SPACE VECTOR MODULATION FOR FIVE-PHASE INDUCTION SPEED DRIVE CONTROL

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A report submitted in partial fulfilment of the requirement for the degree of Bachelor in Electrical Engineering

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Faculty of Electrical Engineering

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MAY 2014

I declare that this report entitle “Space Vector Modulation for Five-phase Induction Speed Drive Control" is the result of my own research except as cited I the reference. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Date : ………………………………

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Dedicate to beloved parents and family.

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ABSTRACT

Multiphase motor drives considered for various applications. Utilization of AC machines with number higher than three can be enables using application of power electronic in electrical drives. The 5-phase motor drive has many advantages compared with the 3-phase motor such as reducing amplitude of torque and current pulsation. Aim of this project is to control the speed response of five-phase induction motor using a space vector modulation. Space vector modulation has chosen as the switching scheme due to its easiness of digital implementation. Space vector modulation gives effective control of multiphase VSI because of large numbers of space vectors. The elaborated aspects include advantages of multiphase induction machines, modeling of five-phase induction machines and five-phase voltage source inverter and control scheme of space vector modulation. . For this project, space vector modulation schemes for a 5-phase VSI generated to drive 5-phase induction motor in order to control the speed of the motor. The speed of the motor should follow the reference speed that give as input. The performance of the five-phase induction motor been analyzed.

ABSTRAK

Pemacu motor berbilang telah meluas penggunaannya. Penggunaan AC motor dengan bilangan fasa melebihi tiga boleh aplikasikan dengan menggunakan peranti elektronik kuasa dalam pemacu elektrik. Pemacu motor lima fasa mempunyai banyak kelebihan apabila dibandingkan dengan pemacu tiga fasa, contoh kelebihannya ialah amplitud tork dan denyutan arus dapat dikurangkan. Tujuan utama projek ini adalah untuk mengawal kelajuan motor aruhan lima fasa dengan menggunakan modulasi vektor ruang. Modulasi vektor ruang dipilih sebagai peralihan skim kerana pelaksanaan digitalnya yang mudah. Modulasi vektor ruang memberikan peralihan skim yang sangat berkesan untuk sumber penyongsang voltan lima fasa kerana modulasi vektor ruang mempunyai banyak ruang. Huraian didalam laporan ini termasuk kebaikan motor aruhan pelbagai fasa, pemodelan motor aruhan lima fasa, sumber penyongsang voltan lima fasa dan peralihan skim untuk modulasi vektor ruang. Untuk projek ini, peralihan skim untuk sumber penyongsang voltan dihasilkan bagi memacu motor aruhan lima fasa. Kelajuan motor mesti mengikut kemasukan yang diberikan. Prestasi motor dianalisa diakhir projek ini.

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d : direct axis

q : quadrature axis

s : stator variable

r : rotor variable

V_{qs}, V_{ds} : d and q-axis stator voltages

V_{qr}, V_{dr} : d and q-axis rotor voltages

I_{qr}, I_{dr} : d and q-axis rotor currents

I_{qr}, I_{dr} : d and q-axis rotor currents

$\emptyset_{qs}, \emptyset_{ds}$: d and q-axis magnetizing flux linkages

p : number of poles

J : moment of inertia

T_e : electrical output torque

ω_a : stator angular electrical frequency

ω_r : rotor angular electrical speed.

CHAPTER 1

INTRODUCTION

1.1 Project Overview

For this project, the speed of the motor has control by space vector modulation. The five-phase voltage source inverter (VSI) is use to run five-phase induction motor. Space vector modulation has chosen as the switching scheme due to its easiness of digital implementation. Space vector modulation gives effective control of multiphase VSI because of large numbers of space vectors. Voltage source inverter (VSI) implemented using ten Metal-oxide Semiconductor Field Effect Transistor (MOSFET). The speed of the motor should follow the reference speed that give as input.

1.2 Project Motivation

Nowadays, multiphase motor drives considered for various applications. Utilization of AC machines with number higher than three can be enables using application of power electronic in electrical drives. The five-phase motor drive has many advantages compared with 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 in order to control the speed of the motor.

1.3 Problem Statement

A 5-phase machine has high fault tolerance. When one of the phase become fault, the machine can operate with three phase left. In order to run 5-phase machine, the drive system need to design and the space vector has chosen because it easy digital implementation.

1.4 Objectives

The research objectives are:

i. To design switching scheme for speed control of a five-phase induction motor and its drive.

ii. Simulate the five-phase speed drive control using a Matlab/Simulink.

iii. To analyze the performance of five-phase induction motor speed by space vector modulation.

1.5 Scope of Project

Scope of this project is running under the simulation environment. First, Matlab software will be use for simulation purposes. Then, the five-phase inverter and five-phase induction motor will stimulate in the Matlab/Simulink. After that, the switching scheme for five-phase inverter will program in Matlab/Simulink. Last, the five-phase induction motor will program in Matlab/Simulink. The drive will slowly design for induction motor and reference will be using space vector modulation.

1.6 Report Outlines

This report contains five chapters that explain in detail about the entire project to provide the understanding of the whole project.

Chapter 1- Introduction of the project

This chapter presents an overview of the project, objectives project, scope project and project outline.

Chapter 2- Literature Review

This chapter discuss about source and article that related to the project. This chapter also contains the theory of the components, equipments and programming software that used in the project. It helps more in understanding the concepts of the project.

Chapter 3- Design Methodology

This chapter covers up all the project implementation to achieve the objectives of the project. This chapter contains the method and procedure to finish the project. It also contains the step taken for the entire task to complete the project. All method and procedure to generate the expected results and the software technical details also explained in this chapter.

Chapter 4- Results and Discussion

This chapter contains the results and analysis of the project that been done. The results and the expected result also discuss in this chapter.

Chapter 5- Conclusion

This chapter contains the conclusion that can conclude from the project and the recommendations to improve the project.

CHAPTER 2

LITERATURE REVIEW

2.1 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 [1].

Interest in multi phase drives has increased in recent years due to several advantages when compared to three-phase drives. Multi phase 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 [2-3].

Power circuit topology for five-phase voltage source inverter with star-connected load presented. Five-phase space vector modulation can be developing 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 number of switching in inverter and decrease switching losses.

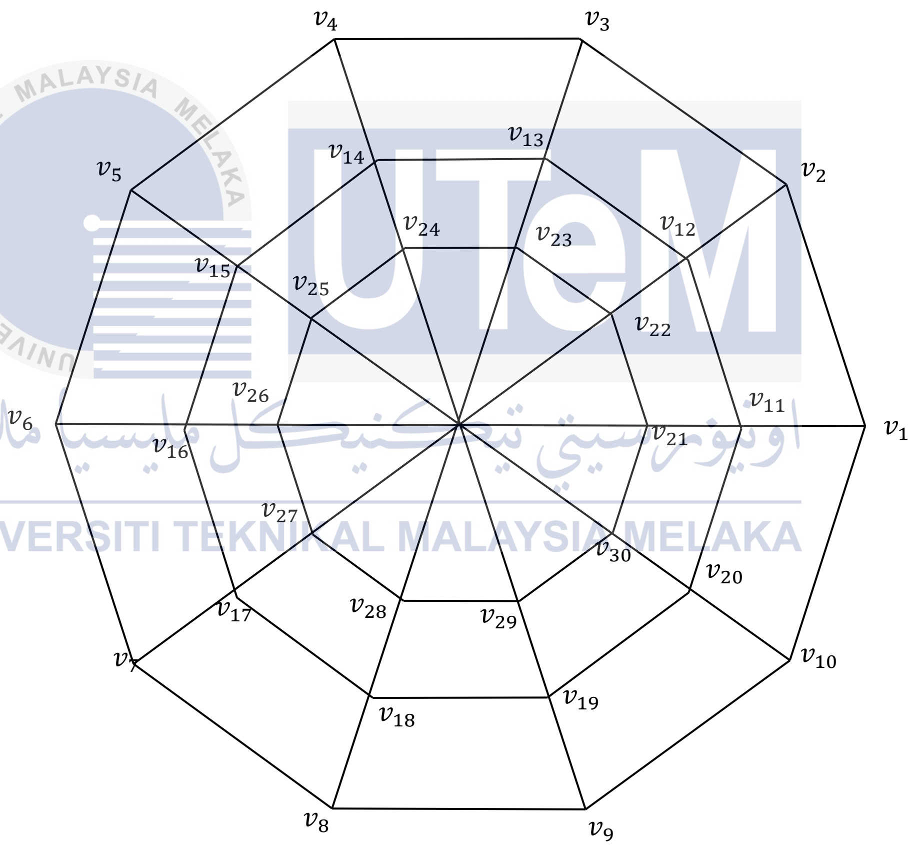

Figure 2.1: Phase to neutral voltage space vector in d-q plane.

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.

