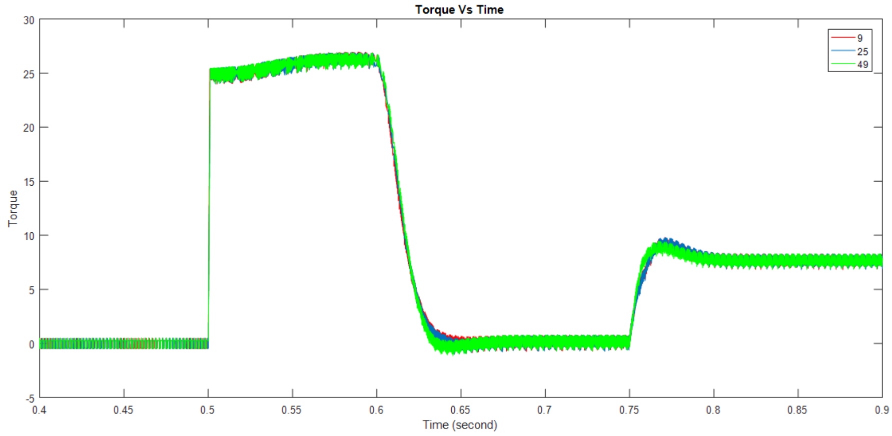
From Figure 4.12 until Figure 4.13 and Table 4.11 until Table 4.14 describe that all three rules obtain performance at transient state with rated speed response 1400 rpm and the changes in load disturbance. From rated load disturbance 10Nm at t=0.75 change to 7.5Nm and 5Nm at rated speed 1400 rpm.



(a)



(b)



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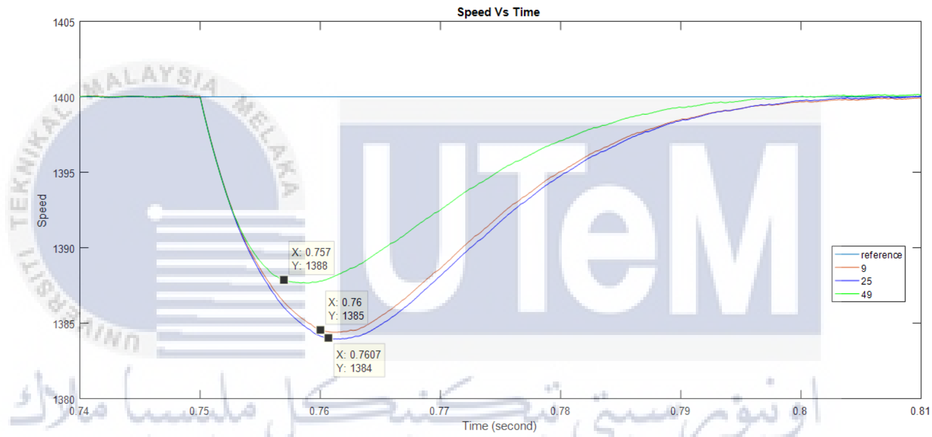


(d)

Figure 4.12: Rated speed response of 1400 rpm for 49, 25 and 9 rules with load disturbance 7.5 Nm at t= 0.75; (a) Speed response; (b) Ia Three phase current; (c) Torque; (d) Closed-view load disturbance

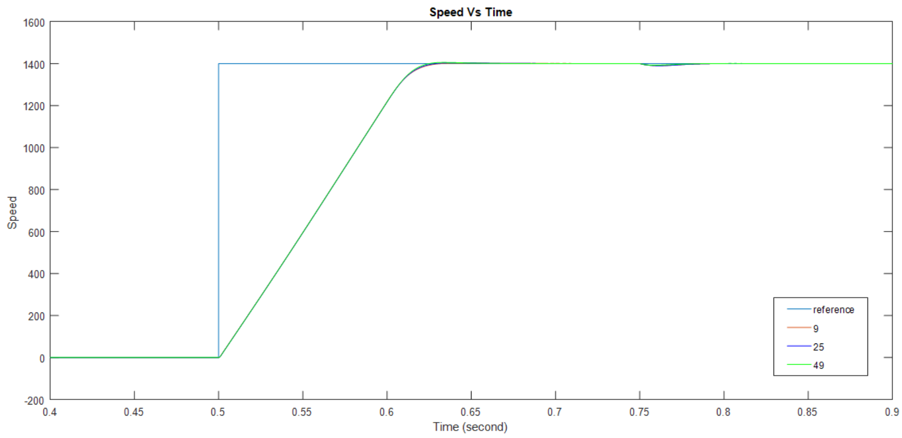
Table 4.11: Forward operation at rated speed

