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FINAL YEAR PROJECT REPORT

DEVELOPMENT OF FIVE PHASE INDUCTION MOTOR SPEED USING FIELD ORIENTED CONTROL METHOD

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DEVELOPMENT OF FIVE PHASE INDUCTION MOTOR SPEED USING FIELD ORIENTED CONTROL METHOD

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A report submitted

in partial fulfillment of the requirements for the Bachelor in Electrical Engineering (Control, Instrumentation and Automation)

Faculty of Electrical Engineering

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2015

DECLARATION

I declare that this report entitle "Development of Five-phase Induction Motor Speed using Field Oriented Control Method" 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 the candidature of any other degree.

Signature : ....

Name : AHMAD KHAIRI BIN ARIFFIN

Date : ....

APPROVAL

I hereby declare that I have read through this report entitle "Development of Five-phase Induction Motor Speed using Field Oriented Control Method" and found that it has complied the partial fulfillment for awarding the Bachelor in Electrical Engineering (Control, Instrumentation and Automation)

Signature : ....

Supervisor's Name : EN. MOHAMED AZMI BIN SAID

Date : ....

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Thank you.

ABSTRACT

Multiphase induction motor drive is considered for various applications. Utilization of AC machines with a number higher than three phase can be enabled using power electronic in electrical drives. The 5-phase motor drive has many advantages compared to 3-phase such as reducing amplitude of torque and current pulsation. The aim of this project is to control the speed of five phase induction motor using Field Oriented Control (FOC). A five phase induction motor has high fault tolerance. The main application of multiphase induction motor are ship propulsion, traction (including electric and hybrid electric vehicles) and electric aircraft. In order to run a five phase induction motor, the drive system need to be designed. Five phase source supplied from five-phase Voltage Source Inverter (VSI) space vector modulation has chosen as the switching scheme due to its easiness of digital implementation. Space Vector Modulation (SVM) gives effective control of multiphase VSI because of higher switching voltage capacity compare to its companion. The Field Oriented Control (FOC) has been selected as a method to control the speed of five phase induction motor. FOC controlling the current space vector directly in the d-q rotor reference frame. Once the stator current is transformed, the control becomes rather straight forward. Two PI controller is used for d and q. This will maximize the torque efficiency and increase the speed. The FOC will also provides smoother motion at slow speeds as well as efficient operation at high speeds. The result is shown in simulation and can be experimental on real five phase induction motor with five phase inverter.

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CHAPTER 1

INTRODUCTION

1.1 Project Overview

For this project, the speed of the motor has control by field oriented control (FOC) technique. The five-phase Voltage Source Inverter (VSI) is used to run five-phase induction motor. Space vector modulation (SVM) is chosen as the switching scheme due to its easiness in digital implementation. Space vector modulation gives effective control of multiphase VSI because of large numbers of space vectors. Voltage source inverter (VSI) implemented Insulated Gate Bipolar Transistor (IGBT). The speed of the motor should follow the reference speed that gives as input reference.

1.2 Project Motivation

Nowadays, multiphase motor drives considered for various applications which required zero fault. The five-phase motor drive has so many advantages compared to the 3-phase motor such as reducing amplitude of torque and current pulsation.

Five phase drives supplied from five-phase Voltage Source Inverter (VSI) and adequate method for VSI pulse width modulation are therefore required. For this project, space vector modulation schemes for a five-phase VSI generated to drive five phase induction motor and Field Oriented Method will be used to control the speed of the five phase induction motor.

1.3 Problem Statement

From the previous project, the five phase induction motor simulation scheme was successfully created and was able to run with constant speed input. The speed of the five phase induction motor is yet to be controlled. To control the speed of the five phase induction motor, the control scheme to be designed.

1.4 Objective

The research objectives are:

i. To control the speed of the five phase induction motor using field oriented method.
ii. To design the PID controller using voltage source inverter through space vector modulation scheme.
iii. To simulate the design using Simulink/Matlab and experiment using actual five phase induction motor in the lab.

1.5 Scope of Project

The scope of this project is running under the simulation using Matlab/Simulink and actual five phase induction motor control in a laboratory environment. Simulink software will be used for simulation of five phase motor drives purposes. The previous project was successfully create switching scheme for the five phase induction motor using Space Vector Modulation (SVM) method. So, for this project, the speed controller, which is Field Oriented Control (FOC) method will be added in order to control the speed of the five phase induction motor. After that, the controller will be simulated in Matlab/Simulink. Lastly, the control and inverter design will be tested in the laboratory using the actual five phase induction motor. The test will be conducted using the actual five phase induction motor, its drives and dspace controller, which is available in the research laboratory.

1.6 Expected Project Outcome

The expected project outcome is the controller is able to control the speed of the five phase induction motor. Besides, able to modeling the simulation block diagram by using simulink for five phase induction motor, five phase inverter circuit and space vector modulation block diagram which is used for switching DC to multiphase AC. The purpose is to fed the induction motor. Other than that, designing PID controller and able to control the d-q components and also to control the speed of the motor. Next, able to model Clarke, park and ipark transformation which is to convert five-phase AC into dq component and from dq component back to five-pahse AC.

Lastly, able to analyse the speed response of the motor and tune PID controller dq components and analyse Vd and Vq response for drive and five phase induction motor. After that capture the response graph in simulation and run experimental on real five phase induction motor using real five phase induction motor using real five phase inverter inverter and capture motor speed response using an oscilloscope and real data capture on Matlab/Simulink.

CHAPTER 2

LITERATURE REVIEW

2.1 Previous Work

Induction motor that consists of three phase surely known advantages of basic development, reliability, roughness, low maintenance and cost which has led to their far reaching use in numerous mechanical operations [7]. Nowadays, more published work has demonstrated that drives with more than three-phase have more advantages over ordinary three-phase such as lower torque and reduction in harmonic currents [7]. From the previous work, the speed response of the motor was controlled by using Space Vector Modulation (SVM). SVM was chose because of its easiness of digital implemetation. Besides, SVM gives better control of multiphase Voltage Source Inverter (VSI) because the numbers of space vector is large [8].

For the previous work the speed of the motor was controlled by using space vector modulation scheme that was used for five-phase VSI to drive five-phase induction motor [8].

2.2 Induction Motor

The induction motor is the one of the most common electrical motor use. This motor runs at speeds lower than synchronous speed and it also known as a synchronous motor. The speed of rotation of the magnetic field in a rotating machine called as synchronous speed. Frequency and number of the machine influence synchronous speed of the motor. Flux generated in the rotor by the rotating magnetic field in the stator make the rotor to rotate.

There will be lag for the flux in the stator and rotor that makes the rotor cannot reach the synchronous speed. That's why the speed of the induction machine always less than synchronous speed. Induction process occurred in the induction motor.

The working principle of the induction motors is as follows. When give supply to the stator winding, the flow of current in the coil will generate the flux in the coil. The arrangement of the rotor winding will make it becomes a short circuit in the rotor itself. When the rotor coil is short circuit, current will flow in the coil of the rotor because the flux of the stator cut the coil of the rotor. The flowing current will generated another flux in the rotor. There will be two fluxes that are stator, rotor flux, and the stator flux will lead the rotor flux. Due to this, the rotor will produce a torque that makes the rotor to rotate in the direction of rotating magnetic flux. Therefore, the speed of the rotor will be depending upon the AC supply and the speed can control by varying the input supply.

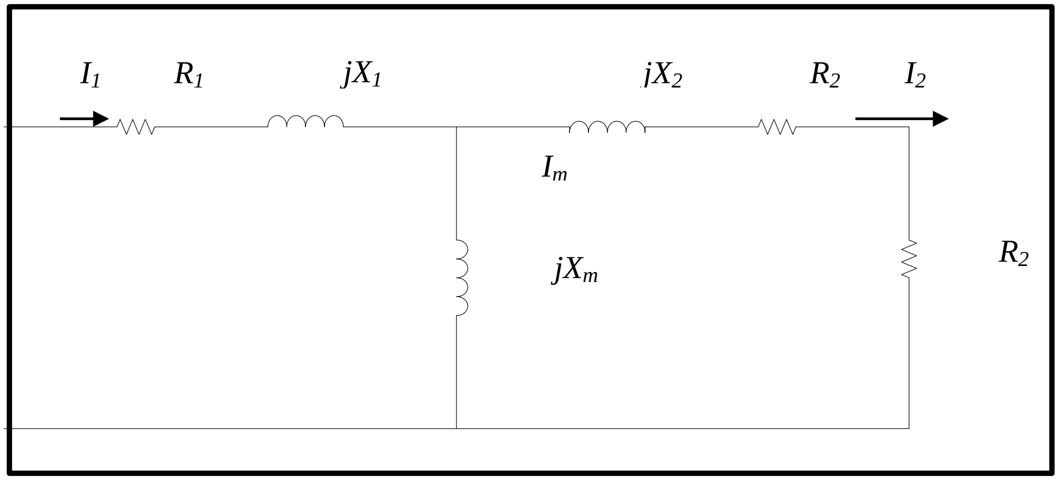
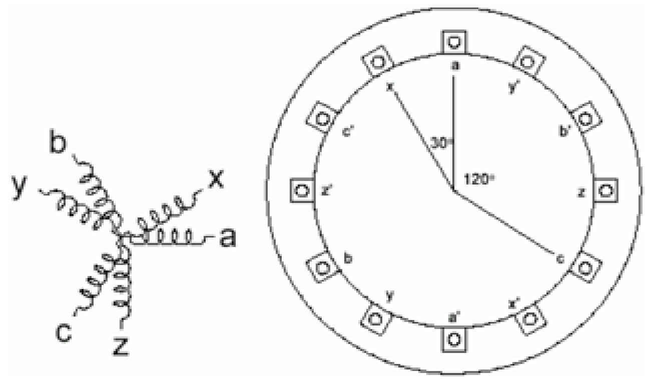


Figure 2.1:Per phase equivalent circuit for induction motor.

2.3 Multiphase Induction Motor

Induction motor more than three-phase have same properties with three-phase induction motor that run without producing a twice line-frequency pulsating torque and accelerate theirs load from the rest. Multiphase induction motors not connected directly to three-phase supplies. Three-phase supply connected to the power electronic converter that drive excitation for the multiphase induction motor. The output of the converter must have the same phase with the stator winding of the motor.

Multiphase machine have some advantages compared to three-phase machine. One of the advantages of multiphase machine is the efficiency of the multiphase machine is higher than three-phase machine because of the multiphase machine produces a field with lower space-harmonic content at the stator excitation. Second, multiphase machine has greater fault tolerance than three-phase machine [1-2].



(a) Electric diagram. (b) Basic construction.

Figure 2.2:Multiphase Induction Motor Circuit Diagram

Last, multiphase machine is less susceptible comparable to a three-phase machine to time harmonic components in the excitation waveform. Multiphase motor can reduce the required rating of power electronic components for the given motor output power. The important role of multiphase machine is to provide the concentrated stator winding rather than distributed stator winding. Injection of higher stator current harmonics can increase torque production [1-2].

Multiphase motor can reduce the stator current without increasing the stator voltage and it has greater fault tolerance [3]. For modeling of five-phase induction machine, assume that the same number of phases of the stator and rotor winding with a spatial displacement between any two phases of $\alpha = 2\pi/5$. Model of the machine transformed into a common reference frame, rotating at an arbitrary angular speed.

2.4 Voltage Source Inverter

Inverter in power electronic denotes a class of power conversion circuits that operates from DC voltage source or a DC current source and converts it into AC voltage or current. The inverter is the reverse of the as to DC converter. The primary source of input power may be utility AC voltage supply that converted to DC by an AC to DC converter and then been inverted back to AC using an inverter. The final AC output may have different frequency and magnitude compared to the input AC of the utility supply.

Figure 2.4 shows the five phase inverter that consist of ten IGBT arranged in parallel. The capital letter is line voltage and the small letter is the phase voltage of the inverter. The relationship of line voltage and phase voltage are shown in equation 2.4.1.

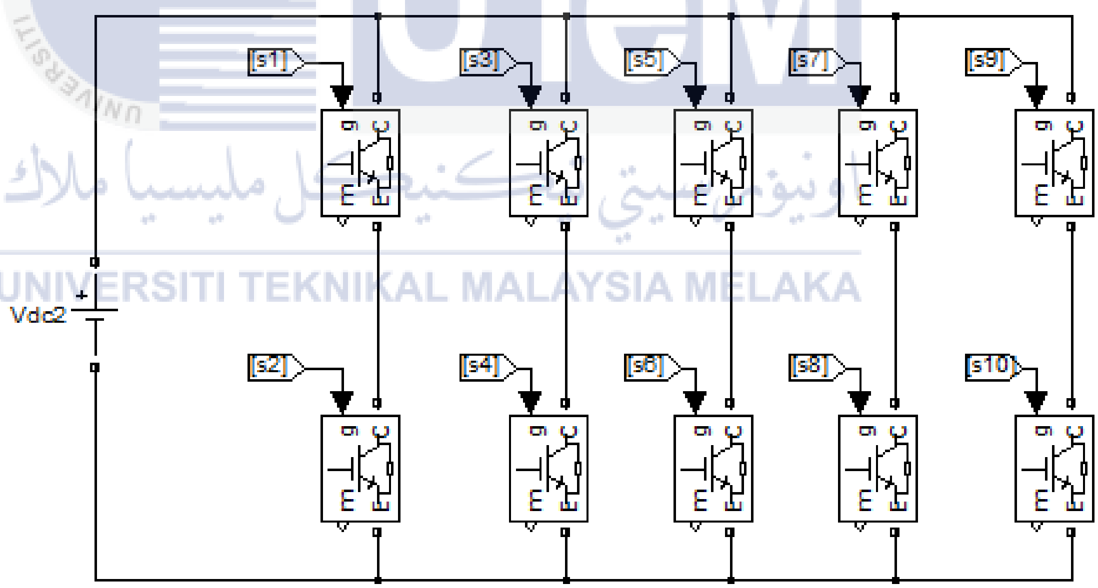


Figure 2.3:Voltage Source Inverter

2.5 Space Vector Modulation

Space vector modulation supplies AC machine with desired phase voltage. The space vector modulation method of generating the pulsed signals fit the requirement and minimizes the harmonic contents. Note that the harmonic content determines copper losses of the machine that account for a major portion of the machine losses [3].

Interest in multi phase drives has increased in recent years due to several advantages when compared to three-phase drives. The multiphase drive has some advantages that are less torque ripple, less acoustic noise and losses, reduced current per phase or increased reliability due to additional number of phases. Space vector modulation (SVM) is one of the most popular choices because it easy digital implementation and better utilization of the available DC bus voltage [4-5]

Power circuit topology for five-phase voltage source inverter with star-connected load presented. Five-phase space vector modulation can be developed as three phase space vector modulation for a period of the fundamental frequency. It shows the basic ten large and ten medium switching vectors for five-phase inverter.

Total voltage space vector in five-phase inverter is 32 vectors, but only 22 vectors used, consists of ten large and ten medium active vectors and two zero vectors. This is to decrease the number of switching in inverter and decrease switching losses.

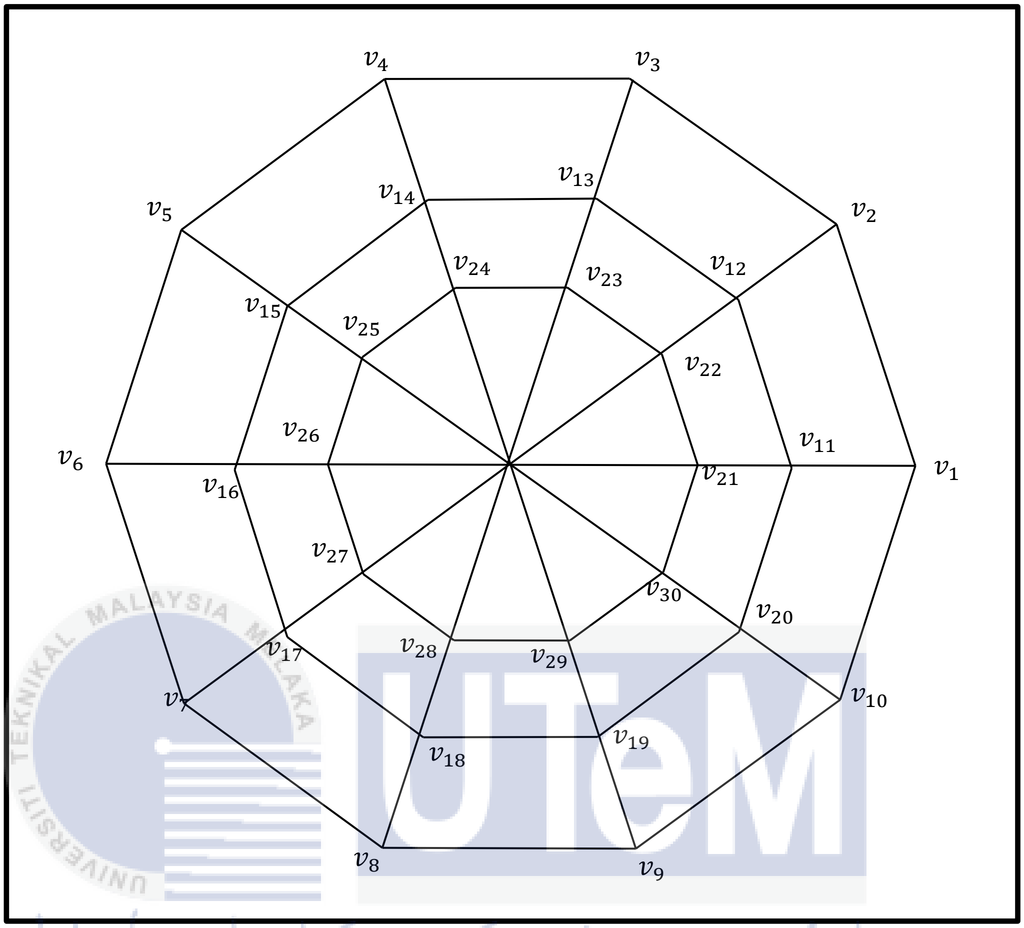


Figure 2.4:phase to neutral voltage space vector on dq plane

When five-phase operated in PWM mode, there will be additional 22 switching states. 2^n is the general equation for number of possible switching states, where n is the number of inverter leg. The remaining twenty-two switching states encompass three possible situations. First, all the states when four switches from upper (or lower) half and one from the lower (or upper) half of the inverter are ‘on’ at state’s 11 until 20. Next, two states when either all the five upper (lower) switches are ‘on’ at state’s 31 and 32. Last, the remaining states with three switches from the upper (lower) half and two switches from the lower (upper) half are ‘on’ at state’s 21until 30.

2.6 Field Oriented Control

Field oriented control controlling the current space vector directly in the dq reference frame of the rotor. in field oriented control, motor currents and voltages are manipulated in the dq reference frame. This means that measured motor currents must be mathematically transformed from the three phase static reference freame of the stator windings to the two axis rotating dq reference frame,prior to processing by the PI controllers. Similarly, the voltages to be applied to the motor are mathematically transformed from the dq frame of he rotor to the three phase reference frame of the stator before they can be used for pwm output [9].