2.2 Induction Motor

Induction motor is the one of the most common electrical motor use. This motor runs at speed lower than synchronous speed and it also known as a synchronous motor. The speed of rotation of the magnetic field in a rotary 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 why speed of the induction machine always less than synchronous speed. Induction process occurred in the induction motor.

The working principle of the induction motors are as follow. When give supply to the stator winding, flow of current in the coil will generate the flux in the coil. The arrangement of the rotor winding will make it becomes short circuit in the rotor itself. When the rotor coil are short circuit, current will flow in the coil of the rotor because 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 is stator, rotor flux, and the stator flux will leading the rotor flux. Due to this, rotor will produce 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.

Fig 2.2 shows the equivalent per-phase electric circuit of an induction motor which consist of traditional parameters that is stator resistance, R_1, stator leakage reactance, X_1, magnetizing reactance, X_m, rotor leakage reactance, X_2 and rotor resistance, R_2.

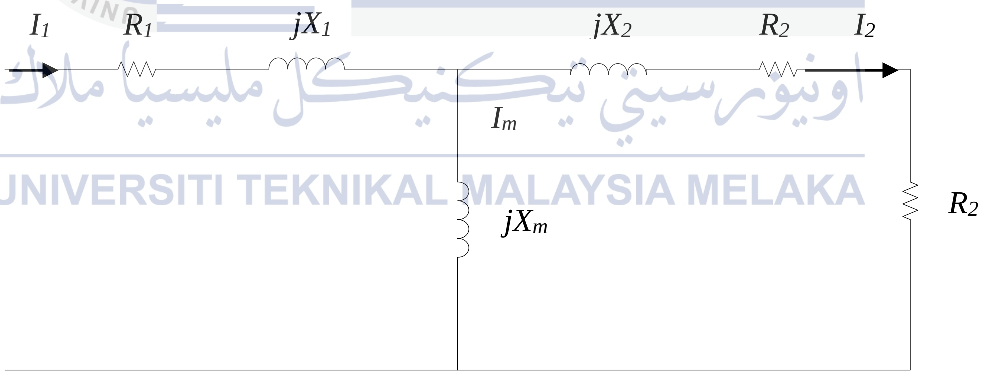

Figure 2.2: Per-phase equivalent circuit for induction motor.

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 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 compare to three-phase machine. One of the advantage 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 have greater fault tolerance than three-phase machine [4-5].

Last, multiphase machine are less susceptible compare to 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. 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 [4-5].

Multiphase motor can reduce the stator current without increasing the stator voltage and it has greater fault tolerance [1]. For modeling of five-phase induction machine, assume that the same number of phases of stator and rotor winding with 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. 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 compare to input ac of the utility supply.

Figure 2.3 shows the five-phase inverter that consist of ten MOSFET 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 shows in equation 2.1.

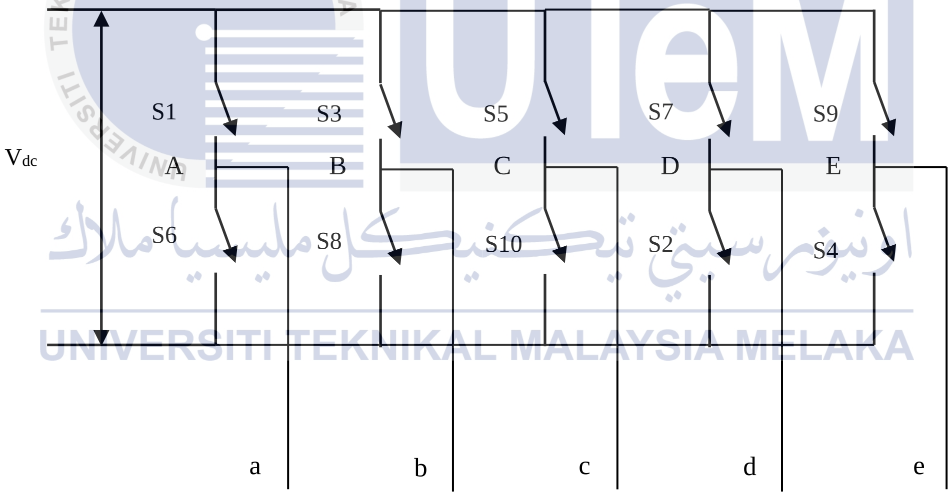

Figure 2.3: Power circuit of five-phase voltage source inverter.

$$v_a = \left({}^{4}/_{5}\right)v_A - \left({}^{1}/_{5}\right)(v_B + v_C + v_D + v_E)$$
$$v_b = \left({}^{4}/_{5}\right)v_B - \left({}^{1}/_{5}\right)(v_A + v_C + v_D + v_E)$$
$$v_c = \left({}^{4}/_{5}\right)v_C - \left({}^{1}/_{5}\right)(v_A + v_B + v_D + v_E) \qquad (2.4.1)$$
$$v_d = \left({}^{4}/_{5}\right)v_D - \left({}^{1}/_{5}\right)(v_A + v_B + v_C + v_E)$$
$$v_e = \left({}^{4}/_{5}\right)v_E - \left({}^{1}/_{5}\right)(v_A + v_B + v_C + v_D)$$

CHAPTER 3

METHODOLOGY

3.1 Project Methodology

This chapter explains about the project path from the beginning until the end of the project implementation. It will discuss the methodology of the whole project. Every selection and action that needs to take for make sure the project done properly explained in details.

In order to achieve the objectives of the project, some step need to follow. First, implement this project to real life for identify its problem. Then, design the system based on the objective. 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 design first. Five-phase inverter can be design same as the three-phase inverter that consist of 6 MOSFET but need to add the number of the MOSFET to ten.

3.2 Flowchart of Methodology

Figure 3.1 shows the flow of development for the project.

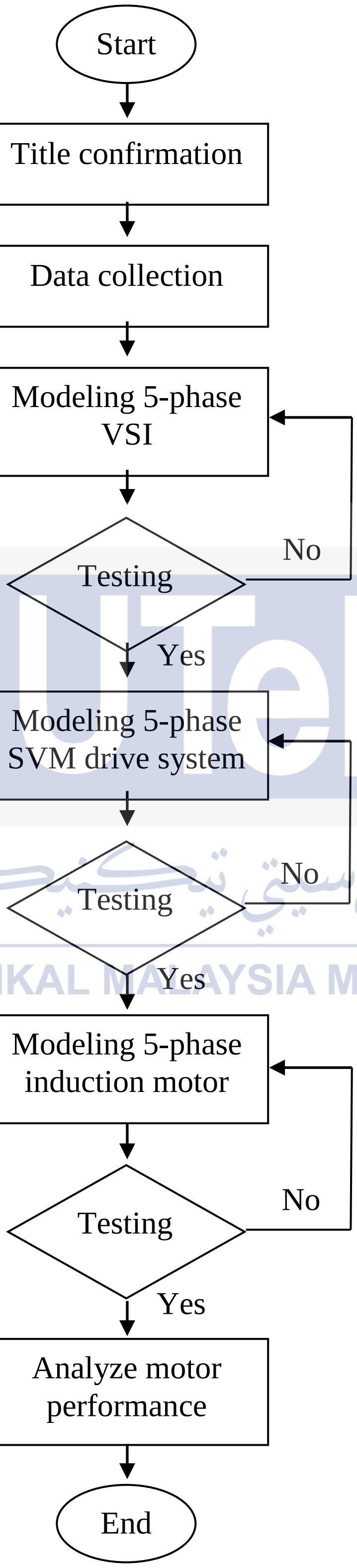

Figure 3.1: Flowchart of development project.

All modeling process using a Matlab/Simulink and the model need to test and the result of the model compare to the reference. When the result obtain like supposes, proceed with other modeling process. Modeling process all start with modeling 3-phase system before model the 5-phase system. When all modeling process complete, all the circuit compiled together and need to test before the motor performance can be analyze.

Five phase supply need to model first before modeling the inverter and the space vector drive. Five-phase supply was model using five sine wave generators that have different value of phase. The phase for first sine wave generator is 0, second is $^{2\pi}/_{5}$, third is $^{4\pi}/_{5}$, forth is $^{6\pi}/_{5}$ and fifth is $^{8\pi}/_{5}$. The entire sine wave generators were 72° apart. The frequency of the supply was 50 Hz.