Numbers of Rules	Overshoot (%)	Rise time (s)	Settling time (s)
49	0.5	0.1606	0.0912
25	0.3	0.1694	0.0912
9	0.2	0.1706	0.0912

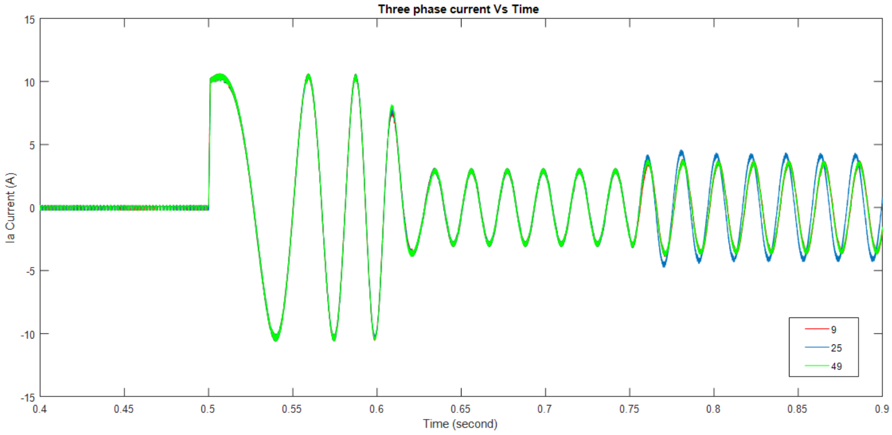
Table 4.12: Load disturbance during forward operation at rated speed

Number of rule	Speed drop (rpm)	Recovery time (s)
49	12	0.0418
25	16	0.0483
9	16	0.0483

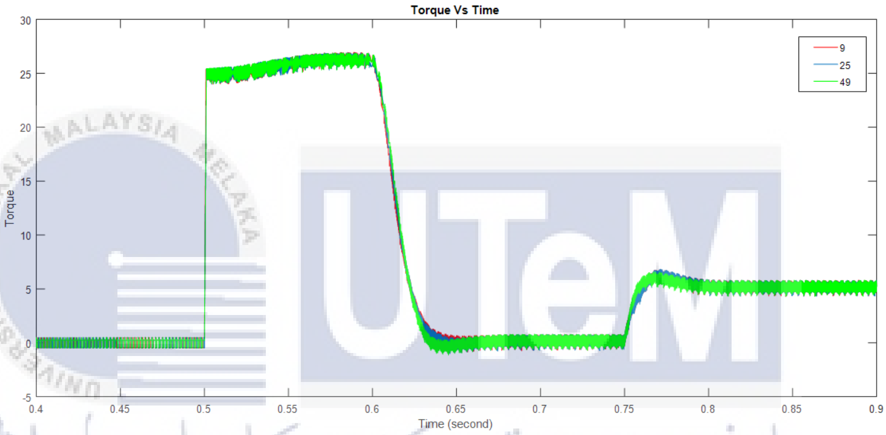
From the Figure 4.12 and Table 4.11 until Table 4.12, 49 rule does produce higher overshoot and followed by 25 and 9 rules. From the result, the rise time is decreases as the number rules is increase. While the settling time for all the rule is remain same. Table 4.12 shows that 49 rule speed drop is the smallest and the recovery time is faster than the other rules. 25 and 9 rule produce same speed drop and recovery time.



(a)



(b)



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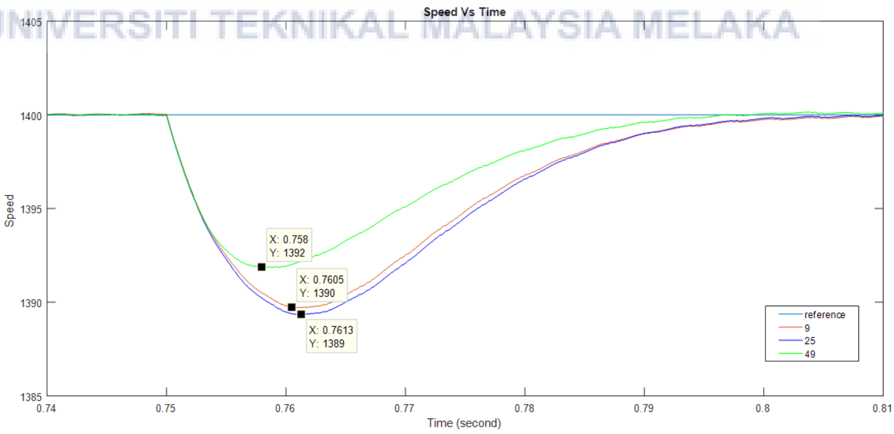