Once the motor currents are transformed to the dq reference frame, control become rather straight forward. Two PI controllers are used one for the direct current component, and one for the quadrature current. The input to the controller for the direct current and has zero input. This drives the direct current component to zero and therefore forces the current space vector to be exclusively in the quadrature direction. Since only the quadrature current produces useful torque, this maximizes the torque efficiency of the system. The second PI controller operates on quadrature current and takes the requested torque as input. This causes the quadrature current to track the requested torque as desired [9].

Field oriented control provides the smooth motion at slow speed as well as efficient operation at high speeds [9].

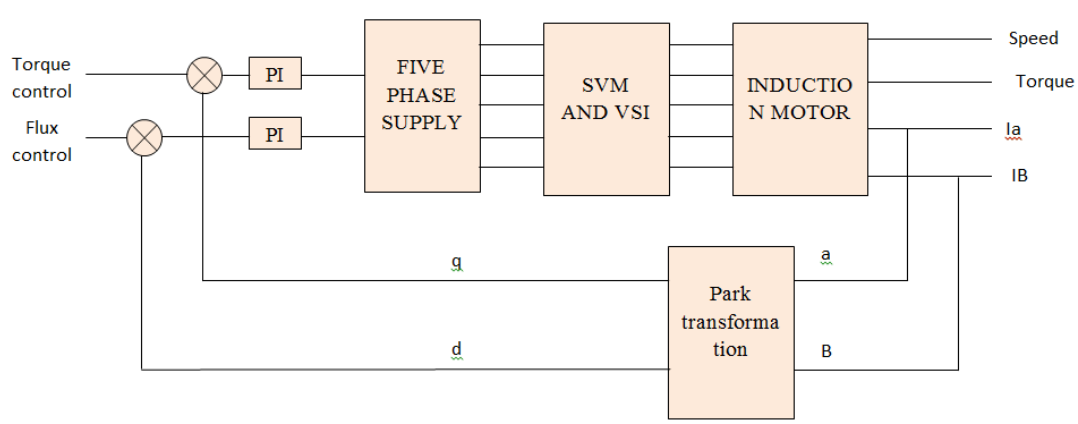


Figure 2.5: Field Oriented Control (FOC)

CHAPTER 3

METHODOLOGY

3.1 Project Methodology

This chapter explains about the project path from the beginning until the latest progress of the project implementation. Besides, this chapter explains about the flow of the whole project. Every selection and action that needs to take to make sure the project done properly also told in this chapter.

In order to achieve the objectives of the project, some step needs to follow. First, implement this project to real life for identifying its problem. Then design the system based on the objective. The aim of this project is to control the speed of the five phase induction motor. In order to design drive system for five phase machine, the five phase inverter should be designed first. Five phase inverter can be design same as the three phase inverter that consists of six IGBT but need to add the number of the IGBT to ten.

In previous projects, all the design has been made. This time, this project has come to make a development of the previous project, which is to control the speed of the five phase induction motor using field oriented method. So the controller needs to be designed in order to control the speed of the five phase induction motor.

3.2 Project Flowchart

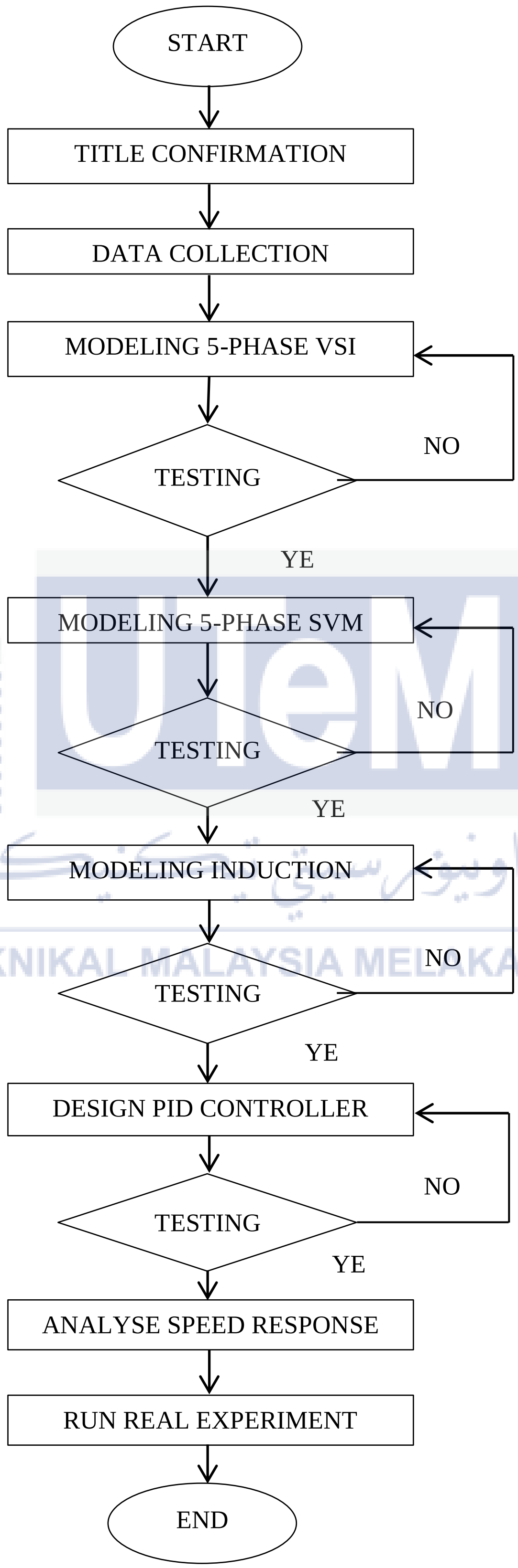


Figure 3.1: Project Flowchart

3.3 Field Oriented Control

Figure 3.2 below shows the diagram of Field Oriented Control. Field oriented control is a method of controlling the current space vector directly in the d-q reference frame of the rotor. The current of the motor will be as a feedback in d-q state. It will be compared with the input which is speed of the motor to produce the error. Then, the controller will correct the error.

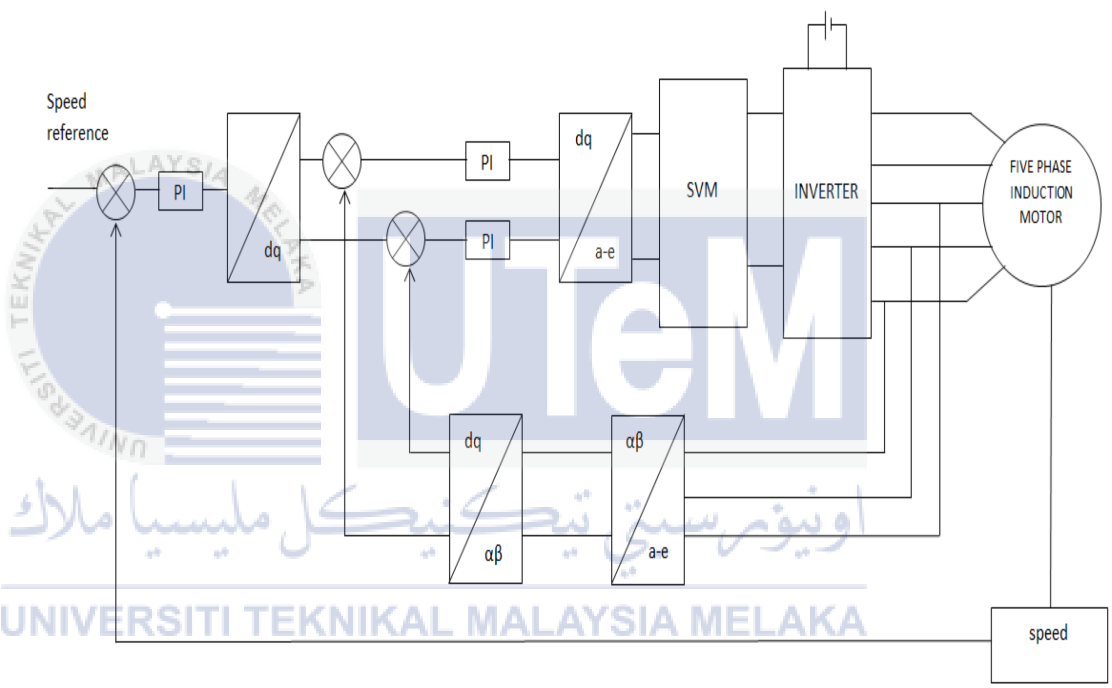


Figure 3.2: Field Oriented Control

Before modeling the five phase inverter, space vector modulation and other parts of this project, the five phase supply need to model first. The five phase supply was model using sine wave generator. The value between each phase is difference. The first phase is 0°, second is $\frac{2\pi}{5}$, third is $\frac{4\pi}{5}$, fourth is $\frac{6\pi}{5}$, and fifth is $\frac{8\pi}{5}$. The difference between each phase was 72°. Figure 3.3 below shows the modeling of the five phase supply using sine wave generator.

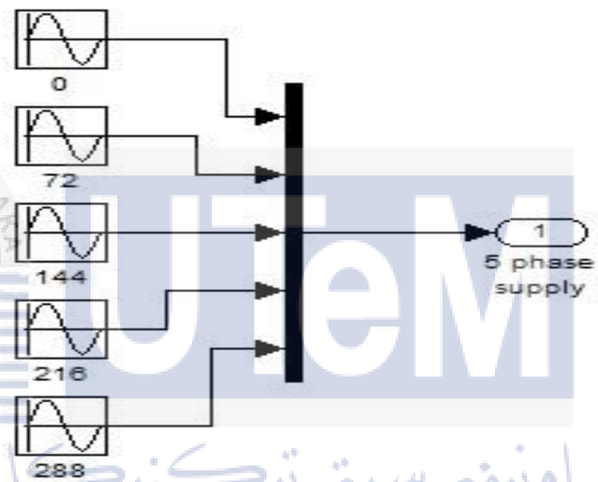


Figure 3.3: Five Phase Supply

3.4 Modeling Five-phase Voltage Source Inverter

Modeling Five-phase Voltage Source Inverter (VSI) is same as modeling the three-phase VSI but the number of insulated-gate bipolar transistor (IGBT) use increase to 10 compare to 6 in three-phase. There are some advantages of IGBT compared to MOSFET. One of the advantages is better in power handling.

Couple of IGBT was connected in series and it was connected in parallel with other couple of IGBT. There is five couple of IGBT connected in parallel in the inverter. The relationship between phase to neutral voltages and the inverter leg voltages has given in equation (3.1). The letter with lower case represented the phase to neutral voltages and the letter with upper case represented the leg inverter voltages.

$$v_a = \left(\frac{4}{5}\right)V_A - (\frac{1}{5})(V_B + V_C + V_D + V_E)$$

$$v_b = \left(\frac{4}{5}\right)V_B - (\frac{1}{5})(V_A + V_C + V_D + V_E)$$

$$v_c = \left(\frac{4}{5}\right)V_C - (\frac{1}{5})(V_A + V_B + V_D + V_E) \quad (3.1)$$

$$v_d = \left(\frac{4}{5}\right)V_D - (\frac{1}{5})(V_A + V_B + V_C + V_E)$$

$$v_e = \left(\frac{4}{5}\right)V_E - (\frac{1}{5})(V_A + V_B + V_C + V_D)$$

Figure 3.4 shows the arrangement of five phase inverter using 10 IGBT that was model using MATLAB/SIMULINK.

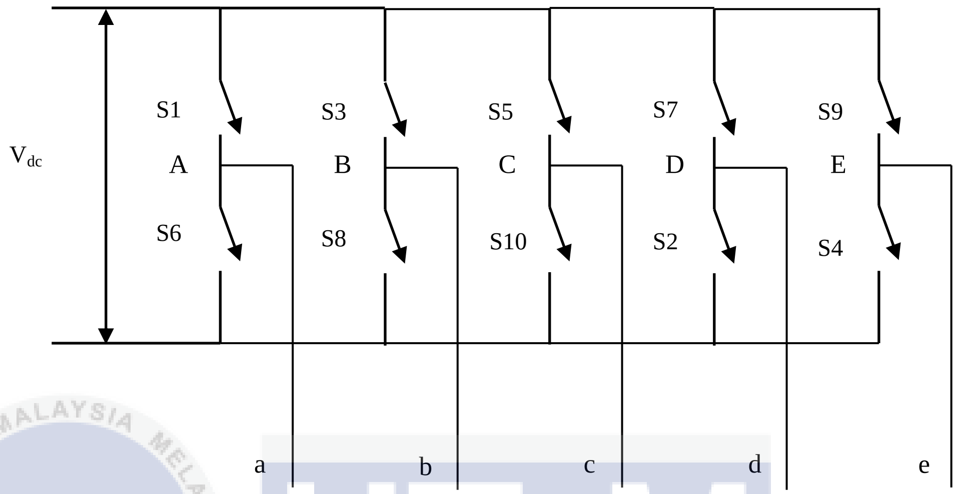


Figure 3.4: Five-phase Voltage Source Inverter

3.5 Space Vector Modulation Scheme

The purpose of this part is to generate the switching signal for five phase inverter. The generation starts with transformation of five-phase supply into two-phase which labeled as alpha and beta. This transformation called as Clarke transformation. Figure 3.5 shows the general block diagram for Clarke transformation.

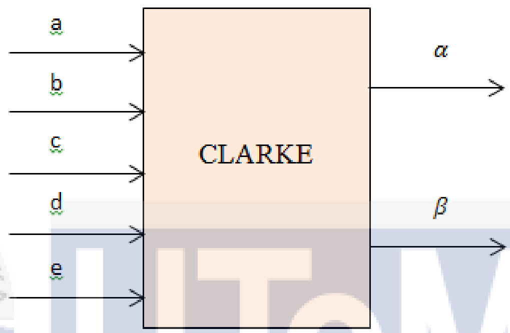


Figure 3.5: General block diagram for Clarke transformation

Figure 3.6 shows that the Clarke transformation by using blocks from Simulink. From five-phase supply, it transformed into two phase by using mathematical equation. The input for this block is five-phase supply and the output is two phase voltage.

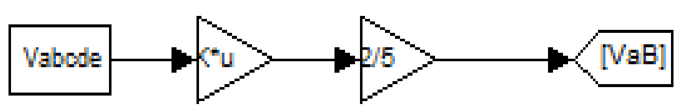


Figure 3.6: Clarke transformation for five-phase supply

The transformation of five-phase voltage to two phase voltage has been done by using following equation:

$$V_\alpha = \frac{2}{5}\left(V_a + V_b\cos\frac{2\pi}{5} + V_c\cos\frac{4\pi}{5} + V_d\cos\frac{6\pi}{5} + V_e\cos\frac{8\pi}{5}\right) \quad (3.2)$$

$$V_\beta = \frac{2}{5}\left(V_b\sin\frac{2\pi}{5} + V_c\sin\frac{4\pi}{5} + V_d\sin\frac{6\pi}{5} + V_e\sin\frac{8\pi}{5}\right) \quad (3.3)$$

Figure 3.7 shows the waveform of five phase voltage before the transformation which is used for space vector modulation. The phase of each of the phase was 72° apart with amplitude which is the voltage 10V and frequency 50Hz.

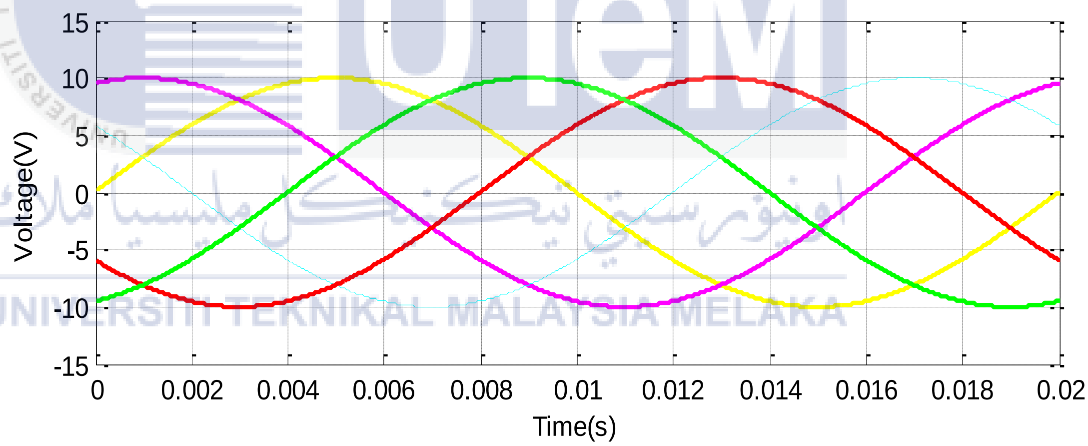


Figure 3.7: Waveform of five-phase supply for space vector modulation

The waveform after the transformation was shown in Figure 3.8. The two-phase waveform was 90° apart. The value of the voltage is 10V with the same frequency, 50Hz.

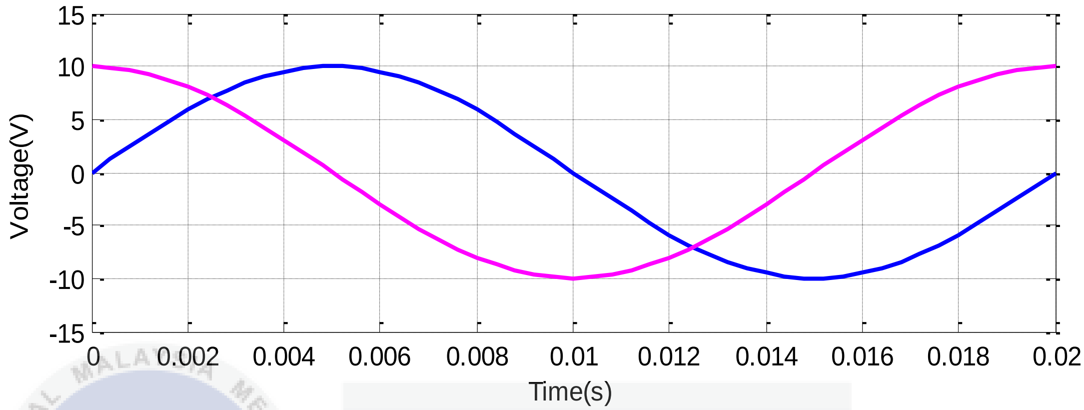


Figure 3.8: Waveform of two phase voltage after transformation

After five-phase voltage was transformed into two phase voltage, then the two phase voltage separated into two to produce voltage reference and angle. This two-phase voltage was passed through Real-Imaginary to complex block and complex to magnitude-angle block to produce the magnitude and angle. Figure 3.9 shows the general block diagram for the separation while block diagram by using Simulink was shown in Figure 3.10.

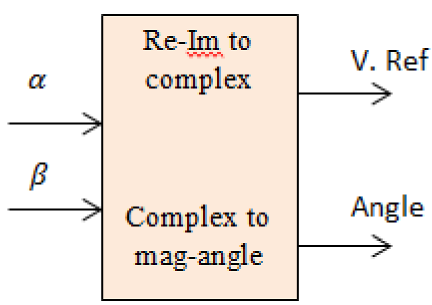


Figure 3.9: General block diagram for separation of $\boldsymbol{\alpha - \beta}$ voltage

The input for this block is the transformed two-phase voltage and the output is magnitude which is voltage reference and angle.