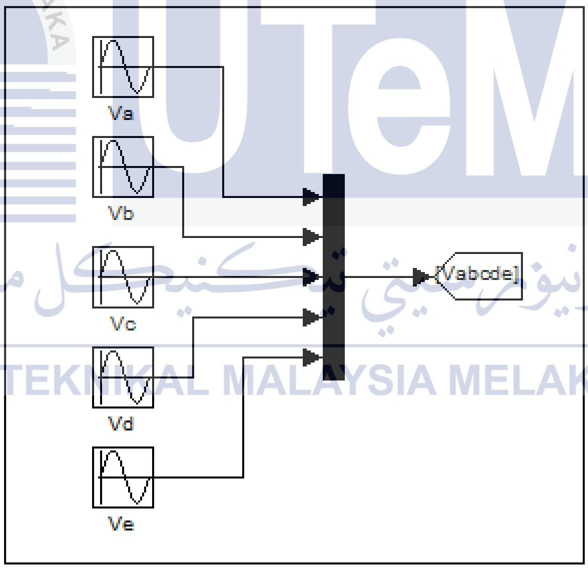

Figure 3.2: Five-phase supply generator for the SVPWM.

3.3 Modeling Five-phase Voltage Source Inverter

Five-phase Voltage Source Inverter (VSI) were model same way as modeling three-phase VSI but the numbers of metal-oxide semiconductor field effect transistor (MOSFET) use increase to 10 compare 6 in three-phase. MOSFET have certain advantages when compare to insulated-gate bipolar transistor (IGBT). The advantages are high switching frequency, increase the dynamic performance even less power from the driver and increase parallel current sharing.

Couple of MOSFET been connected in series while it been connected in parallel with other couple of MOSFET. There is five couple of MOSFET connected in parallel of the inverter. The relationship between machine's phase to neutral voltages and inverter leg voltages has given in equation (3.1). The lower case letters represented phase to neutral voltages and upper case letters represented the leg inverter voltage.

$$\begin{aligned}
v_a &= \left({}^4/_5\right)v_A - \left({}^1/_5\right)(v_B + v_C + v_D + v_E) \\
v_b &= \left({}^4/_5\right)v_B - \left({}^1/_5\right)(v_A + v_C + v_D + v_E) \\
v_c &= \left({}^4/_5\right)v_C - \left({}^1/_5\right)(v_A + v_B + v_D + v_E) \\
v_d &= \left({}^4/_5\right)v_D - \left({}^1/_5\right)(v_A + v_B + v_C + v_E) \\
v_e &= \left({}^4/_5\right)v_E - \left({}^1/_5\right)(v_A + v_B + v_C + v_D)
\end{aligned} \tag{3.1}$$

The five-phase inverter was model in Matlab/Simulink using 10 MOSFET and arranged as Figure 3.3.

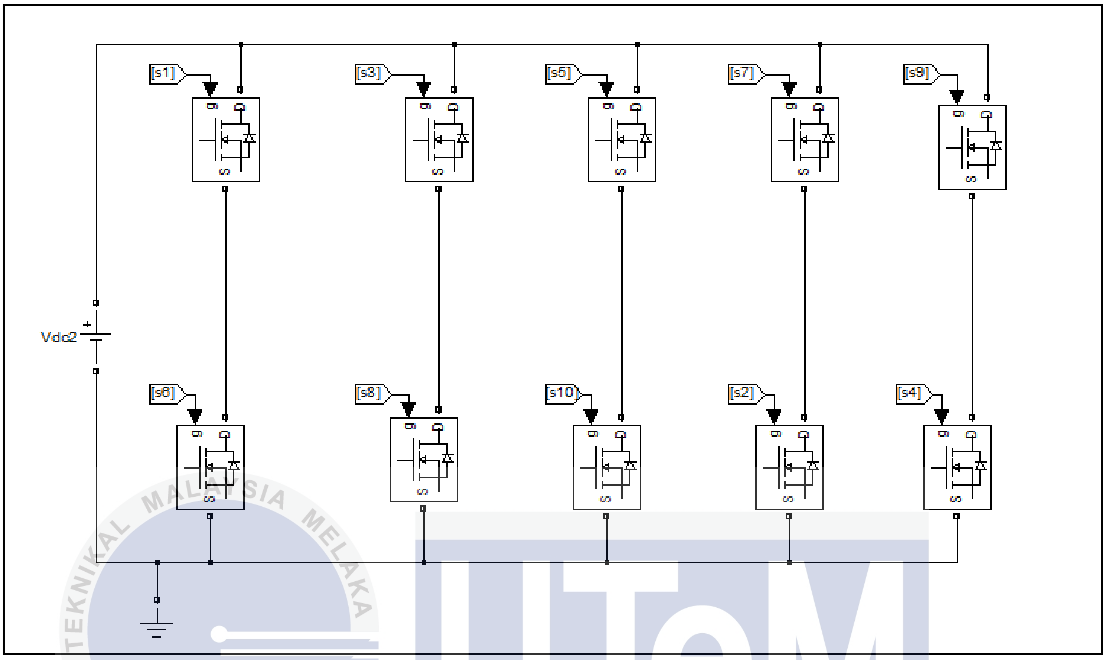

Figure 3.3: Five-phase voltage source inverter.

3.4 Space Vector Modulation Scheme

Generation of space vector switching scheme for the five-phase inverter start with transformed the five-supply into two dynamic rotating reference frames, d-q voltage. The five-phase supply been transformed into d-q voltage using equation (3.4) and (3.5) below. Figure 3.4 shows the block used in transforming the five phase supply into d-q voltage.

$$v_d = \frac{2}{5}\left[v_a \sin \omega t + v_b \sin\left(\omega t - \frac{2\pi}{5}\right) + v_c \sin\left(\omega t + \frac{2\pi}{5}\right) + v_d \sin\left(\omega t - \frac{4\pi}{5}\right) + v_e \sin\left(\omega t + \frac{4\pi}{5}\right)\right] \tag{3.2}$$

$$v_q = \frac{2}{5}\left[v_a \cos \omega t + v_b \cos\left(\omega t - \frac{2\pi}{5}\right) + v_c \cos\left(\omega t + \frac{2\pi}{5}\right) + v_d \cos\left(\omega t - \frac{4\pi}{5}\right) + v_e \cos\left(\omega t + \frac{4\pi}{5}\right)\right] \tag{3.3}$$

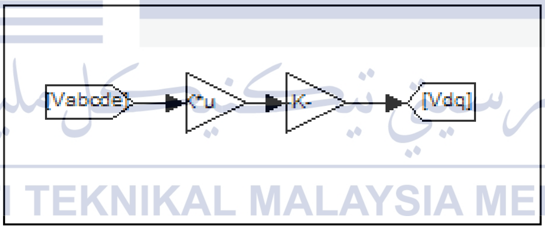

Figure 3.4: d-q transformation for supply.

From the d-q voltage, it passed through Real-Imag to Complex block and Complex to Magnitude-Angle block to produce voltage reference and the angle. The Real-Imag to Complex block converts imaginary inputs to complex valued output signal. The inputs can both be arrays (vectors or matrices) of equal dimensions, or one input can be an array and the other a scalar. If the block has an array input, the output is a complex array of the same dimensions. The elements of the real input are mapped to the real parts of the corresponding complex output elements. The imaginary input is similarly map to the imaginary parts of the complex output signals. If one input is a scalar, it is map to the corresponding component (real or imaginary) of all the complex output signals.

The Complex to Magnitude-Angle block accepts a complex-valued signal of type double or single. Its output the magnitude and/or phase angle of the input signal, depending on the setting of the output parameter. The outputs are real values of the same data type as the block input. The input can be array of complex signals, in which case the output signals are also arrays. The magnitude signal array contains the magnitudes of the corresponding complex input elements. The angle output similarly contains the angles of the input elements. Figure 3.5 shows the transformation of d-q voltage into V_{ref} and angle.

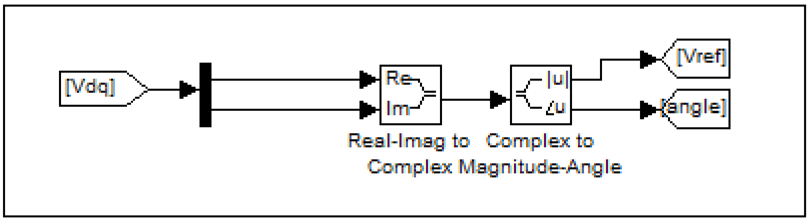

Figure 3.5: d-q voltage change into voltage reference and angle.

The angle output from the Complex to Magnitude-Angle block is the input of the angle to sector calculation block. The angle output from the Complex to Magnitude-Angle was in radian. The angle input for angle to sector calculation need to be in degree. Before entering the angle to sector calculation block, the angle were change to degree by multiply the angle with $180/pi$. Five-phase space vector have 10 sectors that were 36° apart. Figure 3.6 shows the angle to sector calculation block.

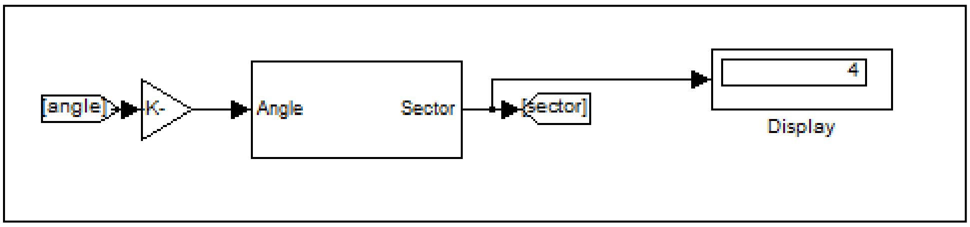

Figure 3.6: Angle to sector calculation block.