(d)

Figure 4.13: Rated speed response of 1400 rpm for 49, 25 and 9 rules with load disturbance 5 Nm at t= 0.75; (a) Speed response; (b) Ia Three phase current; (c) Torque; (d) Closed-view load disturbance

Table 4.13: Forward operation at rated speed

Numbers of Rules	Overshoot (%)	Rise time (s)	Settling time (s)
49	0	0.1620	0.0912
25	0	0.1620	0.0912
9	0	0.1620	0.0912

Table 4.14: Load disturbance during forward operation at rated speed

Number of rule	Speed drop (rpm)	Recovery time (s)
49	8	0.0391
25	11	0.0462
9	10	0.0462

From the Figure 4.13 and Table 4.13 until Table 4.14, all the rule does not produce any overshoot. From the result, the rise time between the rules is the same and the settling time for all the rule is same. Table 4.14 shows that 49 rule speed drop is the smallest and the recovery time is faster than the other rules. 25 rules have the most speed drop at the load disturbance and followed by 9 rules but both of the rule get same recovery time. Even there is change in load disturbance or rated speed, overall, all the three rule managed to maintain their behavior.

4.4.4 Comparison of 49, 25 and 9 rules

From the table 4.8, all three rules with different membership design have the same responses (similar settling time and recovery time) during operation with same speed command at change of load disturbance.

Table 4.15: Comparison of 49, 25 and 9 rules

Description	49	25	9
Operation at rated speed 1400 rpm with no load disturbance	Similar settling time and recovery time but different rise time and speed drop		
Operation at rated speed 1400 rpm with 10 Nm load disturbance	Similar settling time and recovery time but different rise time and speed drop		
Operation at rated speed 1400 rpm with 20 Nm load disturbance	Similar settling time and recovery time but different rise time and speed drop		

The fastest rise time is 49 rules, follow by 25 rules and lastly 9 rules. The speed drop which is small about 2 to 5 rad/s. To produce fair comparison, scaling factors and memberships function are remain fixed and constant in all operation. For overall simulation, all three rules are investigated with different speed command and fixed torque application. The speed performance of all three rules are based on transient responses that are; rise time, settling time, undershoot/overshoot, speed drop and recovery time characteristics.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5 CONCLUSION

Various type of vector control of induction motor drive. Most likely use for induction motor drive is indirect vector control because it has variable speed drive with high performance that need accurate, fast speed response and high reliability. That's why FLC has been choose in this project because it provide good dynamic response, less mathematical model and robust. Just the process need to do man trial-and-error and needed to be tuned correctly. Another disadvantage is need the high performance processor and more storage space for the computer because of the higher number of rule.

This project is focusing on reduction of the rule base. There are three type of the base rule that commonly use such as 49 rule, 25 rules and 9 rules. The comparison between 3 rule base is based on the performance of the speed induction motor drive. The comparison will be conduct in simulation test by using MATLAB/Simulink program to construct the induction motor mathematical model.

The simulation test and result will include the different load disturbance. The comparative analysis that observe on the transient response will plotted based on the rise time, settling time, undershoot recovery time and speed drop. As the previous research, the most operation that provide faster time response and smallest speed drop were 49 rules.

As the conclusion, from the previous research 49 rule give the best result compare to 25 and 9 rule in term s of rise time and speed drop. All three rules have same settling time and recovery time. Lastly, the performance of using FLC rule base in the induction motor drive will give a smooth result and consistency.

5.1 RECOMMENDATION

For the future work, this project can be implemented by using hardware approach and investigate the effect of computational time of fuzzy logic controller. In addition, using other AC motor such as SPMSM and brushless motor can be applied with FLC. Moreover, by combining the mathematical method between Fuzzy Logic and Neural Network can be implemented for control algorithm to tunning the fuzzy rule and membership function to get accurate and faster result. For the hardware, by using reduction method at 49 rule based can be implemented for the hardware to get the optimum performance and result.

REFERENCE

[1] S. Umans, "AC induction motor efficiency," *Proceedings of the 19th Electrical Electronics Insulation Conference*, pp. 99–107, 1989.

[2] M. N. Uddin and M. A. Rahman, "High-speed control of IPMSM drives using improved fuzzy logic algorithms," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 190–199, 2007.