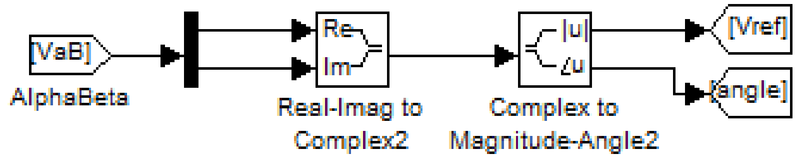


Figure 3.10: Separation into magnitude and angle

The waveform for magnitude was shown in Figure 3.11. The magnitude also acts as voltage reference. Figure 3.11 show that the value of the reference voltage is 10V.

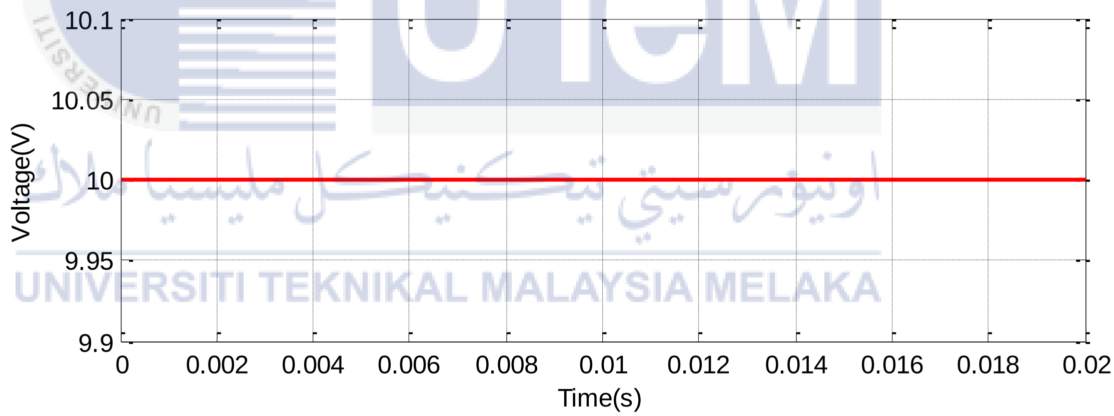


Figure 3.11: Waveform of voltage reference

Besides, Figure 3.12 shows the waveform of the angle that was produced from the split operation. The angle waveform is triangle waveform with frequency of 50Hz for one complete cycle.

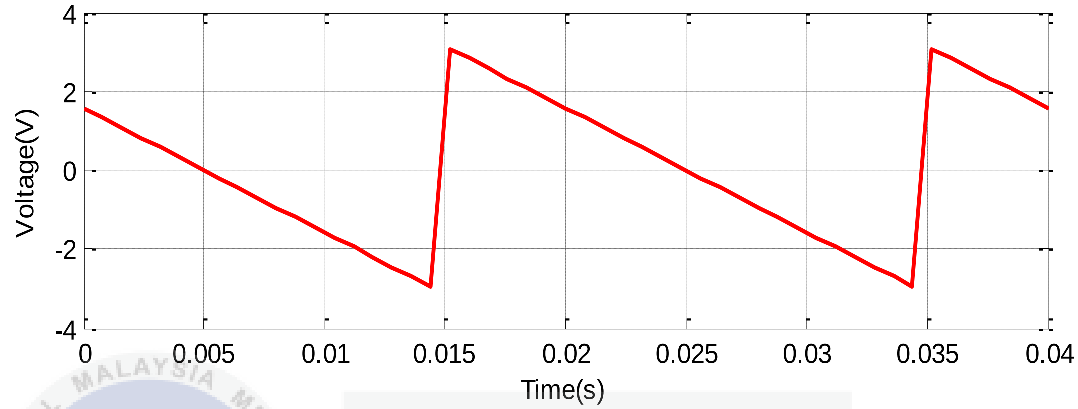


Figure 3.12: Angle waveform

The angle output from the complex to magnitude-angle block was used for sector block. The angle used as an input for the sector block. The angle output was in radian. The angle input for the sector block must be in degree. So, the angle was changed from radian to degree by multiply it with $\frac{180}{\pi}$. The general block diagram for angle to sector was shown in Figure 3.13.

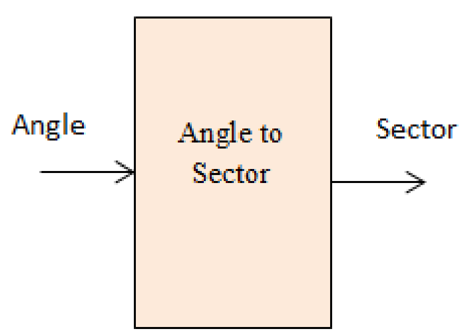


Figure 3.13: General block diagram for angle to sector

Figure 3.14 shows that the block of angle to sector calculation by using Simulink. The detail for the calculation block shown in Figure 3.15.

Figure 3.14: Angle to sector calculation block

Figure 3.15 shows the detail of the calculation block. The method to model angle to sector calculation block was same as model it in three-phase. The changed angle will be as an input for the block. The data type conversion block converts any input signal of the Simulink data to the any specified output data.

For five phase space vector, the total sector is 10. Each sector was 36° apart. The method to decide the sector was by comparing the input angle with the reference angle. For sector 1 the reference angle is 0° to 36°. The method that been through for sector 1 is repeat to decide for other sector.

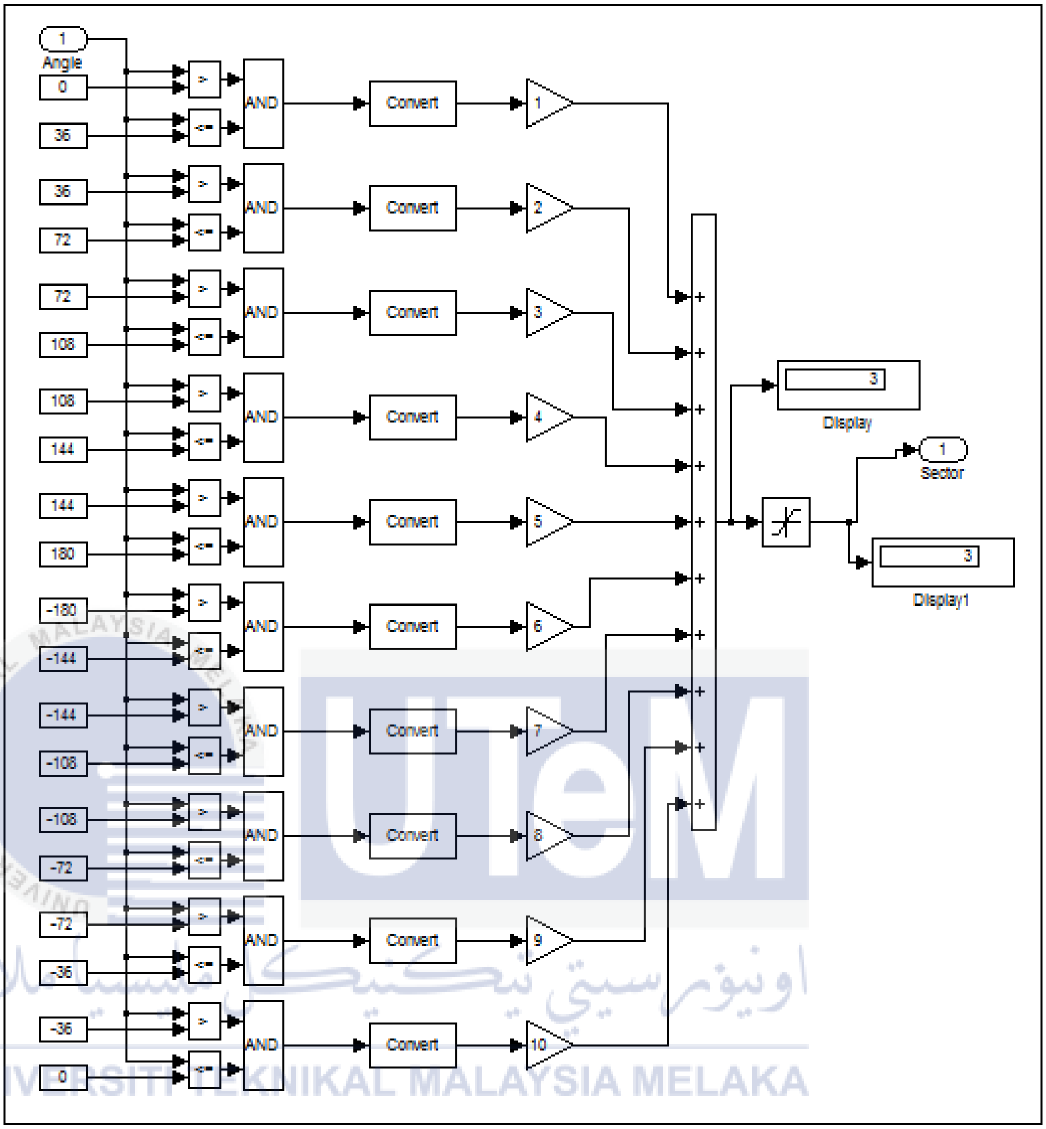


Figure 3.15: Sector calculation based on the angle

The waveform for the sector was shown in Figure 3.16. As mentioned earlier, the sector consists of 10 with each sector is 36° apart.

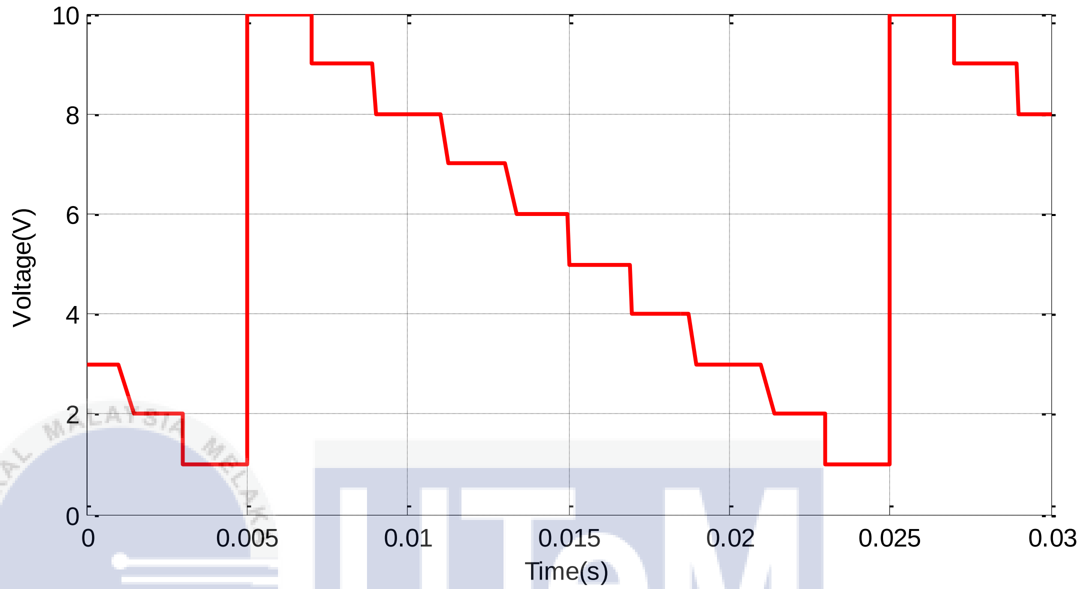


Figure 3.16: Waveform of the sector

The value of voltage reference, angle and sector was used for the calculation of four application times. The four application times are Ta, Tb, Tam and Tbm. The times needed in determine the switching state of the space vector modulation. To generate all four of the application times, mathematical equation is needed. The equation used is [6]:

$$T_a = T_s \frac{|v_s{}^*| \sin\left({}^{k\pi}/_{5} - \alpha\right)}{|v_l| \sin\left({}^{k\pi}/_{5}\right)} \tag{3.4}$$

$$T_b = T_s \frac{|v_s{}^*| \sin\left(\alpha - {}^{(k-1)\pi}/_{5}\right)}{|v_l| \sin\left({}^{k\pi}/_{5}\right)} \tag{3.5}$$

$$T_{am} = T_a \frac{|v_m|}{|v_l| + |v_m|} \tag{3.6}$$

$$T_{bm} = T_b \frac{|v_m|}{|v_l| + |v_m|} \tag{3.7}$$

$$T_{al} = T_a \frac{|v_l|}{|v_l| + |v_m|} \tag{3.8}$$

$$T_{bl} = T_b \frac{|v_l|}{|v_l| + |v_m|} \tag{3.9}$$

$$T_0 = T_s - T_{al} - T_{am} - T_{bl} - T_{bm} \tag{3.10}$$

Where: k = sector

α = angle

$|v_s{}^*| = V_{ref}$

$|v_l| = \frac{2}{5} V_{dc} 2\cos\left({}^{2\pi}/_{5}\right)$: Magnitude for large space vector

$|v_m| = \frac{2}{5} V_{dc}$: Magnitude for medium space vector

The magnitude value of large and medium space vector was substituted into equation (3.4) until (3.9). The equation after the substitution is:

$$T_a = T_s \frac{|v_{ref}| \sin(k^{\pi}/_5 - \alpha)}{^2/_5 V_{dc} \sin(^{2\pi}/_5)} \tag{3.11}$$

$$T_b = T_s \frac{|v_{ref}| \sin(\alpha - (k-1)^{\pi}/_5)}{^2/_5 V_{dc} \sin(^{2\pi}/_5)} \tag{3.12}$$

$$T_{am} = T_a \frac{1}{2\cos(^{\pi}/_5) + 1} \tag{3.13}$$

$$T_{bm} = T_b \frac{1}{2\cos(^{\pi}/_5) + 1} \tag{3.14}$$

$$T_{al} = T_a \frac{2\cos(^{\pi}/_5)}{2\cos(^{\pi}/_5) + 1} \tag{3.15}$$

$$T_{bl} = T_b \frac{2\cos(^{\pi}/_5)}{2\cos(^{\pi}/_5) + 1} \tag{3.16}$$

Figure 3.17 shows the general block for generation of base time Ta and Tb. Equation (3.11) and (3.12) can be rewrite to make it simpler by replacing certain value into constant. That equation used to generate base time Ta and Tb.

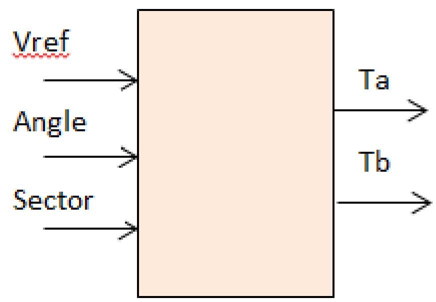


Figure 3.17: General block for generation of base time Ta and Tb

The equation to generate Ta and Tb is:

$$T_a = m\sin\left(k\,{}^{\pi}/_{5} - \alpha\right) \tag{3.17}$$

$$T_b = m\sin\left(\alpha - (k-1)\,{}^{\pi}/_{5}\right) \tag{3.18}$$

Where:

$$m = T_s \frac{|v_{ref}|}{{}^{2}/_{5}V_{dc}\sin({}^{2\pi}/_{5})} \tag{3.19}$$

Figure 3.18 show the generation of base time Ta and Tb by using simulink block. Equation (3.19) was used to find the value of the constant. Voltage reference from the previous block was used as an input. Vdc and Ts was supplied from the constant block and the value set to 400V for Vdc and 1ms for Ts.

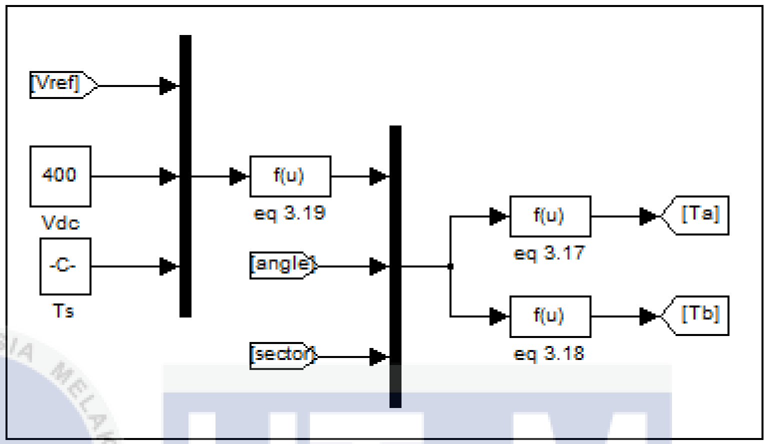


Figure 3.18: Generation of base time Ta and Tb

Figure 3.19 and Figure 3.20 shows the waveform of base time Ta and Tb generated by the simulink block by using mathematical equation. The amplitude is 0.00004V with frequency 500Hz. The amplitude and frequency for Tb is same but only the direction is different.

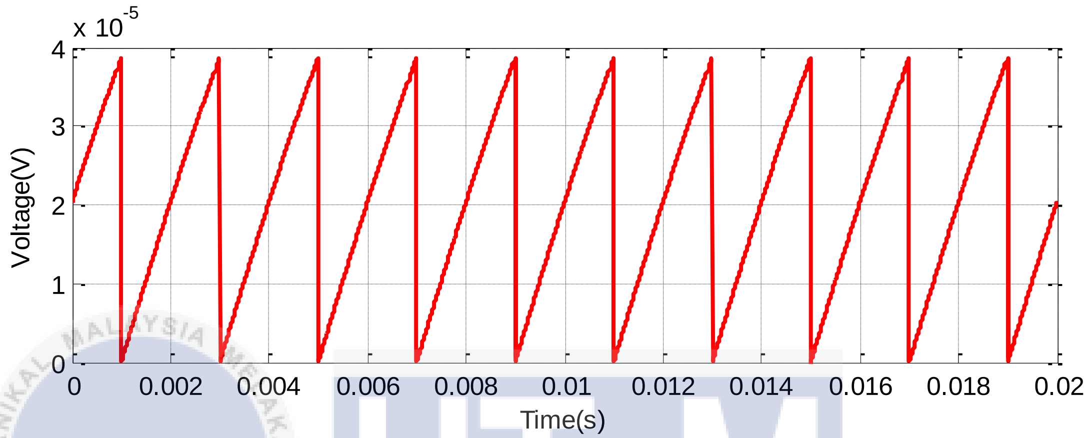


Figure 3.19: Waveform of base time Ta

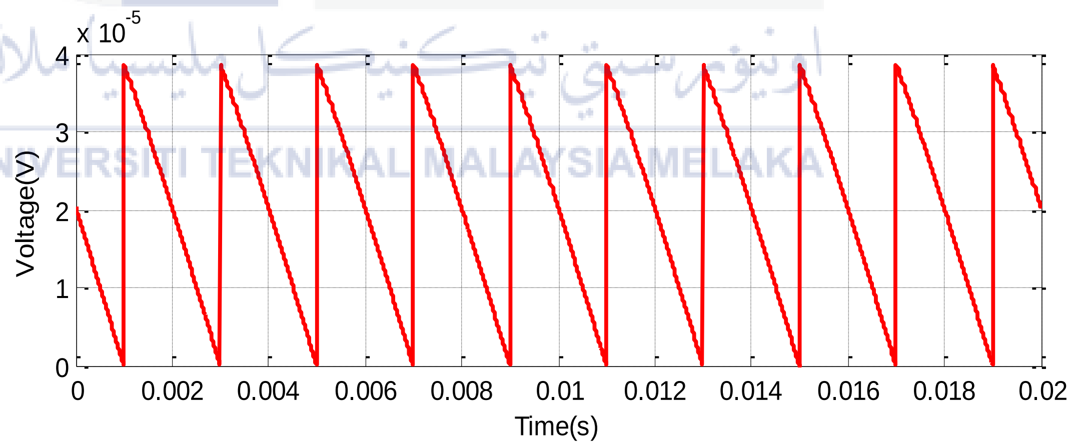


Figure 3.20: Waveform of base time Tb

Next, the output from the previous block which is Ta and Tb will be an input to the next block to generate application time for large and medium vector which is Tal, Tbl, Tam and Tbm. Figure 3.21 shows the general block diagram to generate four application time by using base time Ta and Tb as an input. Figure 3.22 show the modeling by using Simulink.