The angle to sector calculation block were model just like in three-phase angle to sector calculation block. The angle that been changed into degree is the input of the block. Input angle were compare to the reference angle for specific sector and be the input of the convert block. The Data Type Conversion block converts an input signal of any Simulink data type to the data type and scaling for specified Output Data type parameter. The input can be real or complex valued signal. If the input is real, the output is real. If the input is complex, the output is complex.

Five-phase space vector have 10 sectors that were 36° apart. 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 number of switching in inverter and decrease switching losses. For sector 1 the reference angle is 0° until 36° . The input angle been compared with the reference angle for the reference angle to state the sector. The display block displayed the current sector.

Figure 3.7 shows the calculation for the sector according to the reference angle and input angle. The path that been through for sector 1 is repeat for other sector but the reference angle for each sector is changed based on the sector.

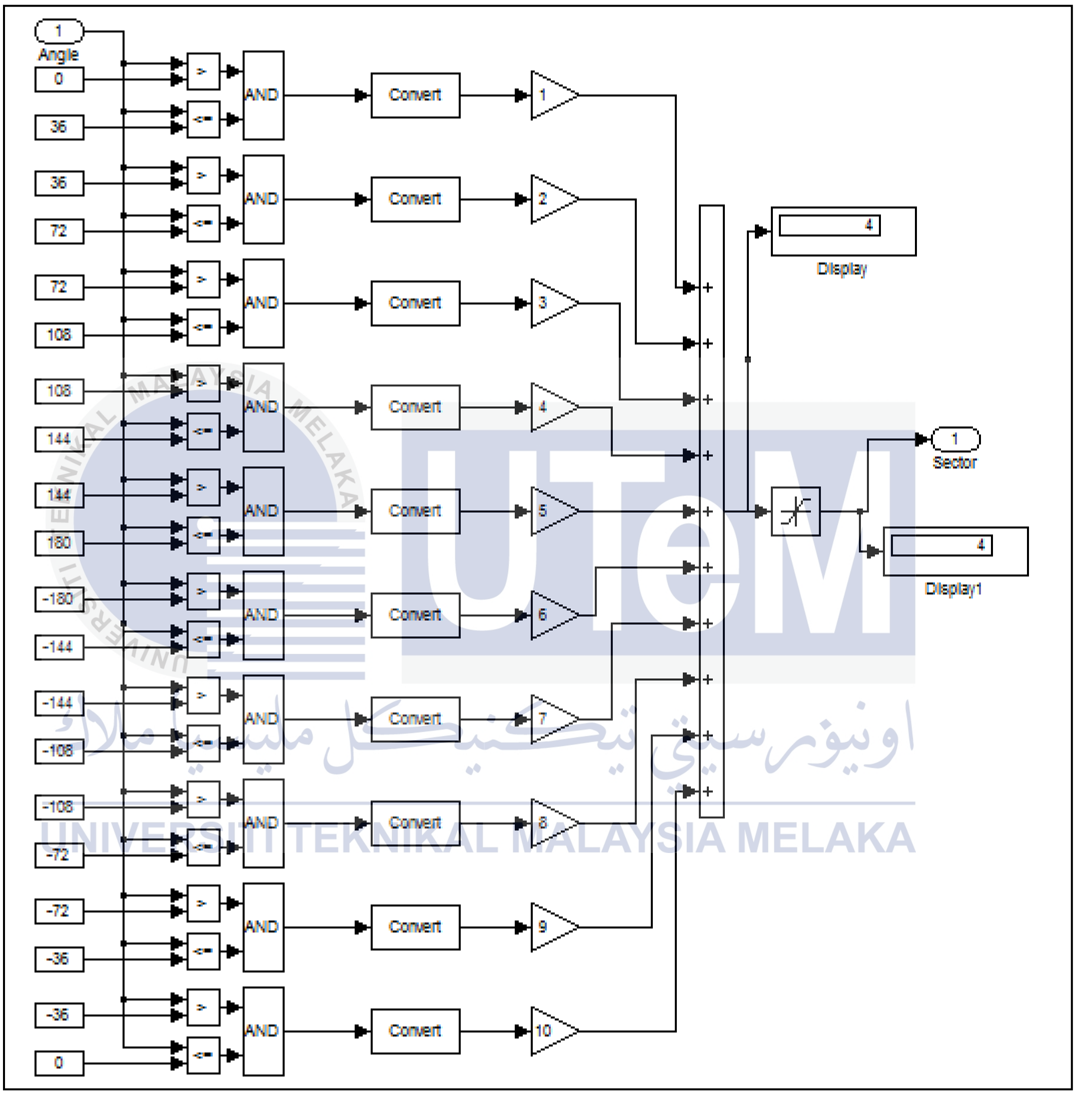

Figure 3.7: Sector calculation according to the angle.

The outputs of the sectors calculation were use for switching calculation. Two neighboring medium active space vectors together with two large active space vectors in each switching period was used here to generate sinusoidal output phase voltage using SVPWM. To use four active spaces vector per switching period need calculation of four application times. This application times needed in determine the switching states for space vector modulation. T_a

There is 32 switching state for five-phase inverter. The two of them are the zero space vectors that give the remaining 30 space vectors. Leg of voltage space vector for states 11 until 20 are identical to the leg voltages of states 1 until 10 except for their magnitude is $\sqrt{\frac{2}{5}V_{DC}}$ and the magnitude of space vectors for states 21 until 30 is $\sqrt{\frac{2}{5}V_{DC}2\cos(2\pi/5)}$.

The corresponding space vectors for 11 until 30 are identical to the leg voltages of the same states and have 36° phase displacement. The switching states 31 and 32 called zero states as they lead to zero phase voltages.

T_a and T_b is the base time on d-q plane to illustrate state 1 until 10. T_{am} and T_{bm} is the time on d-q plane to illustrate the medium space vectors which is state 11 until 20. T_a and T_b is the time to illustrate the large space vectors which is state 21 until 30. $|v_l|$ is the magnitude of voltage large space vector and $|v_m|$ is the magnitude of voltage medium space vector. The equation used as below [9]:

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

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

$$T_{am} = T_a \frac{|v_m|}{|v_l| + |v_m|} \quad (3.6)$$

$$T_{bm} = T_b \frac{|v_m|}{|v_l| + |v_m|} \quad (3.7)$$

$$T_{al} = T_a \frac{|v_l|}{|v_l| + |v_m|} \quad (3.8)$$

$$T_{bl} = T_b \frac{|v_l|}{|v_l| + |v_m|} \quad (3.9)$$

$$T_0 = T_s - T_{al} - T_{am} - T_{bl} - T_{bm} \quad (3.10)$$

Where: k = sector

α = angle

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

$|v_l| = \frac{2}{5} V_{dc} 2 \cos\left({}^{2\pi}/_{5}\right)$

$|v_m| = \frac{2}{5} V_{dc}$

After substitute the value of $|v_l|$ and $|v_m|$ into equation (3.4) until (3.9), the equation can rewrite as:

$$T_a = T_s \frac{|v_{ref}|\sin\left(k^{\pi}/_{5} - \alpha\right)}{^{2}/_{5}V_{dc}\sin\left(^{2\pi}/_{5}\right)} \tag{3.11}$$

$$T_b = T_s \frac{|v_{ref}|\sin\left(\alpha - (k-1)^{\pi}/_{5}\right)}{^{2}/_{5}V_{dc}\sin\left(^{2\pi}/_{5}\right)} \tag{3.12}$$

$$T_{am} = T_a \frac{1}{2\cos\left(^{\pi}/_{5}\right)+1} \tag{3.13}$$

$$T_{bm} = T_b \frac{1}{2\cos\left(^{\pi}/_{5}\right)+1} \tag{3.14}$$

$$T_{al} = T_a \frac{2\cos\left(^{\pi}/_{5}\right)}{2\cos\left(^{\pi}/_{5}\right)+1} \tag{3.15}$$

$$T_{bl} = T_b \frac{2\cos\left(^{\pi}/_{5}\right)}{2\cos\left(^{\pi}/_{5}\right)+1} \tag{3.16}$$

Equation (3.11) and (3.12) been simplified by replaced certain value into constant. The equation can rewrite as:

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

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

Where:

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

The switching scheme for five-phase inverter with the used of medium and large vector as reference were model using equation above. Equation (3.19) been generated first following with equation (3.17) and (3.18). Those equations were generated using previous block output. For generate equation (3.19), V_{ref} from angle to sector calculation block were used. V_{dc} and sampling time, T_s were supply from constant block. For this design, V_{dc} set to $400\ V$ and T_s set to $50e-3s$.