[3] M. H. N. Talib, Z. Ibrahim, Z. Rasin, J. M. Lazi, and M. Azri, "Investigation of Different Rules Size FLSC Performance Applied to Induction Motor Drive," vol. 9, no. 2, pp. 165–169.

[4] M. H. N. Talib, Z. Ibrahim, N. A. Rahim, A. S. A. Hasim, and H. Zainuddin, "Performance improvement of induction motor drive using simplified FLC method," *2014 16th International Power Electronics and Motion Control Conference and Exposition*, pp. 707–712, 2014.

[5] P. No, T. Phase, I. Motor, E. Circuit, D. Speed, and C. Methods, "chapter 3 induction motor and different speed control induction motor and different speed control Three Phase Induction Motor (IM)," no. 3, pp. 57–71.

[6] M. P. Singh and F. O. F. Engineering, "' Parameter Estimation of Three Phase Induction Motor : An Innovative Approach ' ' Parameter Estimation of Three Phase Induction Motor : An Innovative Approach ,'" vol. 282005, 2013.

[7] A. S. Lunardi, A. J. Sguarezi, and Filho, "Experimental results for predictive direct torque control for a squirrel cage induction motor," *2017 Brazilian Power Electronics Conference (COBEP)*, vol. 45, no. 9, pp. 1–5, 2017.

[8] J. Griffin, “DC motors,” *Electronics and Power*, vol. 28, no. 1, p. 109, 1982.

[9] P. M. Menghal and A. J. Laxmi, “Scalar control of an induction motor using artificial intelligent controller,” *2014 International Conference on Power, Automation and Communication (INPAC)*, 2014.

[10] G. Kohlrusz and D. Fodor, “Comparison of Scalar and Vector Control Strategies of Induction Motors,” *Hungarian J. Ind. Chem. Veszprém*, vol. 39, no. 2, pp. 265–270, 2011.

[11] S. Vector, M. Basic, R. Transformation, and T. Dq, “Stationary Coordinate System and 2) a Transformation From the,” *Transformation*.

[12] J. Mohana, R. Malla, M. K. Sahu, and P. P. K. Subudhi, “DTC-SVM of Induction Motor by Applying Two Fuzzy Logic Controllers,” pp. 4941–4945, 2016.

[13] M. Miloševic, “Hysteresis current control in three-phase voltage source inverter,” pp. 1–15, 2003.

[14] N. A. Patel and J. C. Baria, “A Hysteresis Current Control Technique for Electronics Convertor,” pp. 2203–2210, 2016.

[15] E. H. E. Aboadla, T. Majdee, K. A. B. Aznan, A. Khalil, S. Khan, M. H. Habaebi, T. Gunawan, B. A. Hamidah, and M. B. Yaacob, “A comparative study between SPWM and SHE-PWM modulation techniques for DC-AC inverters,” *2017 IEEE 3rd International Conference on Engineering Technologies and Social Sciences (ICETSS)*, 2017.

[16] K. R. Feistel and L. A. C. Lopes, “Design procedure for the LPF of a three-phase SPWM VSC operating with a wide range of output power, voltage and

frequency with low harmonic distortion," *2018 IEEE International Conference on Industrial Technology (ICIT)*, 2018.

[17] J. A. Ali, M. A. Hannan, A. Mohamed, and M. G. M. Abdolrasol, "Fuzzy logic speed controller optimization approach for induction motor drive using backtracking search algorithm," *Measurement*, vol. 78, pp. 49–62, 2016.

[18] Y. S. Rao and A. J. Laxmi, "Fuzzy logic based indirect vector control of induction generator in Wind Energy Conversion System," *2012 International Conference on Power, Signals, Controls and Computation*, 2012.

[19] M. Comanescu, "An Induction-Motor Speed Estimator Based on Integral Sliding-Mode Current Control," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 9, pp. 3414–3423, 2009.

[20] P. Mlodzikowski, A. Milczarek, S. Stynski, M. Malinowski, and S. Kouro, "Control of simplified multilevel AC-DC-AC converter for small power generation systems," *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, 2013.

[21] J.-Y. Chen, G.-J. Chiou, T.-C. Chen, M.-J. Chen, and M.-J. Hsu, "A ds-qsaxis transformation with adjustable angle for three-phase current source induction motor drive," *2014 9th IEEE Conference on Industrial Electronics and Applications*, pp. 272–277, 2014.

[22] A. Jidin, N. R. N. Idris, and A. H. M. Yatim, "A Fast Dynamic Torque Control for Direct Torque Control Hysteresis-based Induction Machines," no. 1, pp. 1–5, 2008.