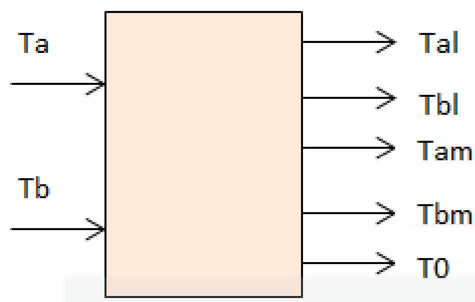


Figure 3.21: General block to generate four application times

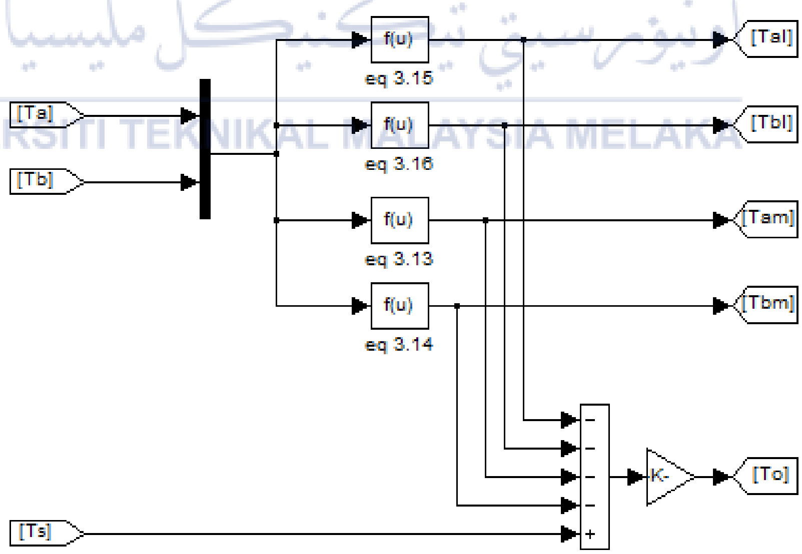


Figure 3.22: Generation of four application time

Figure 3.23 and Figure 3.24 shows the waveform of application time Tal and Tbl which represent the large space vectors. The frequency Tal and Tbl is same which is 500Hz for one complete cycle but the direction is different.

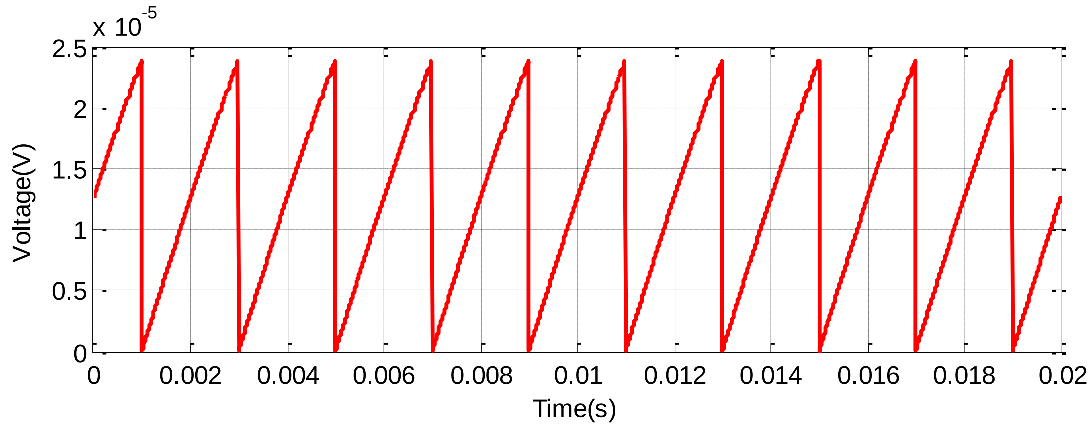


Figure 3.23: Waveform of time that represent large vector, Tal

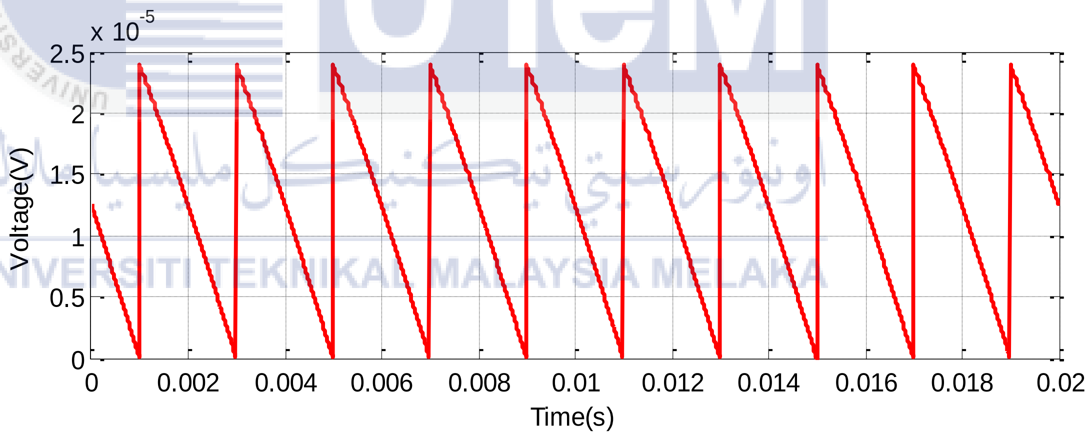


Figure 3.24: Waveform of time that represent large vector, Tbl

Figure 3.25 and Figure 3.26 shows the waveform of the application time Tam and Tbm which represent the medium space vectors. The frequency is the same as the previous waveform. The case is the same which is the direction for Tbm is different from the Tam waveform.

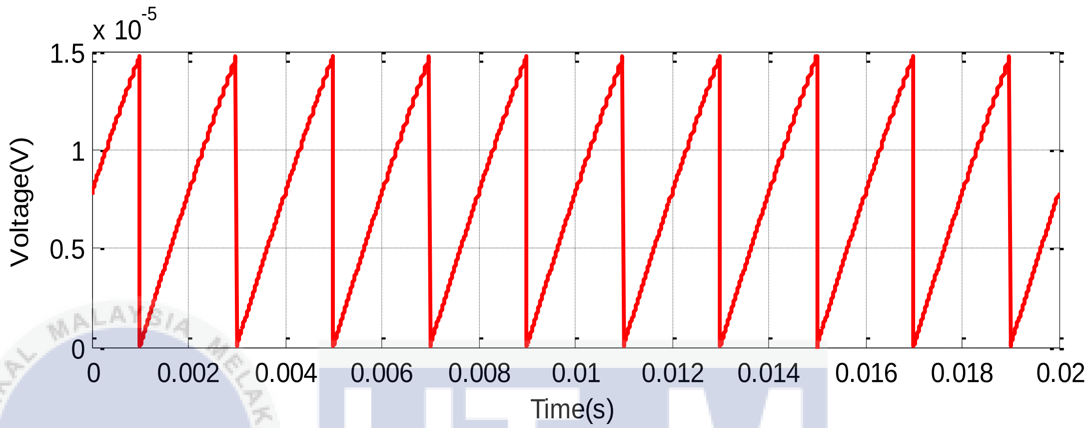


Figure 3.25: Waveform that represents time for medium vector, Tam

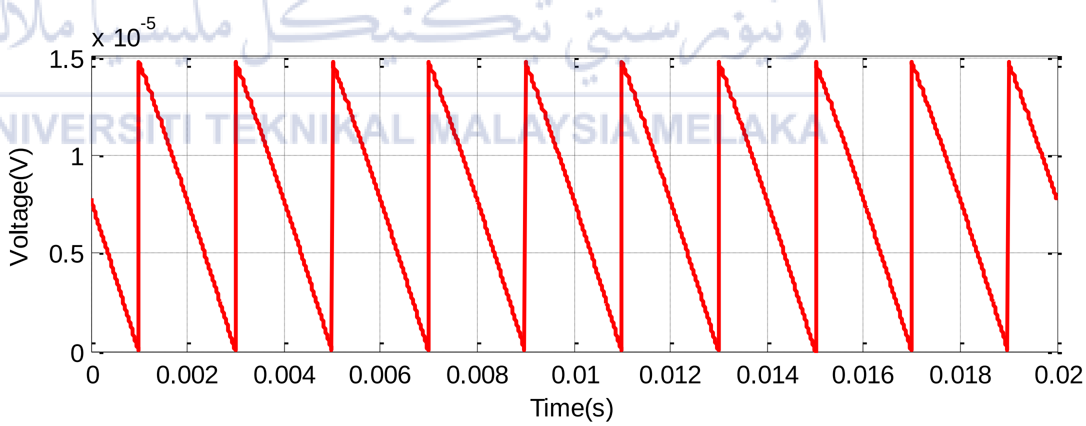


Figure 3.26: Waveform that represents time for medium vector, Tbm

Figure 3.27 show the waveform for the zero space vectors. It was generated by subtractions of Tal, Tbl, Tam and Tbm. The value of the frequency is the same as the previous waveform.

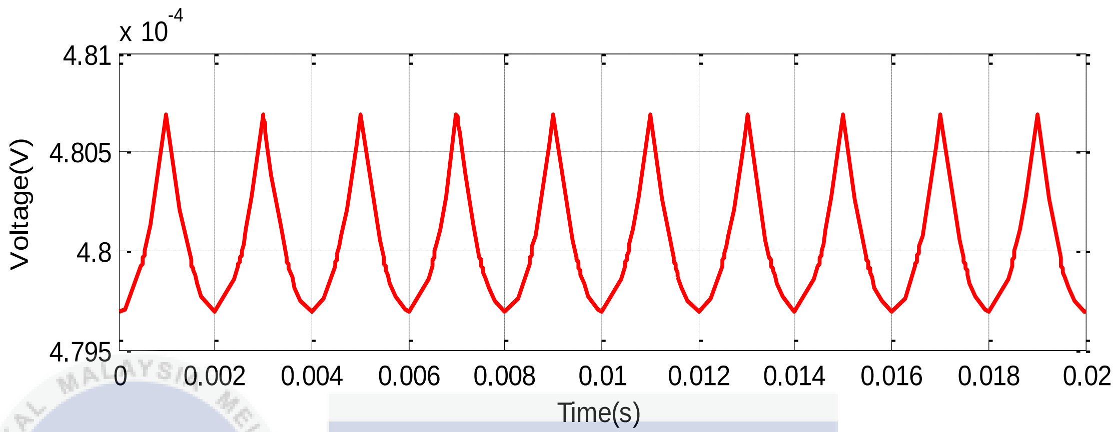


Figure 3.27: Waveform that represents time for zero space vectors, To

Next is the generation of switching pattern for upper part of the inverter which consists of five IGBT. The output from the previous block used as an input for this block. Mathematical equation was used in order to generate the output. Figure 3.28 shows the general block diagram for generation of switching state for the upper part of the inverter. The output from the previous block which is Tal, Tbl, Tam, Tbm, T0 and sector used as an input for this block.

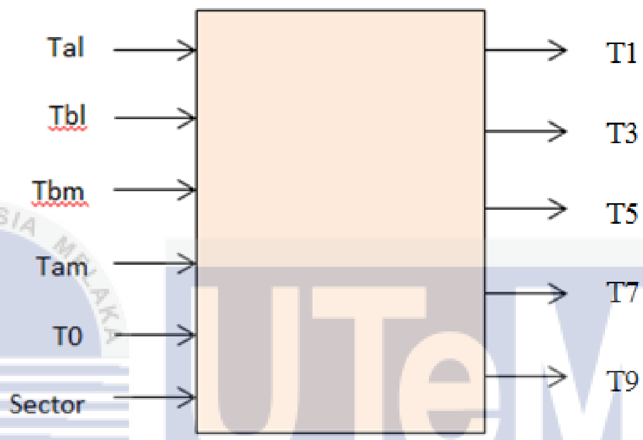


Figure 3.28: General block diagram for generation of switching pattern for upper part of inverter

Figure 3.29 shows simulink block for the generation of switching pattern for upper part of the inverter which is T1, T3, T5, T7 and T9. The function block used to enter the equation to generate the switching pattern.

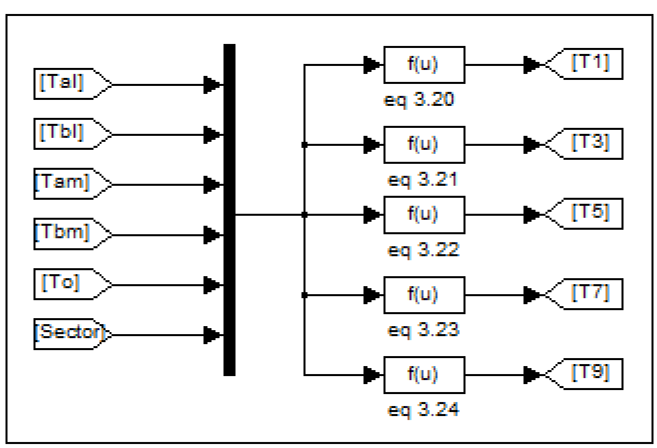


Figure 3.29: Generation of switching state for upper part of the inverter

The equation used is:

$$
\begin{aligned}
T_1 = {} & (k == 1)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) + (k == 2)(v_{am}, v_{bl}, v_0) \\
& + (k == 3)(v_{al}, v_{bm}, v_0) + (k == 4)(v_{am}, v_0) \\
& + (k == 5)(v_0) + (k == 6)(v_0) + (k == 7)(v_{bm}, v_0) \\
& + (k == 8)(v_{am}, v_{bl}, v_0) + (k == 9)(v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 10)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0)
\end{aligned} \tag{3.20}
$$

$$
\begin{aligned}
T_3 = {} & (k == 1)(v_{bl}, v_{al}, v_{bm}, v_0) + (k == 2)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 3)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 4)(v_{am}, v_{bl}, v_{al}, v_0) + (k == 5)(v_{al}, v_{bm}, v_0) \\
& + (k == 6)(v_{am}, v_0) + (k == 7)(v_0) + (k == 8)(v_0) \\
& + (k == 9)(v_{bm}, v_0) + (k == 10)(v_{am}, v_{bl}, v_0)
\end{aligned} \tag{3.21}
$$

$$
\begin{aligned}
T_5 = {} & (k == 1)(v_{bm}, v_0) + (k == 2)(v_{am}, v_{bl}, v_0) \\
& + (k == 3)(v_{bl}, v_{al}, v_{bm}, v_0)\ (k = \\
& = 4)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 5)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 6)(v_{am}, v_{bl}, v_{al}, v_0) + (k == 7)(v_{al}, v_{bm}, v_0) \\
& + (k = 8)(v_{am}, v_0) + (k == 9)(v_0) + (k == 10)(v_0)
\end{aligned} \tag{3.22}
$$

$$
\begin{aligned}
T_7 = {} & (k == 1)(v_0) + (k == 2)(v_0) + (k == 3)(v_{bm}, v_0) \\
& + (k == 4)(v_{am}, v_{bl}, v_0) + (k == 5)(v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 6)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 7)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 8)(v_{am}, v_{bl}, v_{al}, v_0) + (k == 9)(v_{al}, v_{bm}, v_0) \\
& + (k == 10)(v_{am}, v_0)
\end{aligned} \tag{3.23}
$$

$$
\begin{aligned}
T_9 = {} & (k == 1)(v_{am}, v_{bl}, v_0) + (k == 2)(v_{am}, v_0) + (k == 3)(v_0) \\
& + (k == 4)(v_0) + (k == 5)(v_{bm}, v_0) \\
& + (k == 6)(v_{am}, v_{bl}, v_0) + (k == 7)(v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 8)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 9)(v_{am}, v_{bl}, v_{al}, v_{bm}, v_0) \\
& + (k == 10)(v_{am}, v_{bl}, v_{al}, v_0)
\end{aligned} \tag{3.24}
$$

Figure 3.30 until Figure 3.34 below shows that the output waveform of the switching pattern for T1, T3, T5, T7 and T9. The frequency for all waveform is same which is 50Hz. The shape for all waveform also same but the different is the phase. The phase is 72° apart.