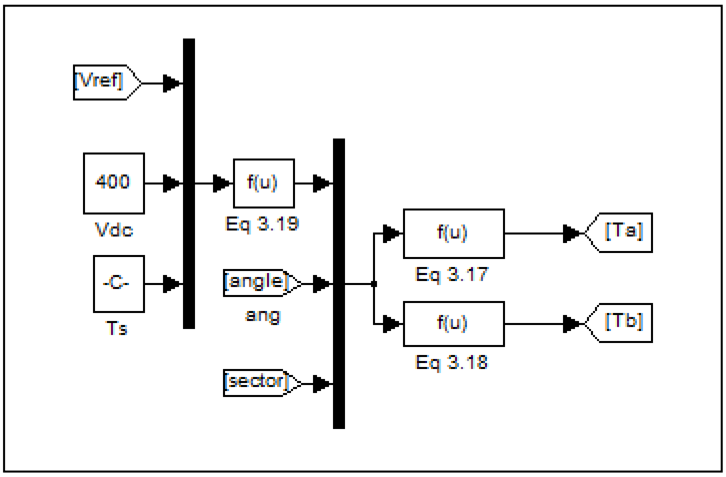

Figure 3.8: Switching calculation for two active vectors.

After generated basic time vector, the reference medium and large vector need to generate next. The used of medium and large vector as reference was to get the output phase voltage of the inverter approaching to sinusoidal waveform. The medium and large vector time generated using equation (3.13) until (3.16). The output of previous block used as input to generate the equation. The input for this block is T_a, T_b and T_s. The sampling time for this part is same with previous.

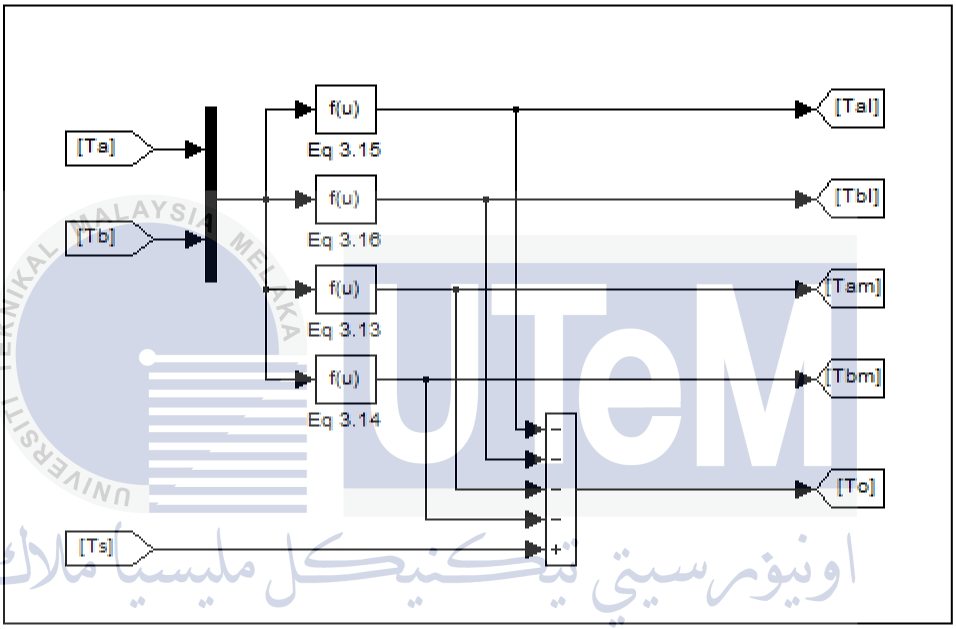

Figure 3.9: Switching calculation for four active vectors.

After four active vectors tine has generated, the calculation for sectors based on the four active vectors has made. The driving control gate signals for the ten switches of the inverter stated in Table 1. One complete cycle of operation of the inverter divided into ten distinct modes. There are five switches are ‘on’ and five switches are ‘off’ at any instant time. Table 1 shows the mode of operation for five-phase voltage source inverter.

Table 3.1: Modes of operation of the five-phase voltage source inverter.

Mode	Switches ON	Terminal polarity
9	1,7,8,9,10	$A^+B^-C^-D^+E^-$
10	8,9,10,1,2	$A^+B^-C^-D^-E^+$
1	9,10,1,2,3	$A^+B^+C^-D^-E^+$
2	10,1,2,3,4	$A^+B^+C^-D^-E^-$
3	1,2,3,4,5	$A^+B^+C^+D^-E^-$
4	2,3,4,5,6	$A^-B^+C^+D^-E^-$
5	3,4,5,6,7	$A^-B^+C^+D^+E^-$
6	4,5,6,7,8	$A^-B^-C^+D^+E^-$
7	5,6,7,8,9	$A^-B^-C^+D^+E^+$
8	6,7,8,9,10	$A^-B^-C^-D^+E^+$

Table 2 shows the additional switching states. 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 21 until 30.

Table 2: Mode of operation for remaining state.

Switching state	Switches ON	Terminal polarity
11	1,2,4,8,10	$A^+B^-C^-D^-E^-$
12	1,2,3,5,9	$A^+B^+C^+D^-E^-$
13	2,3,4,6,10	$A^-B^+C^-D^-E^-$
14	1,3,4,5,7	$A^+B^+C^+D^+E^-$
15	2,4,5,6,8	$A^-B^-C^+D^-E^-$
16	3,5,6,7,9	$A^-B^+C^+D^+E^+$
17	4,6,7,8,10	$A^-B^-C^-D^+E^-$
18	1,5,7,8,9	$A^+B^-C^+D^+E^+$
19	2,6,8,9,10	$A^-B^-C^-D^-E^+$
20	1,3,7,9,10	$A^+B^+C^-D^+E^+$
21	2,3,6,9,10	$A^-B^+C^-D^-E^+$
22	1,3,4,7,10	$A^+B^+C^-D^+E^-$
23	1,2,4,5,8	$A^+B^-C^+D^-E^-$
24	2,3,5,6,9	$A^-B^+C^+D^-E^+$
25	3,4,6,7,10	$A^-B^+C^-D^+E^-$
26	1,4,5,7,8	$A^+B^-C^+D^+E^-$
27	2,5,6,8,9	$A^-B^-C^+D^-E^+$
28	3,6,7,9,10	$A^-B^+C^-D^+E^+$
29	1,4,7,8,10	$A^+B^-C^-D^+E^-$
30	1,2,5,8,9	$A^+B^-C^+D^-E^+$
31	1,3,5,7,9	$A^+B^+C^+D^+E^+$
32	2,4,6,8,10	$A^-B^-C^-D^-E^-$

From the both table, the switching state were draft using the sequence $v_0, v_{am}, v_{bl}, v_{al}, v_{bm}, v_0, v_{am}, v_{bl}, v_{al}, v_{bm}$. For five-phase inverter, the switching signal is only generate for the upper part of the inverter. While the switching for lower part is the reverse from their upper part. The switching state for upper part were generate based on above table. There is five set of switching state, which is for five MOSFET on the upper part of the inverter. Set of switching state for upper part of inverter is given name as T_1, T_3, T_5, T_7 and T_9.

Table below shows the switching state for each set of every sector. Table 3 shows the switching state for T_1 for every sector. $T_0, T_{am}, T_{bl}, T_{al}, T_{bm}$ is used to represent the voltage vector for each vector either medium or large.

Table 3.3: Voltage vectors that involved in representing every sector of T_1.

Sector	T_1
1	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
2	v_{am}, v_{bl}, v_0
3	v_{al}, v_{bm}, v_0
4	v_{am}, v_0
5	v_0
6	v_0
7	v_{bm}, v_0
8	v_{am}, v_{bl}, v_0
9	$v_{bl}, v_{al}, v_{bm}, v_0$
10	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$

Data from the table can conclude into the equation as below. k is the sector. This equation filled into the function block to built switching scheme block.

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

Table 3.4: Voltage vectors that involved in representing every sector of T_3.

Sector	T_3
1	$v_{bl}, v_{al}, v_{bm}, v_0$
2	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
3	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
4	$v_{am}, v_{bl}, v_{al}, v_0$
5	v_{al}, v_{bm}, v_0
6	v_{am}, v_0
7	v_0
8	v_0
9	v_{bm}, v_0
10	v_{am}, v_{bl}, v_0

Data from the table can conclude into the equation as below. k is the sector. This equation filled into the function block to built switching scheme block.

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

Table 3.5: Voltage vectors that involved in representing every sector of T_5.