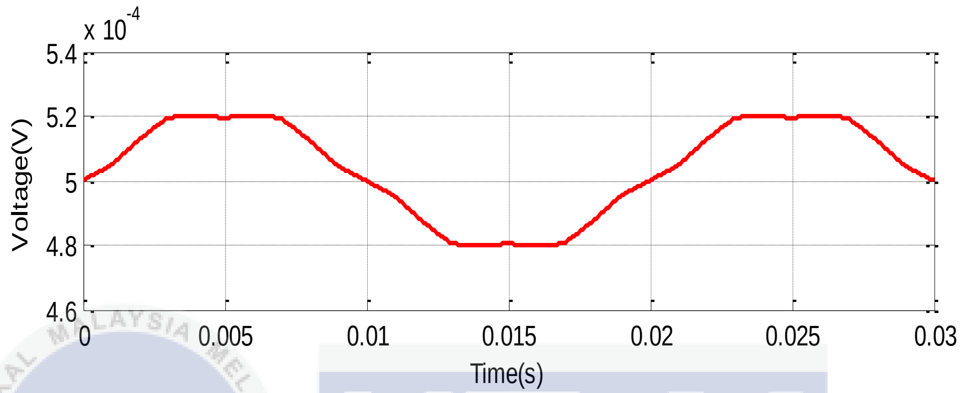


Figure 3.30: Waveform for switching pattern T1

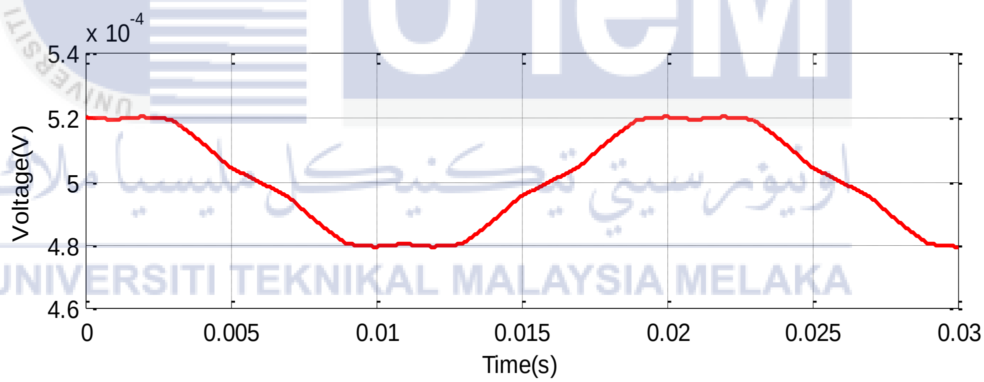


Figure 3.31: Waveform for switching pattern T3

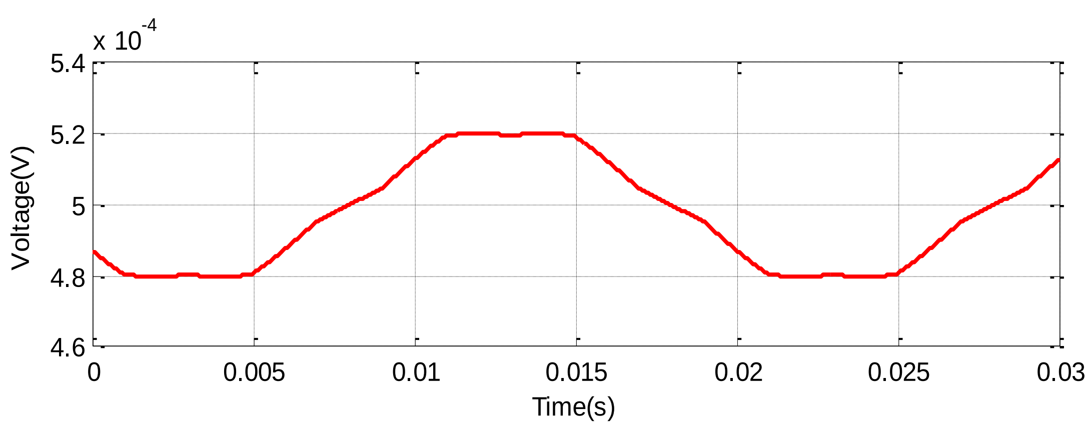


Figure 3.32: Waveform for switching pattern T5

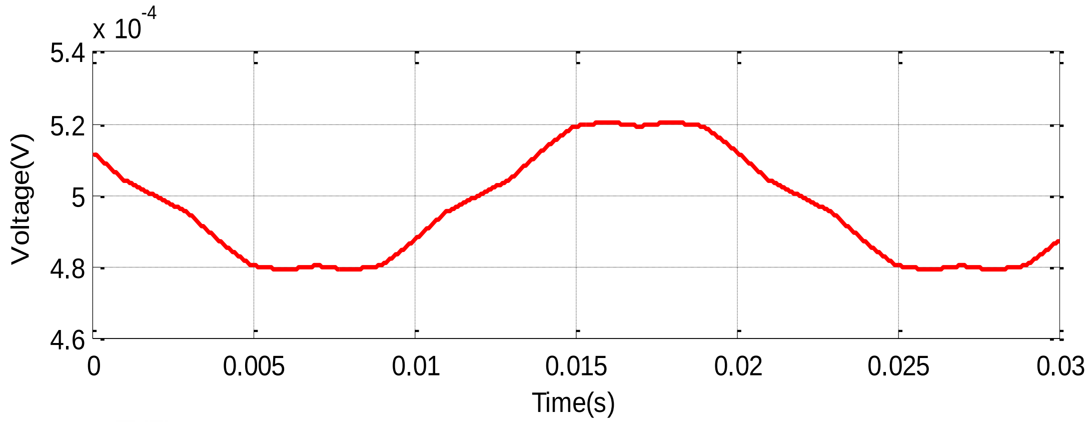


Figure 3.33: Waveform for switching pattern T7

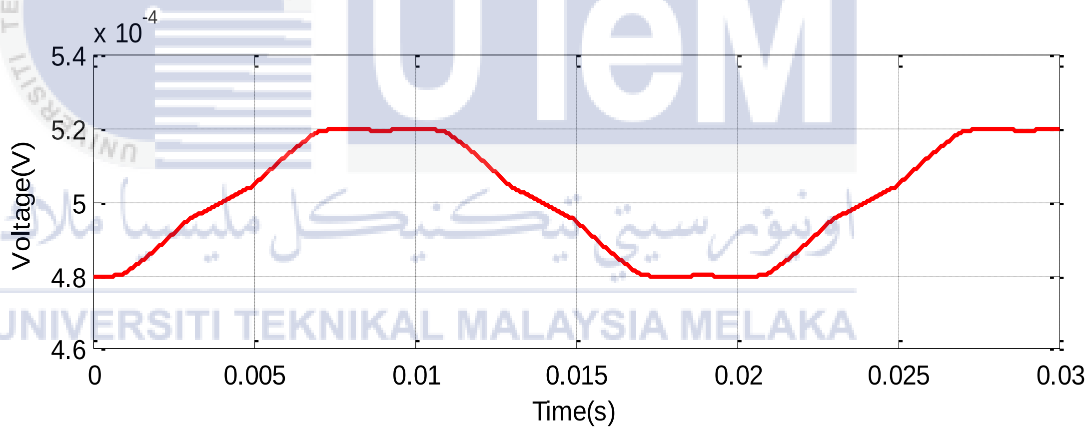


Figure 3.34: Waveform for switching pattern T9

Figure 3.35 shows that the waveform of the switching pattern for T1, T3, T5, T7 and T9. The frequency as mentioned earlier is all the same. The difference between each waveform is 72° apart.

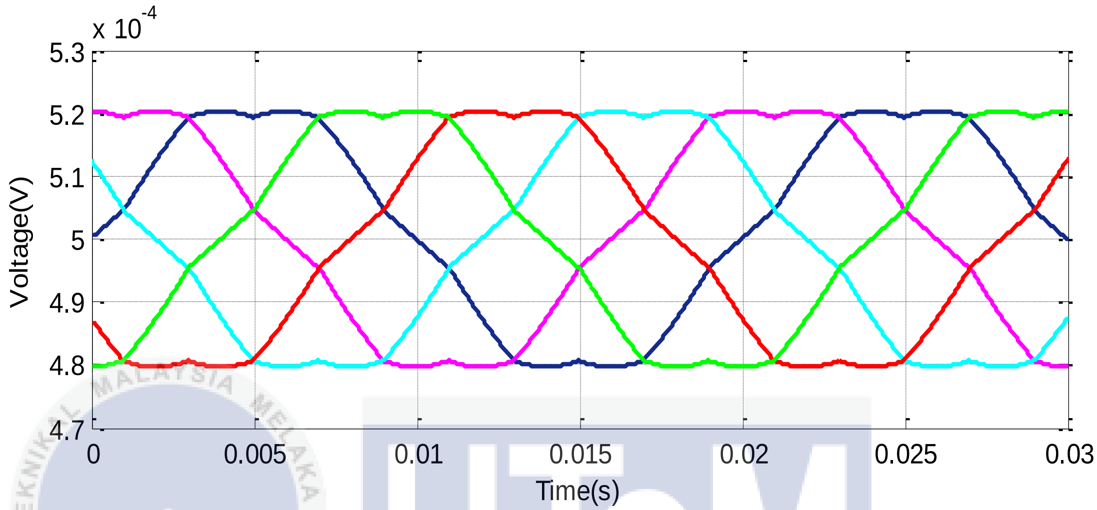


Figure 3.35: Waveform for switching pattern T1, T3, T5, T7 and T9

The outputs from the previous block which is T1, T3, T5, T7 and T9 was used as an input for the next model. The next model is to generate switching signal for the five-phase voltage source inverter. Figure 3.36 shows the general block diagram for the generation of switching signal.

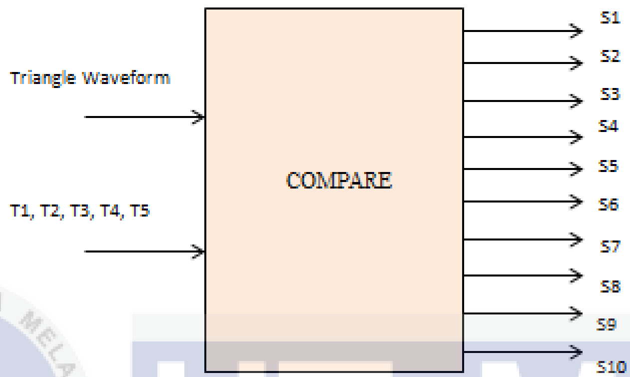


Figure 3.36: General block diagram for generating the switching signal

Figure 3.37 shows the block for generating switching signal by using Simulink. The method to generate the switching signal is by comparing the triangle wave with the switching pattern from the previous output which is T1, T3, T5, 7 and T9. The triangle wave generated from the repeating sequence block in Simulink.

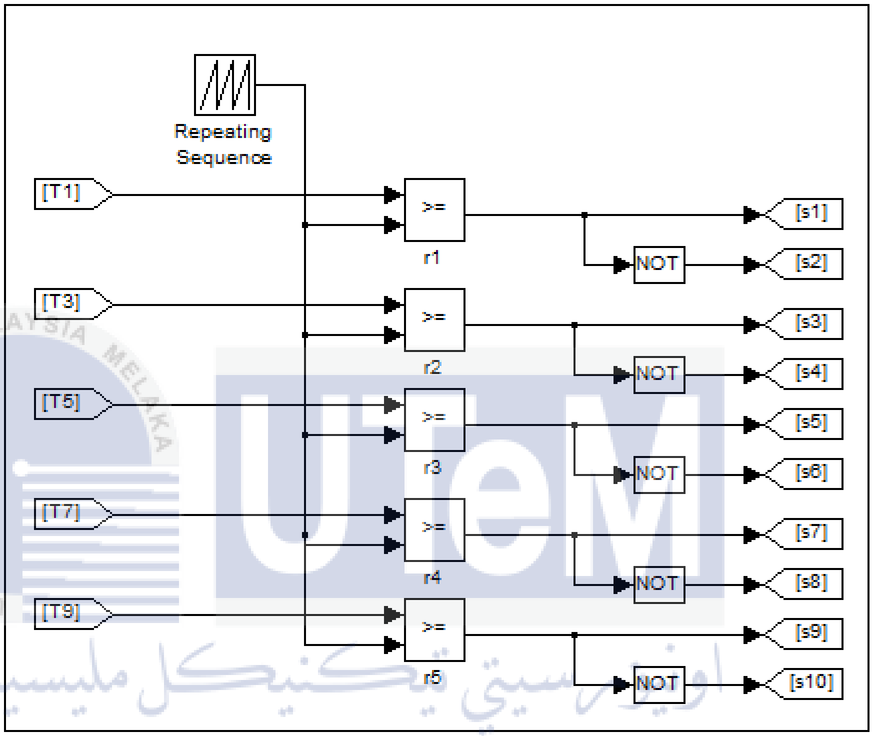


Figure 3.37: Generating switching signal

Figure 3.38 shows that the triangle wave generated from the repeating sequence block from the Simulink. The frequency is 10 kHz for one complete cycle with amplitude of 0.001V.

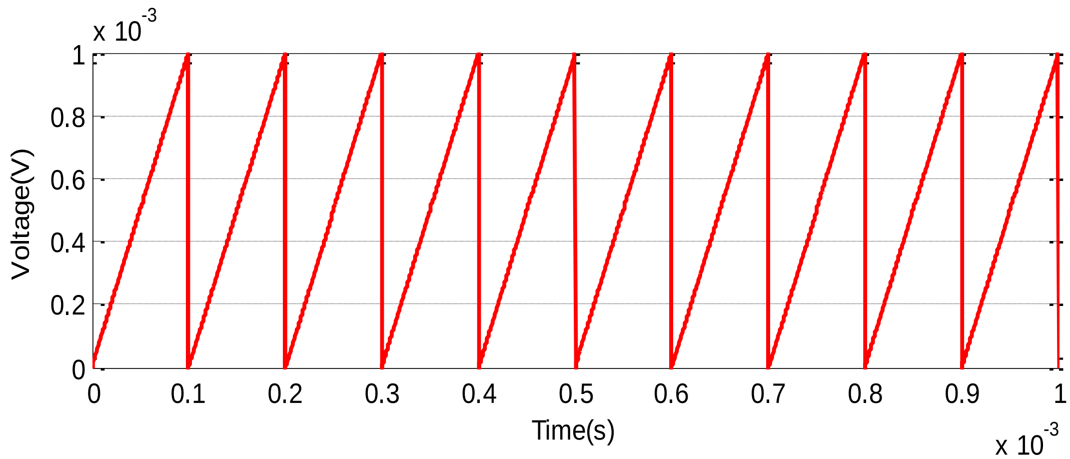


Figure 3.38: Triangle wave generated from repeating sequence block

3.6 Modeling of the drive system

The voltage that was produced from the leg of the inverter need to transform into phase voltage so that it can connect to the induction motor. To transform the leg voltage into phase voltage, it must be transformed into line voltage first. The relationship between line voltage and leg voltage of the inverter was shown in the equation (3.25). Different between two leg voltages can be defined as line voltage.

$$\begin{aligned} V_{EA} &= V_E - V_A \\ V_{AB} &= V_A - V_B \\ V_{BC} &= V_B - V_C \\ V_{CD} &= V_C - V_D \\ V_{DE} &= V_D - V_E \end{aligned} \tag{3.25}$$

The relationship between phase voltage and line voltage was shown in equation (3.26). Equation (3.1) produced by substitute equation (3.25) into equation (3.26). Once the line voltage transformed into phase voltage, it will connect to the induction motor. When two leg voltage was compared, it produced line voltage. The output of this block is phase voltage and line voltage. Figure 3.39 shows the conversion of leg voltage to phase voltage.

$$\begin{aligned} v_a &= \frac{1}{5}(V_{AB} - V_{CD} - 2V_{DE} - 3V_{EA}) \\ v_b &= \frac{1}{5}(V_{BC} - V_{DE} - 2V_{EA} - 3V_{AB}) \\ v_c &= \frac{1}{5}(V_{CD} - V_{EA} - 2V_{AB} - 3V_{BC}) \\ v_d &= \frac{1}{5}(V_{DE} - V_{AB} - 2V_{BC} - 3V_{CD}) \\ v_e &= \frac{1}{5}(V_{EA} - V_{BC} - 2V_{CD} - 3V_{DE}) \end{aligned} \tag{3.26}$$

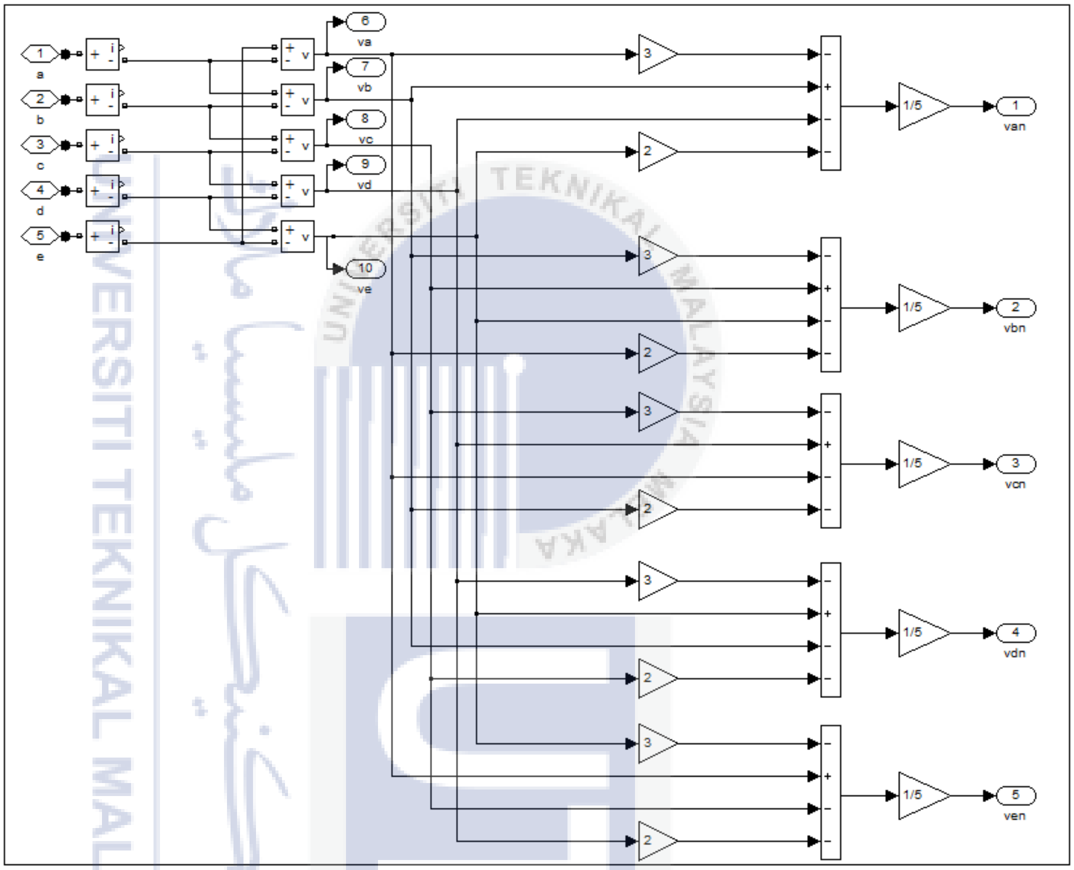


Figure 3.39: Conversion from leg voltage to phase voltage

3.7 Modeling of the Induction Motor

After modeling the five-phase Voltage Source Inverter (VSI), the five-phase induction motor was built. Five-phase supply was used as an input for this block. First step to build induction motor is to transform the five-phase supply into two phase voltage. The purpose of the induction motor is to produce speed and torque of the motor. There are some calculation that must be done before the speed and torque can be produced. The voltage for the stator and rotor must be found first. Besides, the flux for the stator and rotor also need to find. Mathematical equation was involved in this part to produce speed and torque of the motor. Figure 3.40 shows the general block diagram for the induction motor.

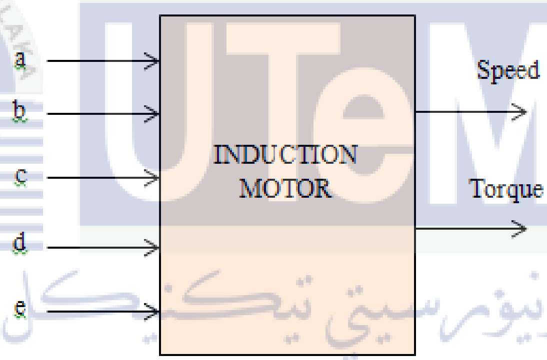


Figure 3.40: General block diagram for induction motor

The equation that was used to find the stator and rotor voltage is [7]:

$$V_{ds} = R_s I_{ds} - \omega_a \phi_{qs} + p\phi_{ds} \tag{3.27}$$

$$V_{qs} = R_s I_{qs} - \omega_a \phi_{ds} + p\phi_{qs} \tag{3.28}$$

$$V_{dr} = R_r I_{dr} - (\omega_a - \omega)\phi_{qr} + p\phi_{dr} \tag{3.29}$$

$$V_{qr} = R_r I_{qr} - (\omega_a - \omega)\phi_{dr} + p\phi_{qr} \tag{3.30}$$

The flux for the stator and rotor can be identify by using equation below [7]:

$$\phi_{ds} = (L_{ls} + L_m)I_{ds} + L_m I_{dr} \tag{3.31}$$

$$\phi_{qs} = (L_{ls} + L_m)I_{qs} + L_m I_{qr} \tag{3.32}$$

$$\phi_{dr} = (L_{lr} + L_m)I_{dr} + L_m I_{ds} \tag{3.33}$$

$$\phi_{qr} = (L_{lr} + L_m)I_{qr} + L_m I_{qs} \tag{3.34}$$

Lastly, the mathematical equation for speed and torque was stated in equation below [7]:

$$T_e = PL_m\left(I_{dr}I_{qs} - I_{qr}I_{ds}\right) \tag{3.35}$$

$$\omega_r = \int \frac{P}{2J}(T_e - T_L)\, dt \tag{3.36}$$

Figure 3.41 shows that the block that produced flux for rotor and stator. The input for the block is Vds, Vqs, ids, iqs, wr, idr and iqr. Equation (3.31) until equation (3.34) was used to produce the flux for the rotor and stator.

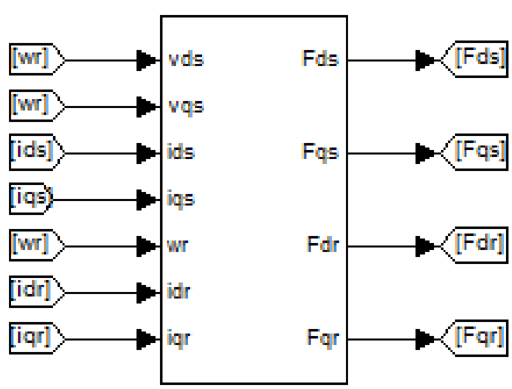


Figure 3.41: First block that produced flux

The mathematical block that was built to produce the output for the first block which is the flux for the rotor and stator was shown in Figure 3.42.

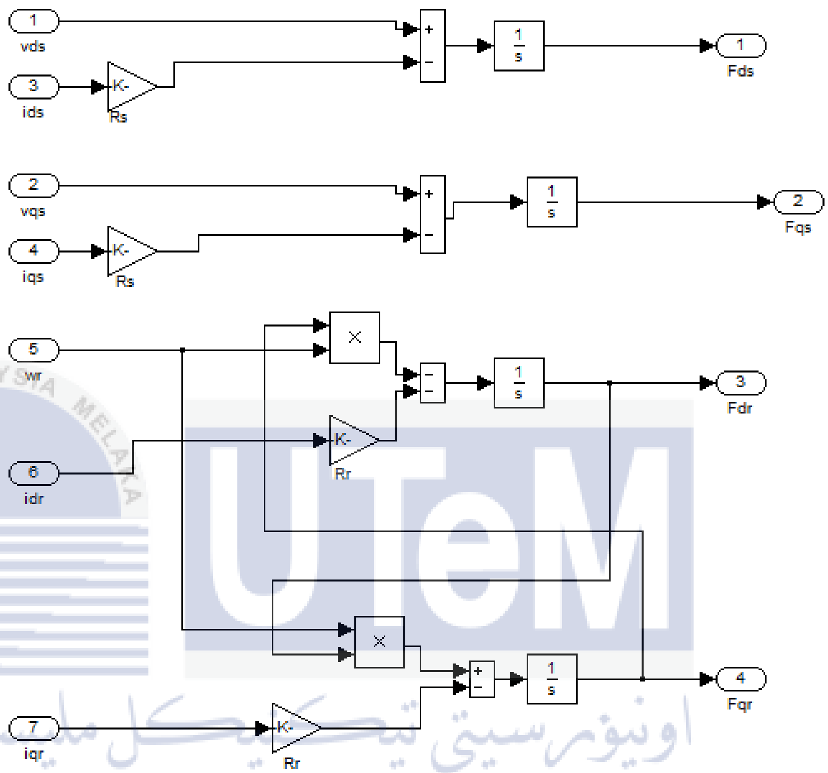


Figure 3.42: Mathematical block inside first block

After the first block finished, the second block was built. The input for the second block is flux of the stator and rotor. The output for this second block is the current for the stator and rotor. Figure 3.43 shows the block for the second block.

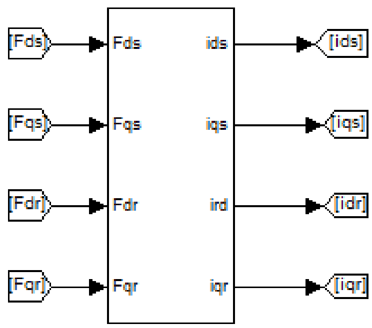


Figure 3.43: Second block that produced current for stator and rotor

The mathematical model for the equation (3.27) and (3.30) was shown in Figure 3.44. This model was the model that contains inside the second block.

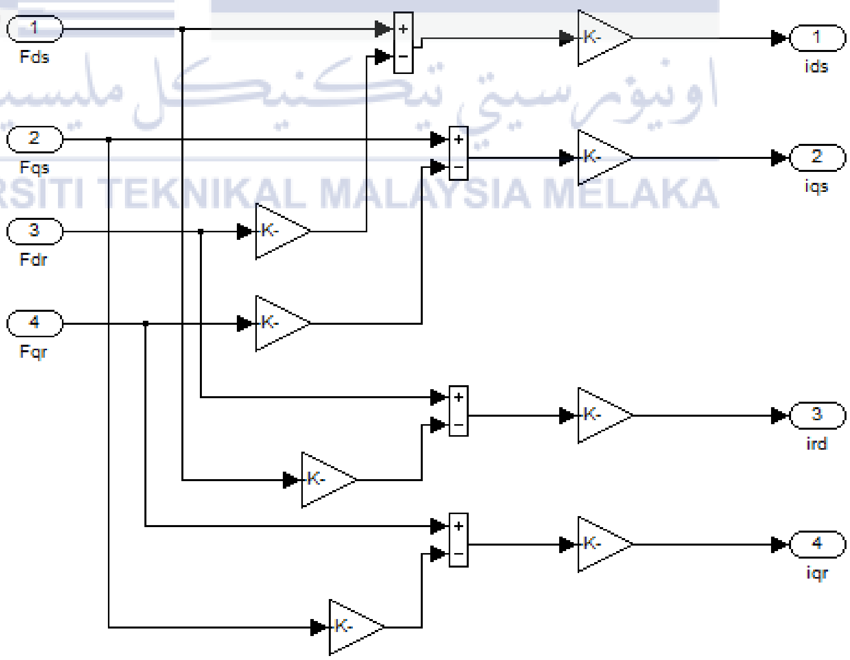


Figure 3.44: Mathematical block inside second block

The output from the second block which is the current of the stator and rotor was used as an input for the last block. This block produced the speed and torque of the motor. Figure 3.45 shows the last block which is produced speed and torque. Equation (3.35) and (3.36) was used to produced the output for this block.

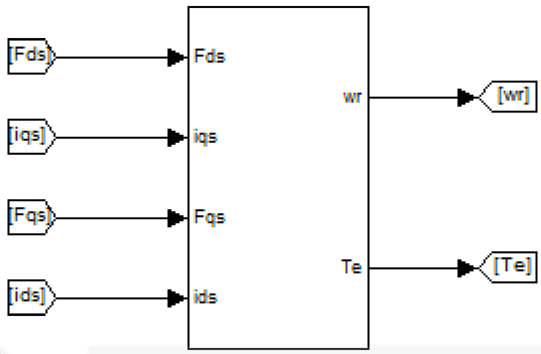


Figure 3.45: Block that produced speed and torque

Figure 3.46 shows that the component that exists inside the last block which is the block that produced speed and torque of the motor.

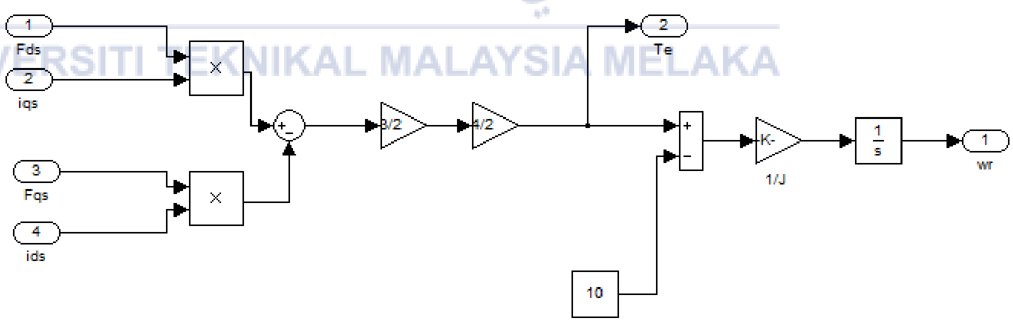


Figure 3.46: Components inside the last block

3.8 Field Oriented Control (FOC)

After completed modeling five-phase Space Vector Modulation (SVM), Voltage Source Inverter (VSI) and induction motor, the next step is about the control method which is Field Oriented Control (FOC) Method. As mentioned earlier, FOC is a method of controlling the current space vector directly in the d-q rotor reference frame where d is refer as flux and q is refer as torque.

The stator current labeled as ids and iqs that was produced from the induction motor block is a two phase current Iα and Iβ. This two currents was transformed into actual d-q reference frame by using park transformation. After the transformation, this two components will be feedback to be compared with the reference. The reference for the flux is zero and the reference for the torque is torque which is from the speed of the motor. Figure 3.47 shows that the general block diagram of FOC while Figure 3.48 shows the arrangement of all the blocks with FOC.

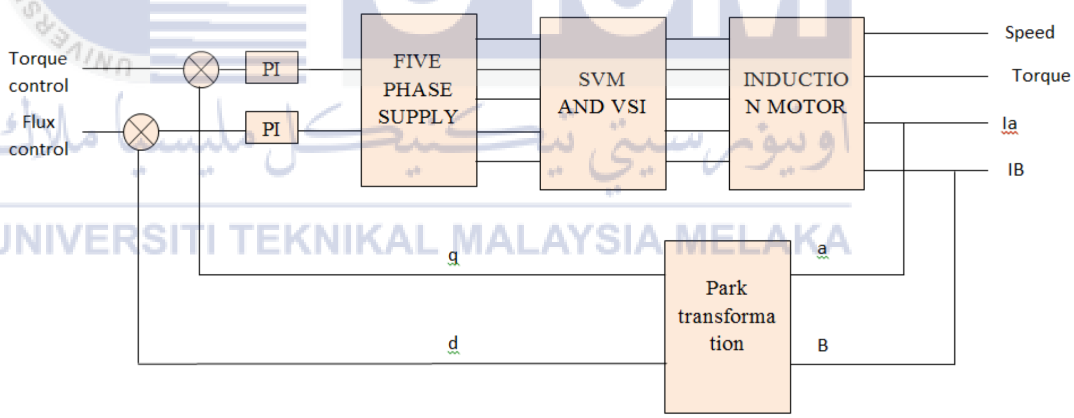


Figure 3.47: General block diagram of FOC

Figure 3.48 shows that the arrangement of all block which consists of Space Vector Modulation (SVM), Voltage Source Inverter (VSI), induction motor and Field Oriented Control (FOC) arrangement.

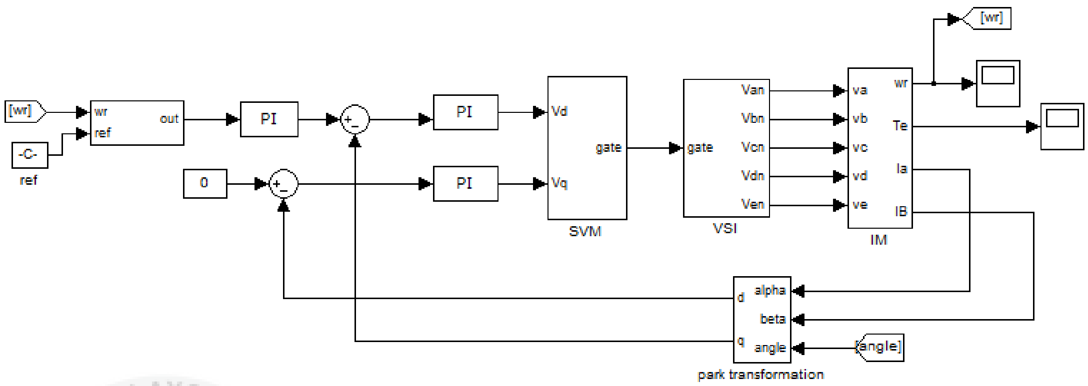


Figure 3.48: Arrangement of all blocks

CHAPTER 4

RESULT AND DISCUSSION

4.1 Five-phase Voltage Source Inverter

Figure 4.1 until 4.5 shows the phase voltage for five phase inverter. The output from the space vector modulation part which is the switching signal was used to operate the IGBT. The waveform of the phase voltage close to sinusoidal wave to make sure the motor run smoothly with better performance.

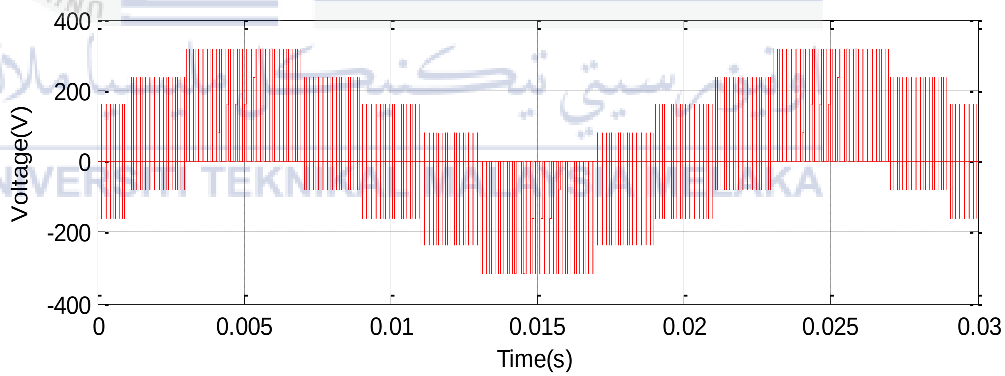


Figure 4.1: Phase voltage for phase a of the voltage source inverter

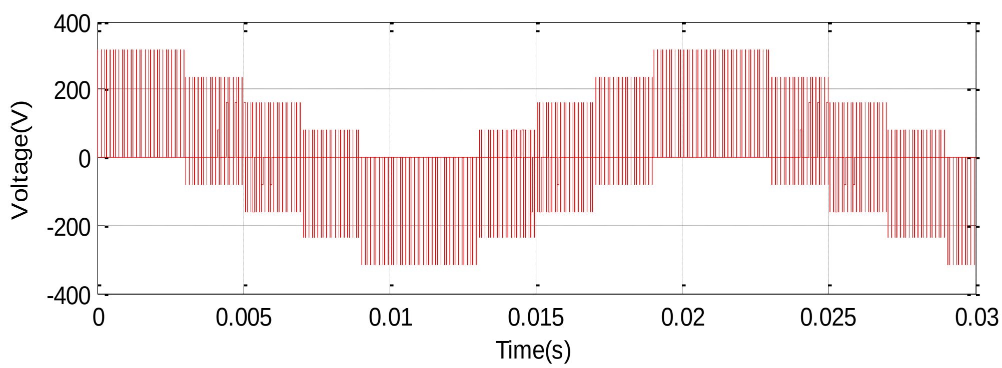


Figure 4.2: Phase voltage for phase b of the voltage source inverter

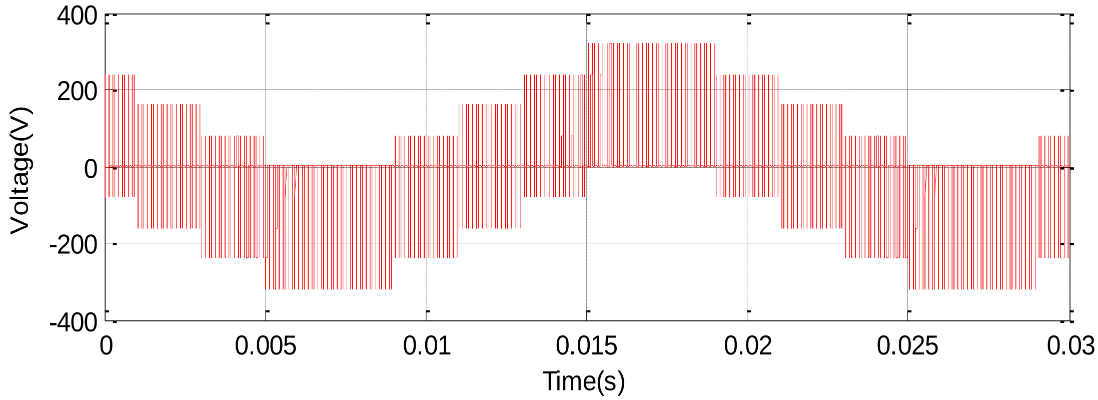


Figure 4.3: Phase voltage for phase c of the voltage source inverter

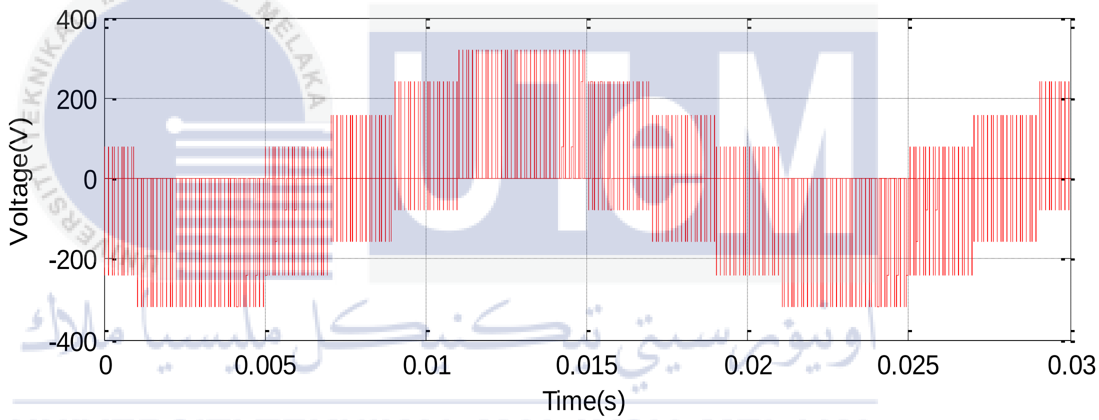


Figure 4.4: Phase voltage for phase d of the voltage source inverter

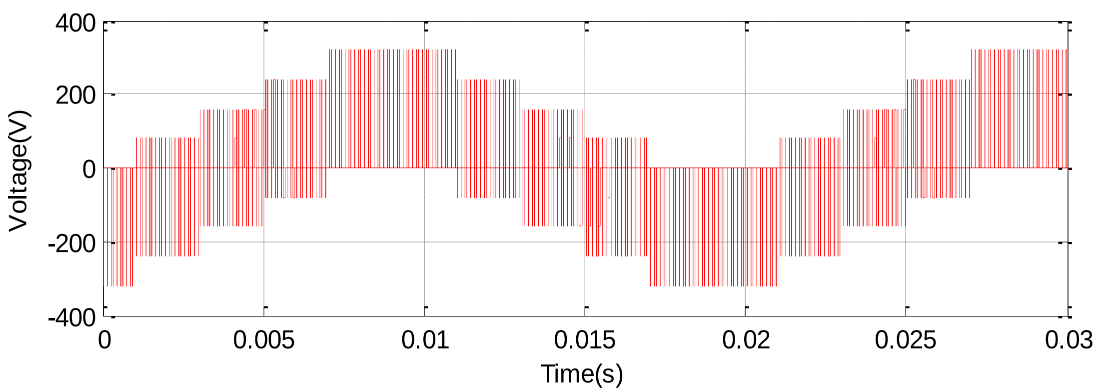


Figure 4.5: Phase voltage for phase e of the voltage source inverter

Next is the line voltage that is produced from the leg voltage of the inverter. As mentioned in chapter 3, the leg difference between two leg voltage produced line voltage. Figure 4.6 until 4.10 show the waveform of the line voltage for the leg inverter A, B, C, D and E.