Sector	T_5
1	v_{bm}, v_0
2	v_{am}, v_{bl}, v_0
3	$v_{bl}, v_{al}, v_{bm}, v_0$
4	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
5	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
6	$v_{am}, v_{bl}, v_{al}, v_0$
7	v_{al}, v_{bm}, v_0
8	v_{am}, v_0
9	v_0
10	v_0

Data from the table can conclude into the equation as below. k is the sector. This equation filled into the function block to built switching scheme block.

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

Table 3.6: Voltage vectors that involved in representing every sector of T_7.

Sector	T_7
1	v_0
2	v_0
3	v_{bm}, v_0
4	v_{am}, v_{bl}, v_0
5	$v_{bl}, v_{al}, v_{bm}, v_0$
6	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
7	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
8	$v_{am}, v_{bl}, v_{al}, v_0$
9	v_{al}, v_{bm}, v_0
10	v_{am}, v_0

Data from the table can conclude into the equation as below. k is the sector. This equation filled into the function block to built switching scheme block.

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

Table 3.7: Voltage vectors that involved in representing every sector of T_9.

Sector	T_9
1	v_{am}, v_{bl}, v_0
2	v_{am}, v_0
3	v_0
4	v_0
5	v_{bm}, v_0
6	v_{am}, v_{bl}, v_0
7	$v_{bl}, v_{al}, v_{bm}, v_0$
8	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
9	$v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$
10	$v_{am}, v_{bl}, v_{al}, v_0$

Data from the table can conclude into the equation as below. k is the sector. This equation filled into the function block to built switching scheme block.

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

From the tables above, the switching pattern for upper part of the inverter of each sector summarized. Figures below show the switching pattern for each sector. The switching patterns have designed from the vector in the specific sector based on the d-q plane.

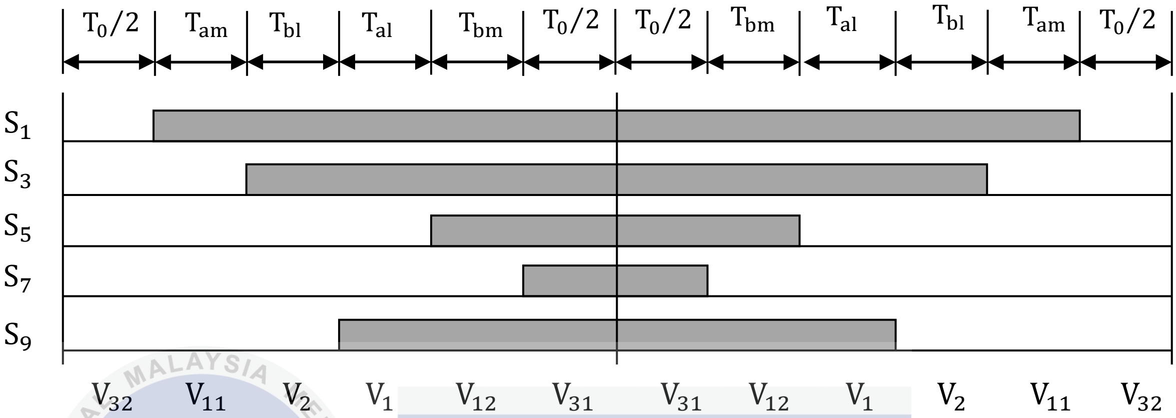

Figure 3.10: The switching pattern for sector 1.

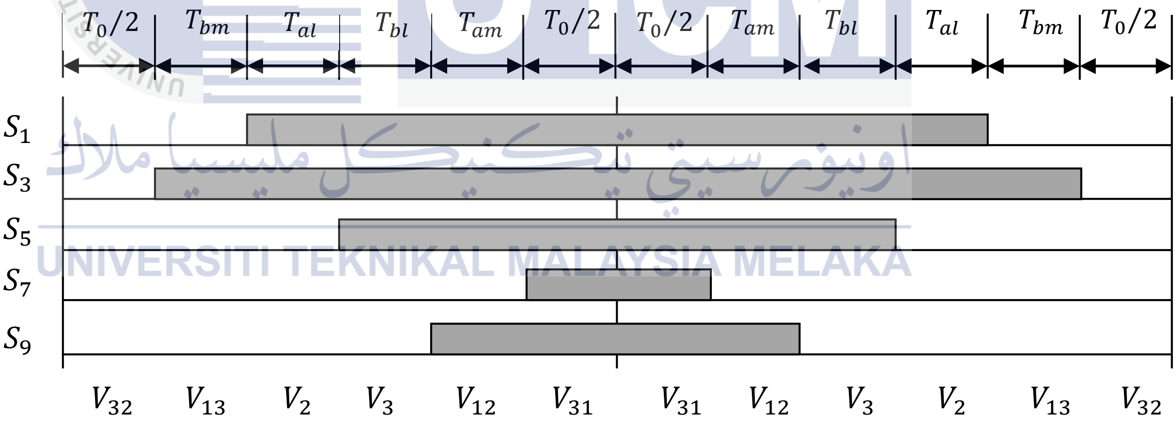

Figure 3.11: The switching pattern for sector 2.

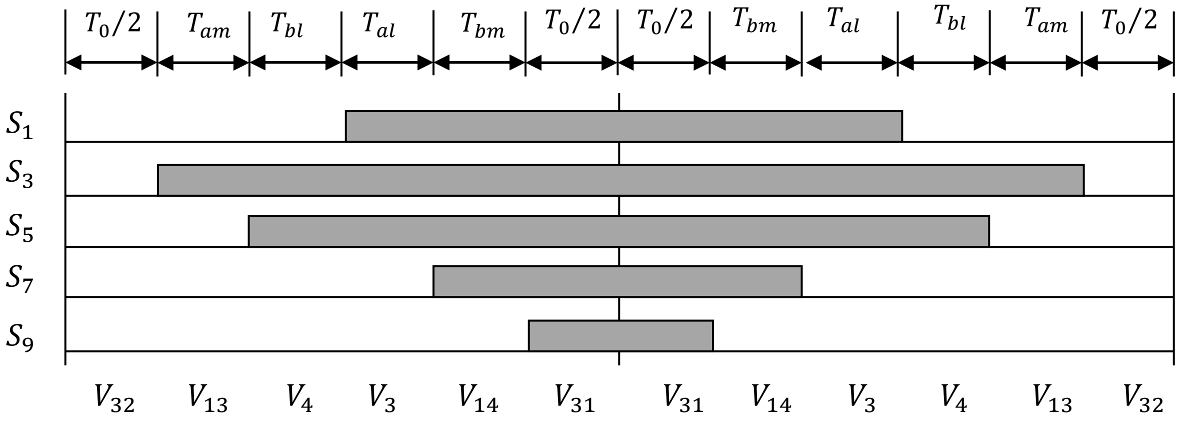

Figure 3.12: The switching pattern for sector 3.

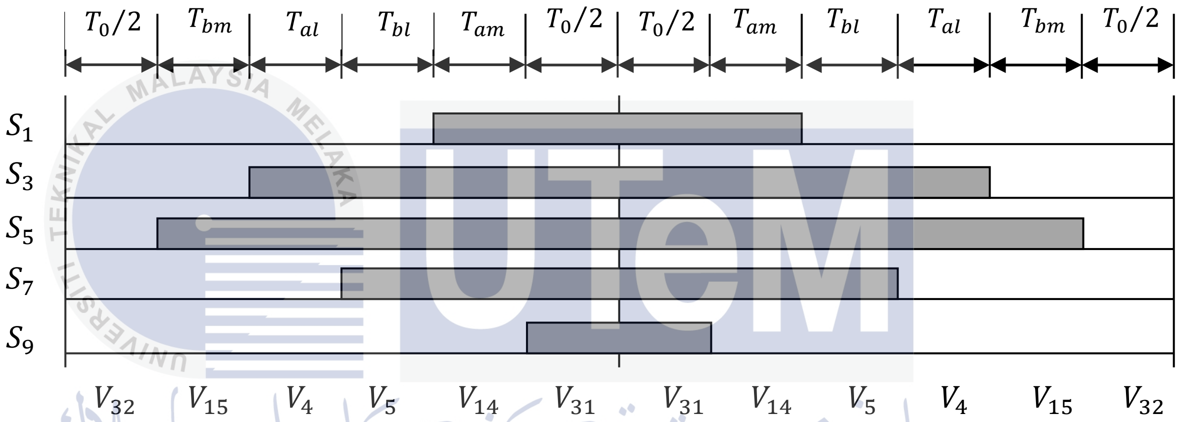

Figure 3.13: The switching pattern for sector 4.