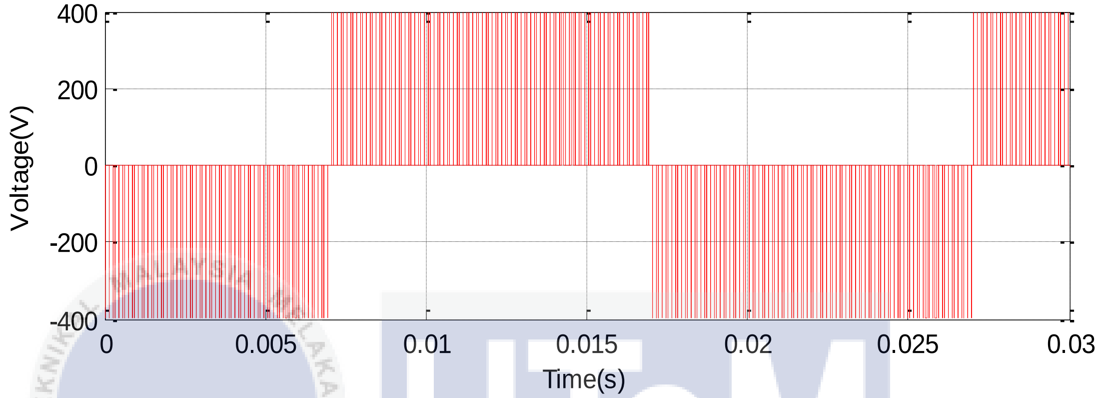


Figure 4.6: Line voltage for leg A

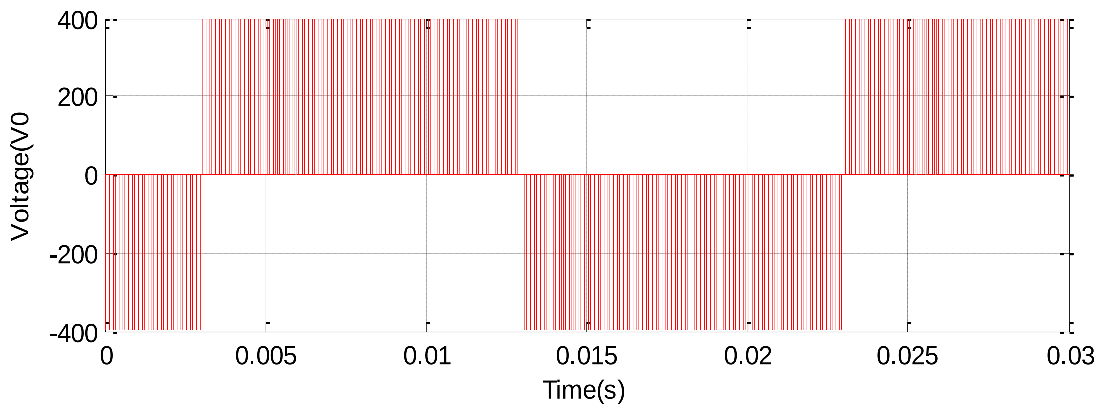


Figure 4.7: Line voltage for leg B

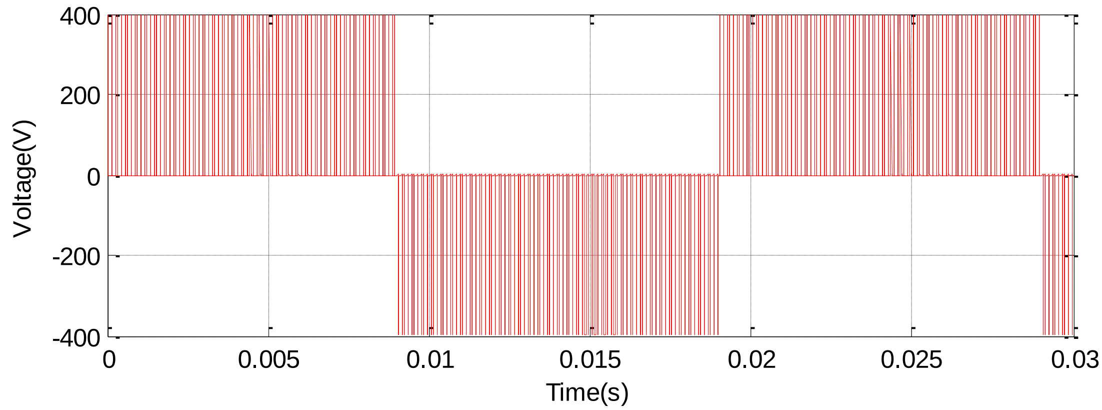


Figure 4.8: Line voltage for leg C

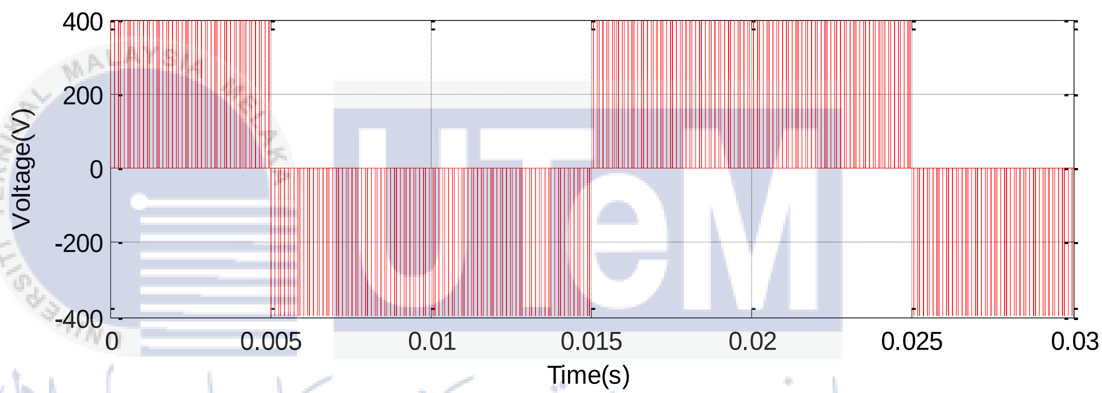


Figure 4.9: Line voltage for leg D

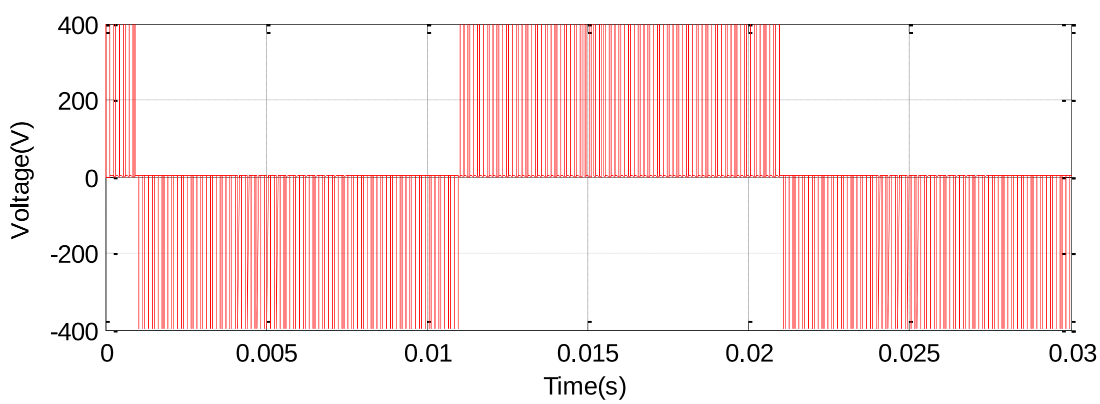


Figure 4.10: Line voltage for leg E

4.2 Space Vector Modulation (SVM)

Figure 4.11 until Figure 4.20 shows that the switching signal for each IGBT. This switching signal produced from comparing the triangular wave with the switching pattern T1, T3, T5, T7 and T9. The frequency of this waveform is 10 kHz.

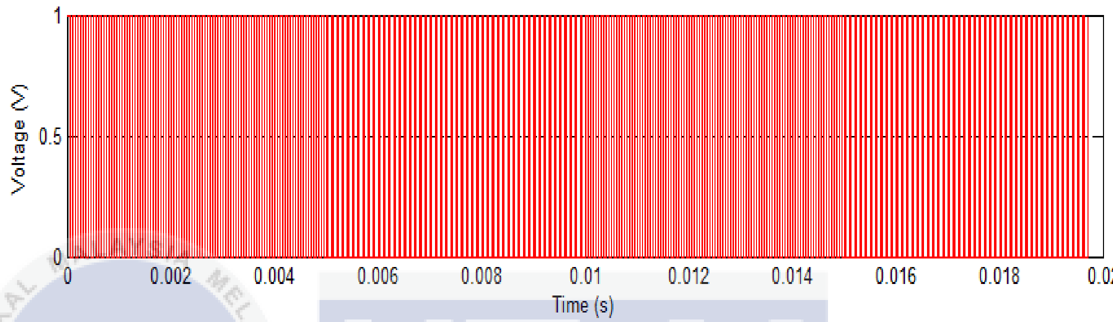


Figure 4.11: Switching signal s1

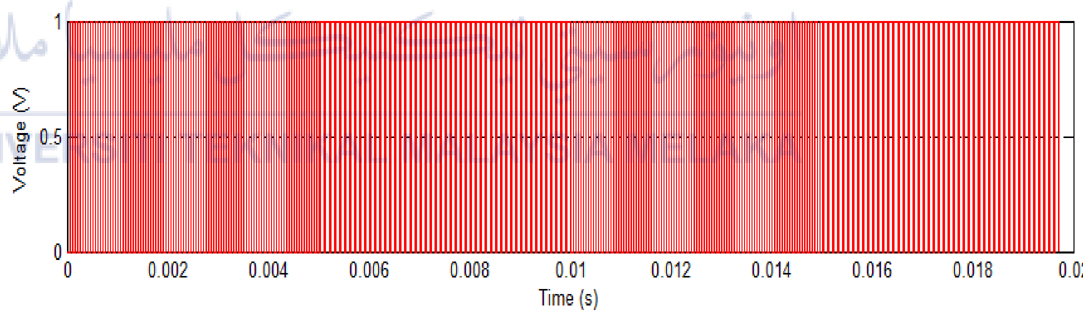


Figure 4.12: Switching signal s2

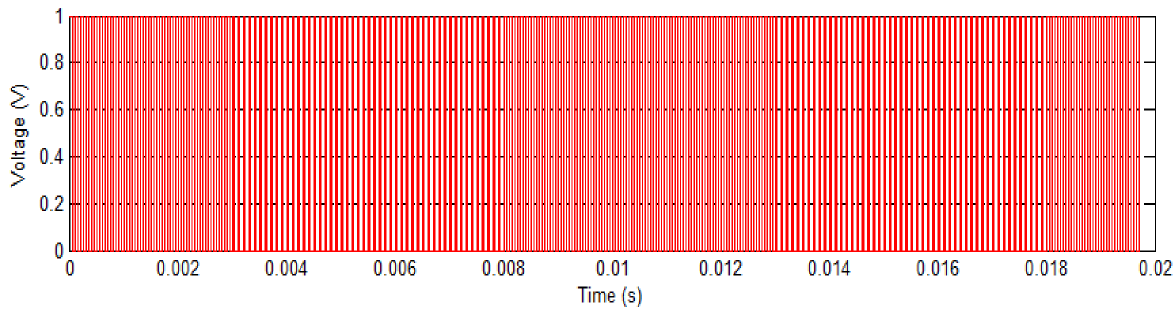


Figure 4.13: Switching signal s3

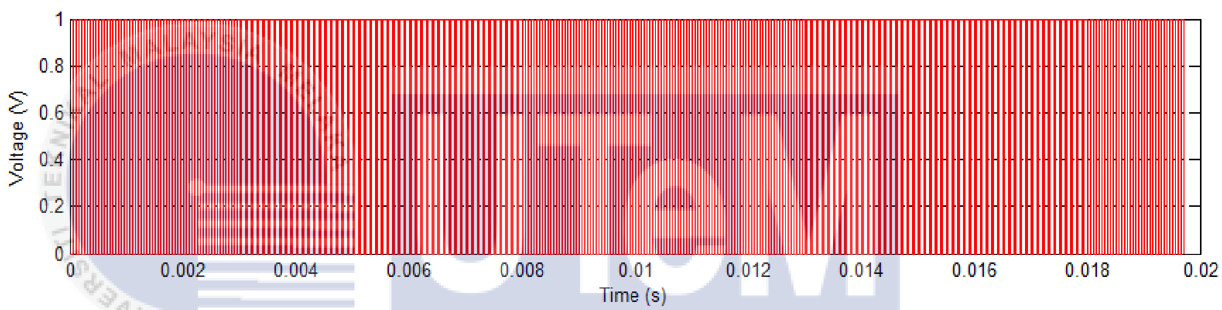


Figure 4.14: Switching signal s4

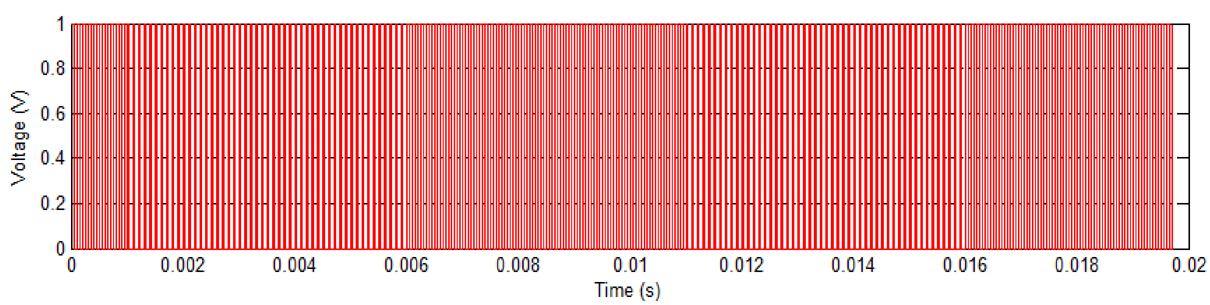


Figure 4.15: Switching signal s5

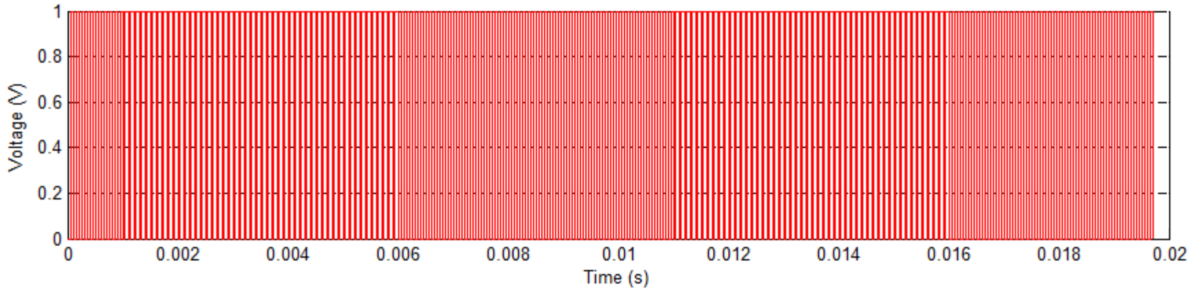


Figure 4.16: Switching signal s6

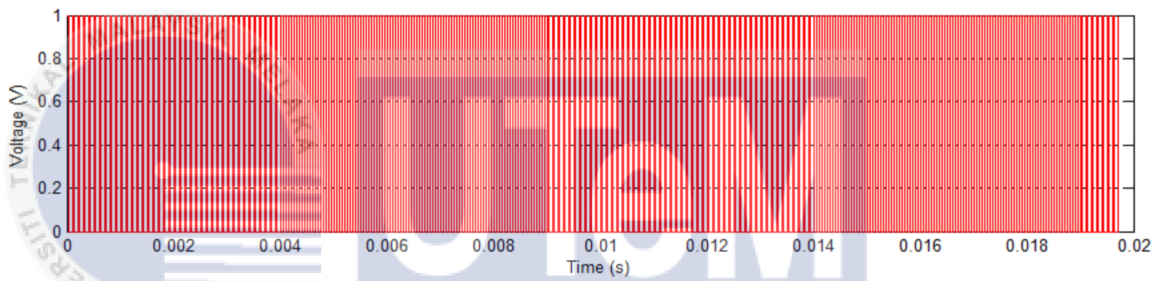


Figure 4.17: Switching signal s7

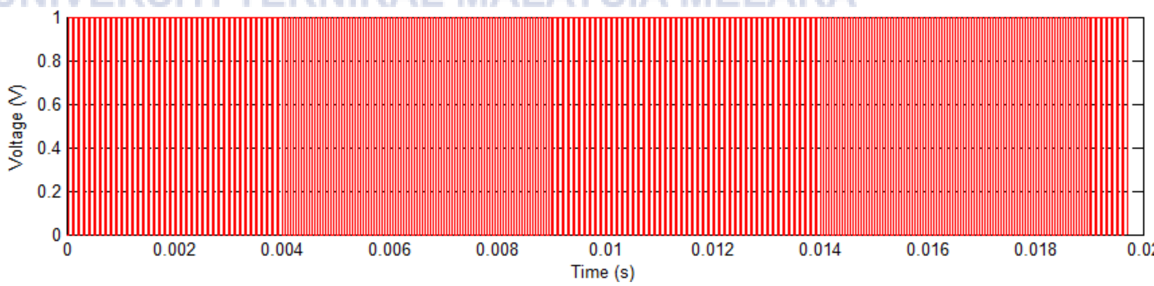


Figure 4.18: Switching signal s8

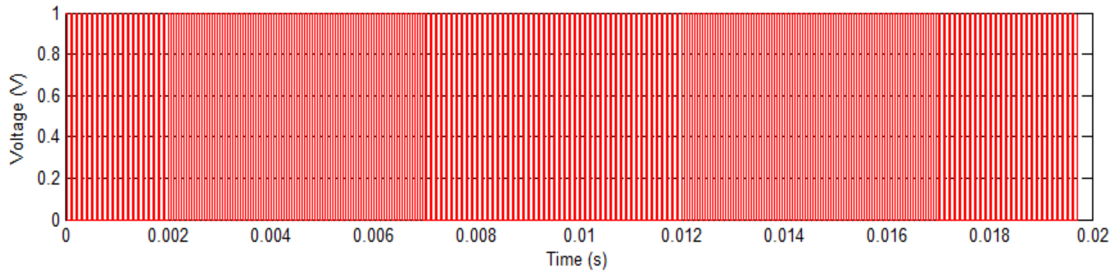


Figure 4.19: Switching signal s9

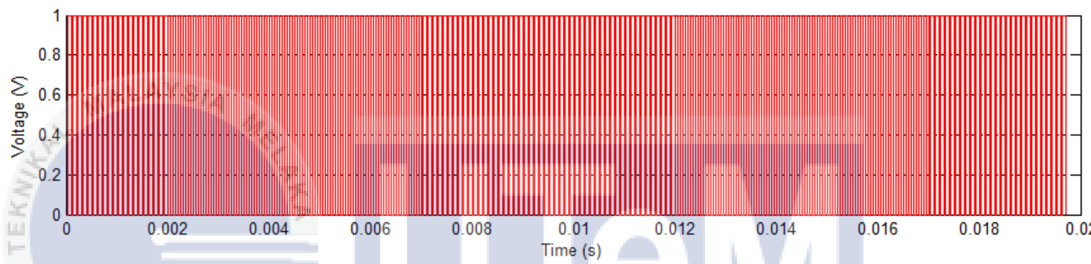


Figure 4.20: Switching signal s10

4.3 Induction Motor

As mentioned earlier in chapter 3, the second block for the induction motor produced current for stator. Figure 4.21 shows that the current alpha (Iα) and beeta (Iβ) for the stator. At the beginning, there is some over current occur. The reason is because the rotor needs to start and rotate to achieve constant speed.