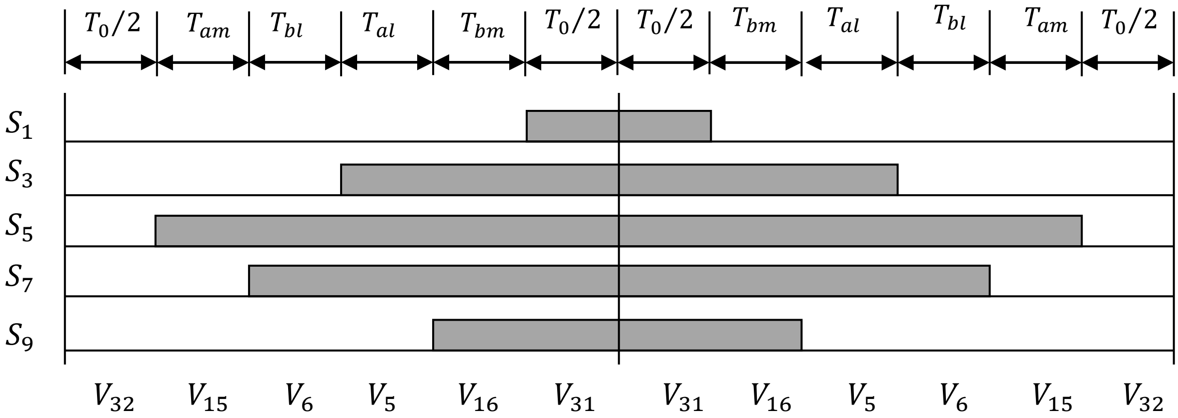

Figure 3.14: The switching pattern for sector 5.

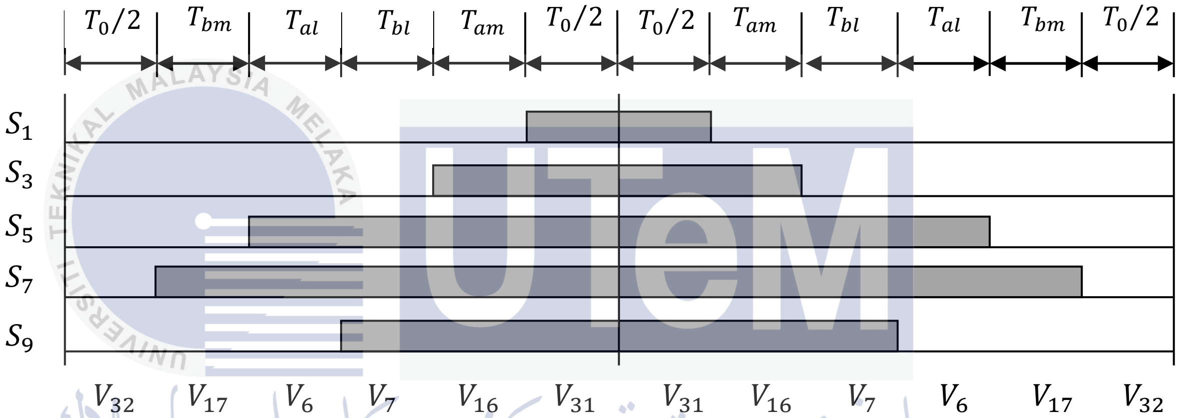

Figure 3.15: The switching pattern for sector 6.

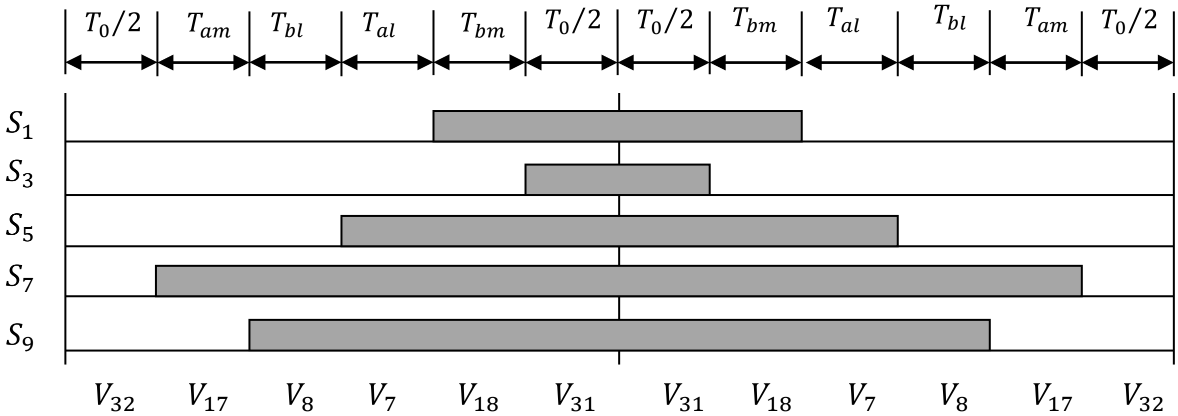

Figure 3.16: The switching pattern for sector 7.

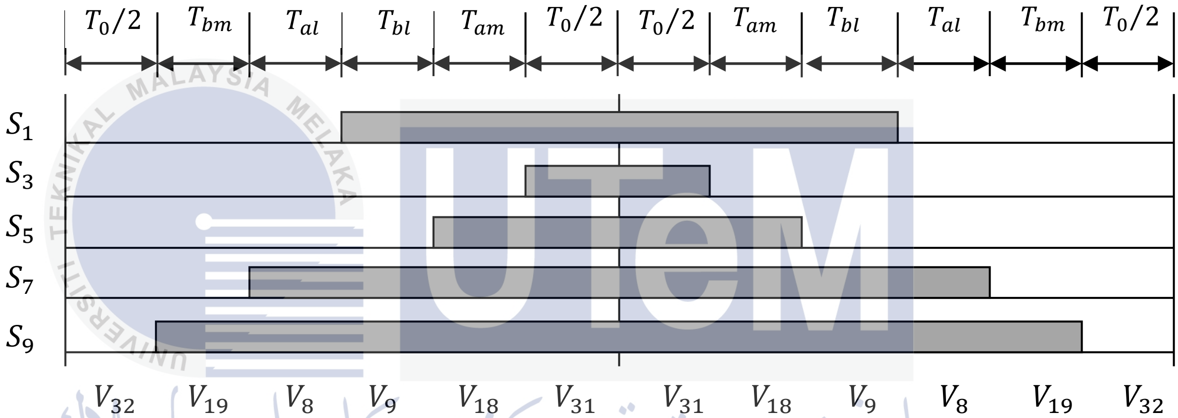

Figure 3.17: The switching pattern for sector 8.

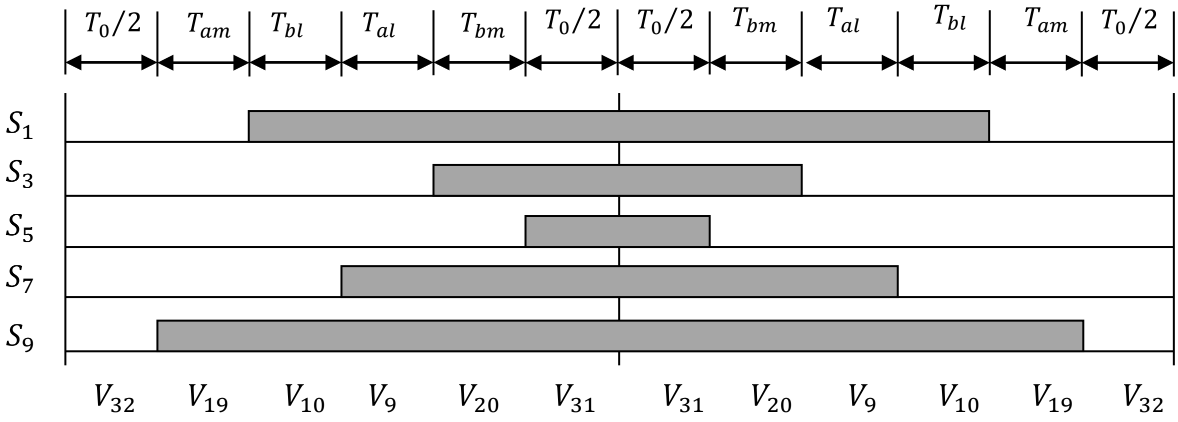

Figure 3.18: The switching pattern for sector 9.

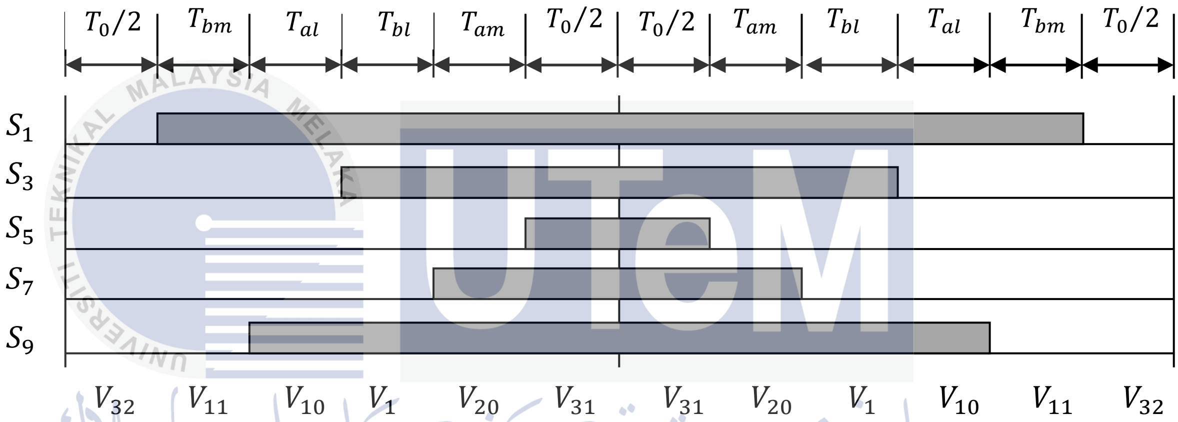

Figure 3.19: The switching pattern for sector 10.