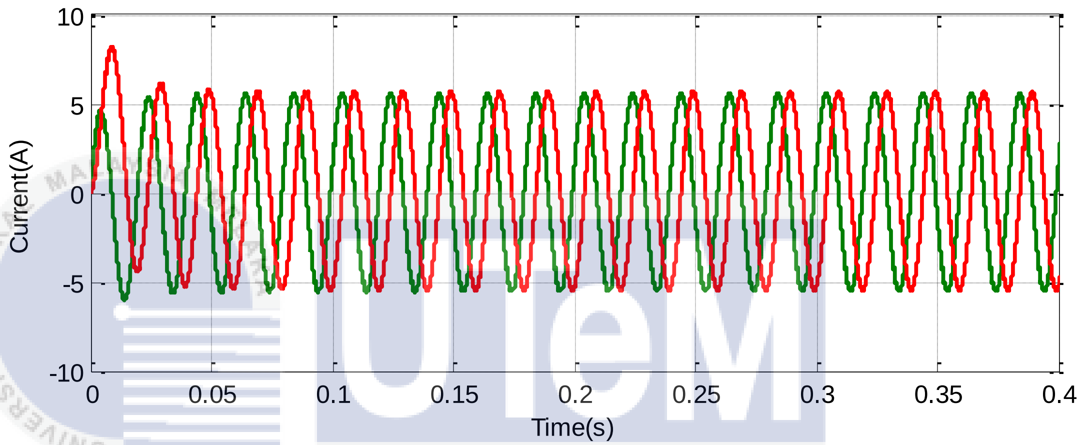


Figure 4.21: Two-phase stator current

To obtain the current for each phase, the two phase stator current needs to be transformed by using transformation block. Figure 4.22 until Figure 4.26 shows that the current for phase a until phase e.

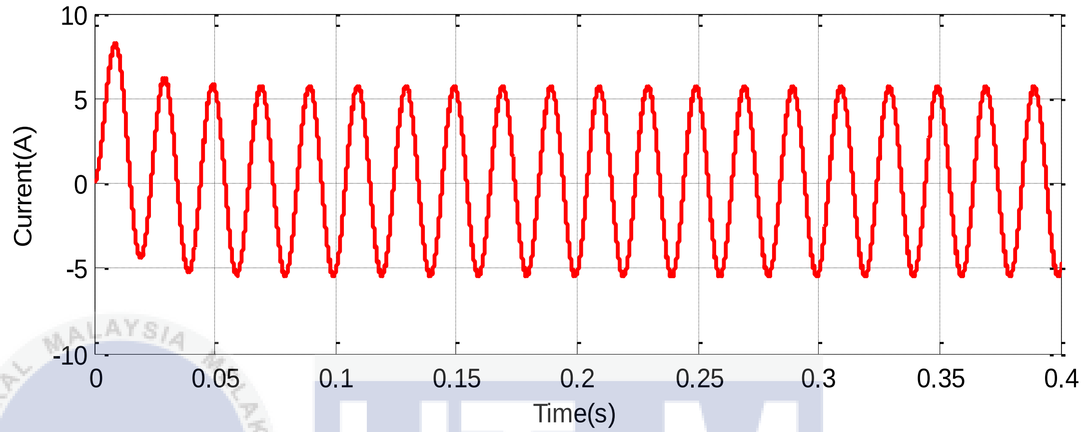


Figure 4.22: Stator current for phase a

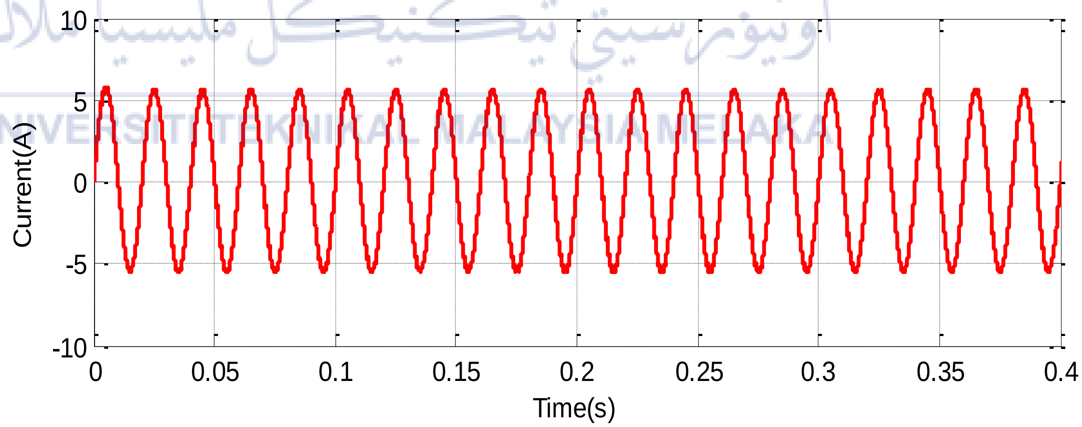


Figure 4.23: Stator current for phase b

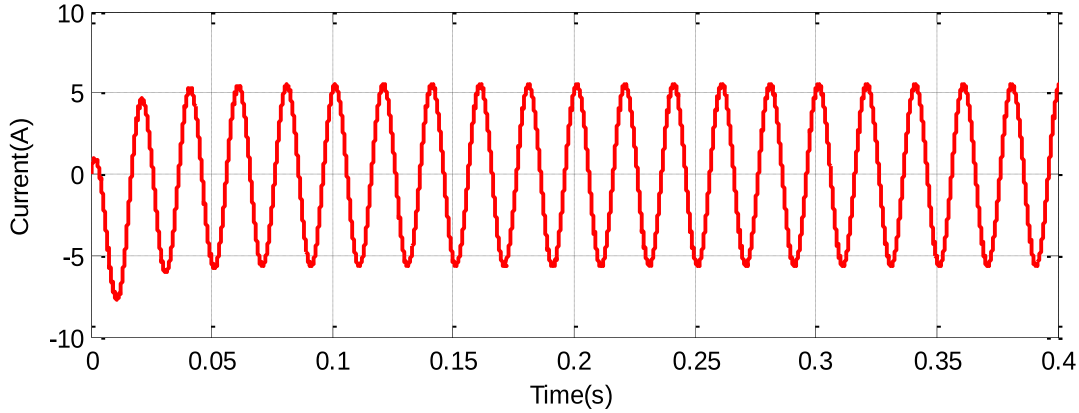


Figure 4.24: Stator current for phase c

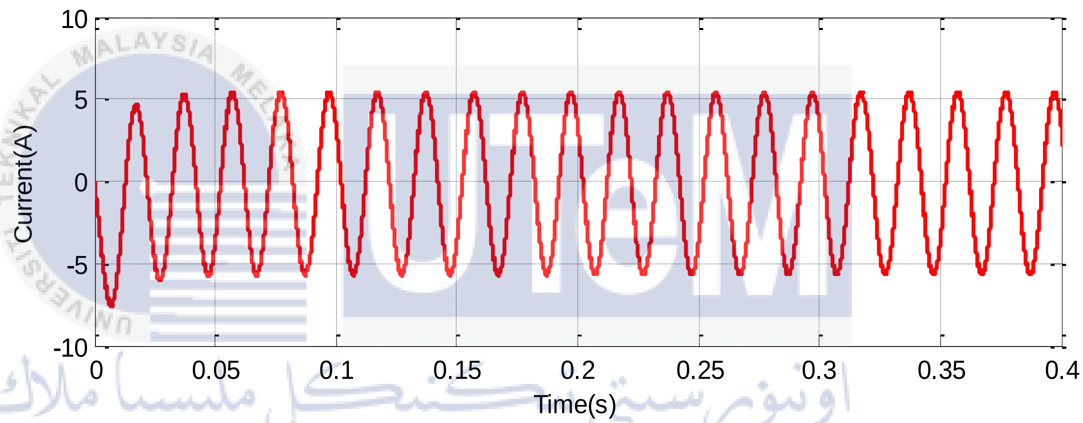


Figure 4.25: Stator current for phase d

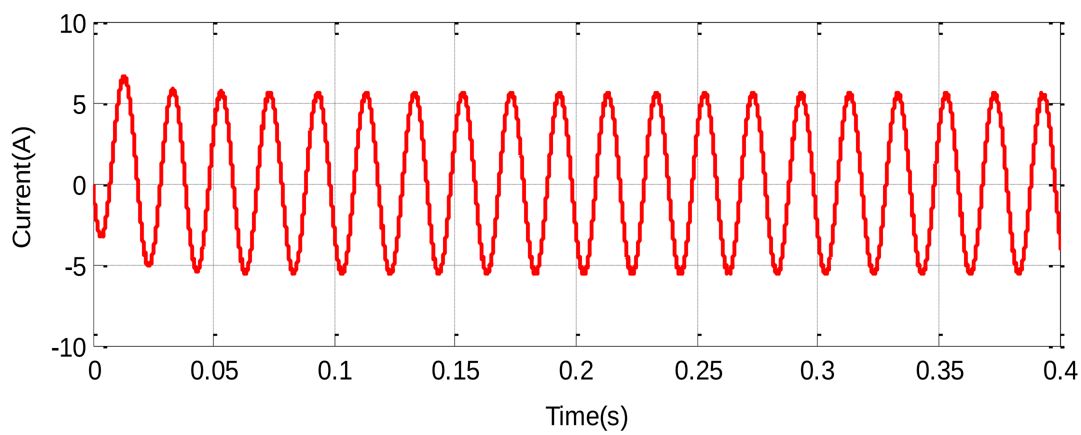


Figure 4.26: Stator current for phase e

For the last part of the induction motor block, block that produces speed and torque of the motor. Figure 4.27 shows the torque of the induction motor. Rotating force developed by the motor is called as torque. At the early stage, the torque of the motor nearly approach 0.2 Nm. This early stage shows that the torque that need by the motor to rotate. As the motor nearly approach constant speed, the torque decreasing and nearly approach zero value.

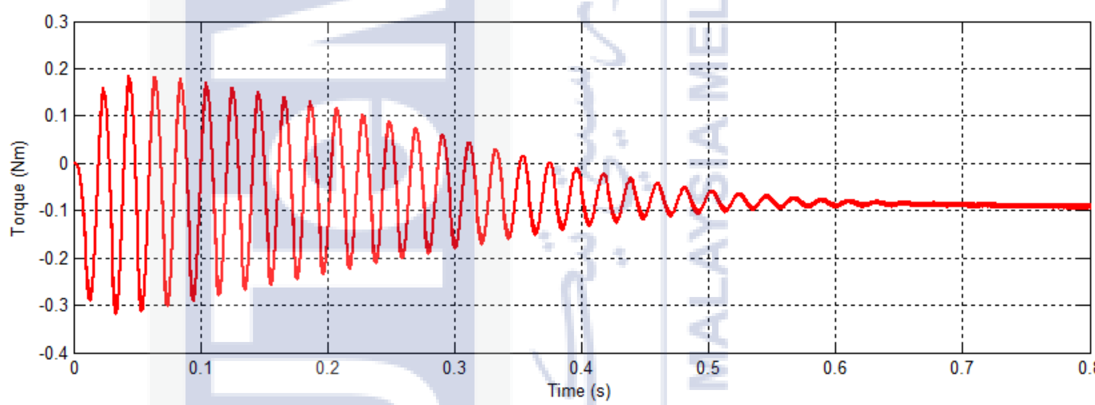


Figure 4.27: Torque of the motor

Figure 4.28 shows that the speed of the induction motor. Based on the waveform, the speed increased from zero until achieved constant speed. The speed is constant at almost 1500 rpm. It takes about 10 s for the induction motor to reach constant speed.

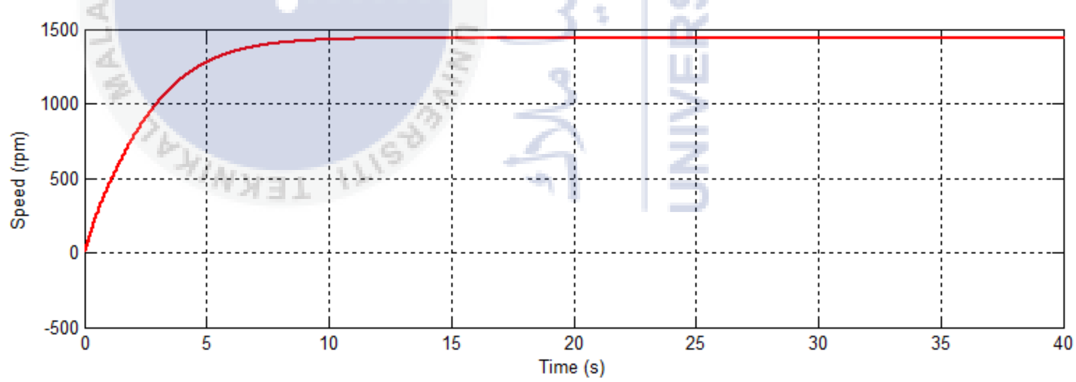


Figure 4.28: Speed of the induction motor

4.4 Experimental Part

For the experimental part, the hardware consists of gate driver and dspace. The result of the simulation can be implemented on real five phase induction motor with five phase inverter. The gate driver parts is already done and tested. The simulation can be uploaded into the dspace. By using dspace, the signals can be monitored and the parameters can be tuned while the application runs. Figure 4.29 and 4.30 shows the setup of the hardware. Figure 4.31 shows the result of the tested gate driver that confirms the functionality of the gate driver.

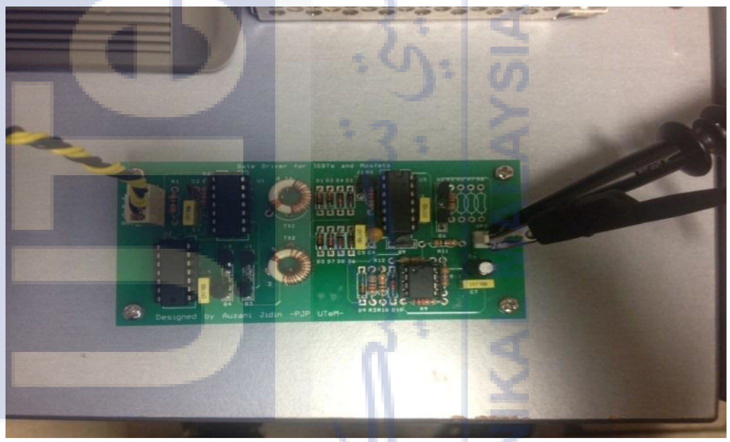


Figure 4.29: Gate driver

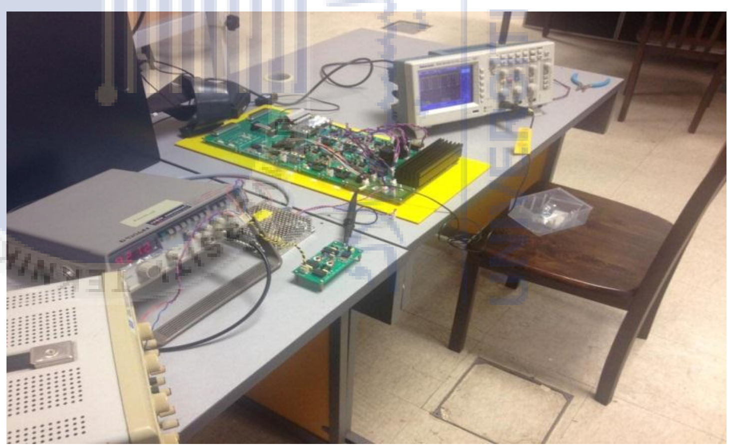


Figure 4.30: Setup of the hardware

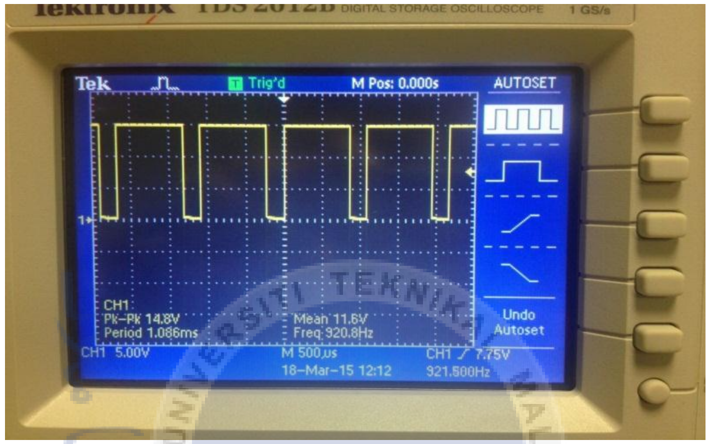


Figure 4.31: Result of the tested gate driver

CHAPTER 5

CONCLUSION

5.1 Conclusion

For a conclusion, all the topics that covered in this project should be understand by student. Besides, students able to applied the theoretical and skills related to the topic in this project. This projects also improves the skills and knowledge on troubleshooting, analyzing and simulation.

Space Vector Modulation (SVM) part is important. The output from SVM must be produced and generated accurately. The reason is if the output is not accurate, so the performance of the induction motor will be low. The waveform will have high harmonics which can cause motor not run smoothly and can cause the motor to have large vibrations. For that reasons, each part to modeling the SVM must be done carefully so that the output can drive the five-phase Voltage Source Inverter (VSI) effectively.

The objective of this project is to control the speed of the induction motor by using Field oriented Control (FOC) method. FOC is a method that controlling the current space vector in d-q rotor reference frame. Once the components changed into d-q state, the control becomes rather straight forward. FOC also provides smooth motion at slow speeds as well as efficient operations at high speeds.

5.2 Future Work

For future work, the simulation result can be implemented using the real five phase induction motor and five phase voltage source inverter. Besides, the simulation can be continued for the futher part.

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