The outputs from previous block used as input for this block. Generation of switching state for upper part of the inverter, which consisted of five MOSFET are used equation (3.20) until (3.24). Function block used to enter those equations to the model. $v_{am}, v_{bl}, v_{al}, v_{bm}, v_0$ from the equation was replaced by $T_{am}, T_{bl}, T_{al}, T_{bm}, T_0$ in built the model.

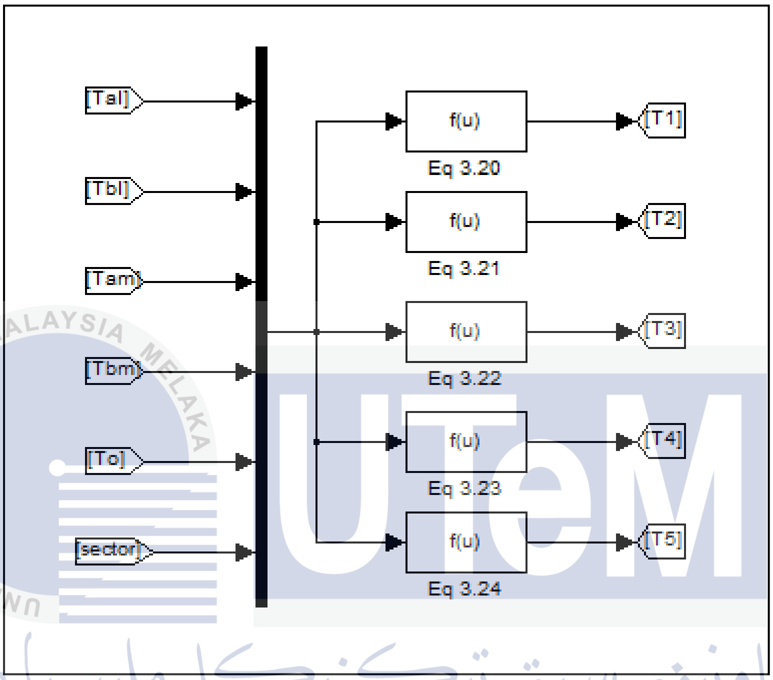

Figure 3.20: Equation block for switching five-phase voltage source inverter.

The outputs from previous model used as input for next model. T_1, T_2, T_3, T_4, T_5 which is output from previous model used as input from this model. T_1, T_2, T_3, T_4, T_5 in this model that was in square wave been compare to the triangle wave in order to produce the switching signal for the five-phase voltage source inverter. The triangle waves generated from the repeating sequence block.

The Repeating Sequence block outputs a periodic scalar signal having a waveform that specified using the Time values and Output values parameters. The Time values parameter specifies a vector of output times. The Output values parameter specifies a vector of signal amplitudes at the corresponding output times. Together, the two parameters specify a sampling of the output waveform at points measured from the beginning of the interval over which the waveform repeats (the period of the signal). The frequency of the Repeating Sequence Block set to 1e-3 s.

The signals from previous model compared with the triangle wave by using the Relational Operator. The Relational Operator block compares two inputs using the Relational operator parameter that specified. The first input corresponds to the top input port and the second input to the bottom input port. The parameter used in this block is '>=' which is means 'TRUE if the first input is greater than or equal to the second input'.

This model using one repeating sequence block and five relational operators block. The output of the relational block is the switching signal for the upper part of the inverter. To generate the switching signal for lower part of the inverter, the switching signal of their upper part reversed. The output was the switching signal gate for ten MOSFET used in five-phase voltage source inverter for them to ON or OFF. The output signal was either ‘0’ or ‘1’ that represented the gate ON or OFF. Figure 10 show the generated switching model for five-phase voltage source inverter.

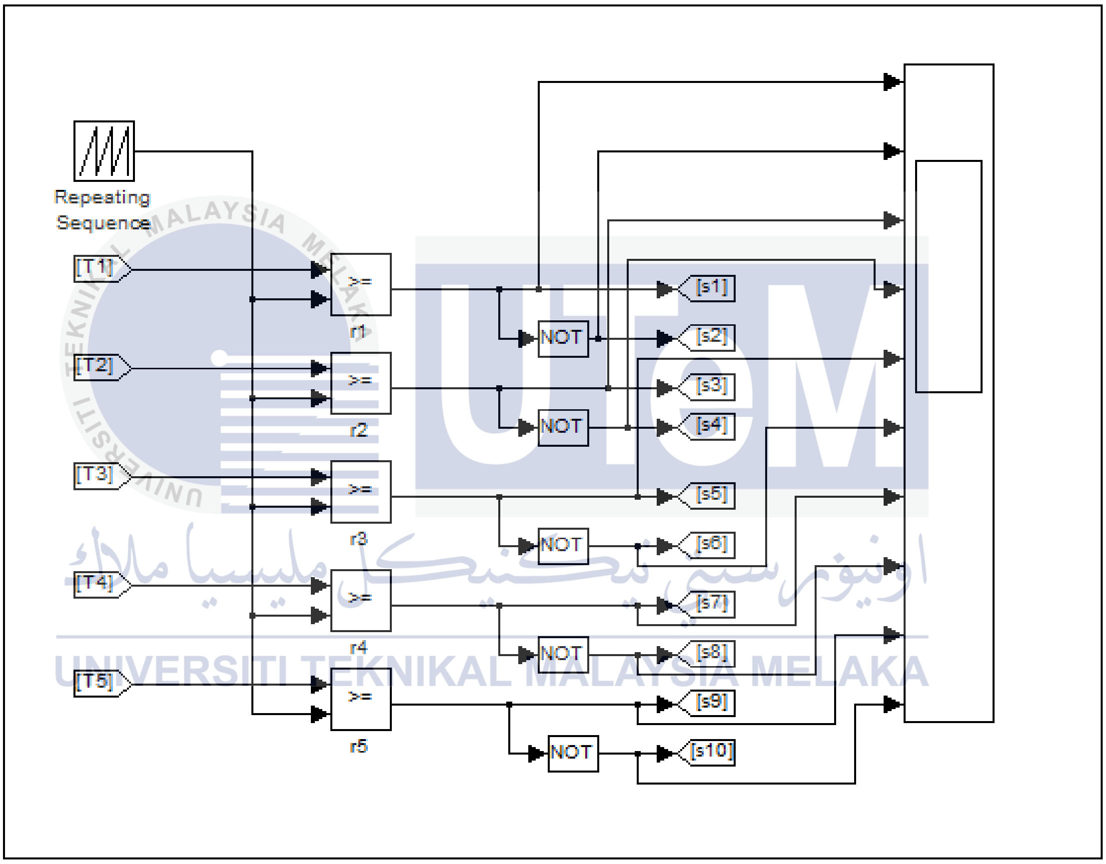

Figure 3.21: Generated switching model for five-phase voltage source inverter.

3.5 Modeling Five-phase Induction Machine

Five-phase induction model were model same way like three-phase induction model. The five supply were used the same as the above five-phase supply. The five-phase supply been transformed into the dynamic rotating reference frame, d-q voltage. d-q component lead to fundamental flux and torque production. Stator to rotor coupling appears only in d-q equation.

For five-phase machine, there will extra component that is x-y component. x-y components completely decoupled from all other component and there is no stator to rotor coupling appears. When assumed the sinusoidal distribution of flux around air-gap, x-y component not contribute to torque production. Since rotor winding short circuit, x-y component does not exist and only d-q component been considered. The five-phase to two-axis voltage transformation achieved using following equation:

$$v_q = \frac{2}{5}\left(v_a + v_b cos\frac{2\pi}{5} + v_c \cos\frac{4\pi}{5} + v_d \cos\frac{6\pi}{5} + v_e \cos\frac{8\pi}{5}\right) \quad (3.25)$$

$$v_d = \frac{2}{5}\left(v_b \sin\frac{2\pi}{5} + v_c \sin\frac{4\pi}{5} + v_d \sin\frac{6\pi}{5} + v_e \sin\frac{8\pi}{5}\right) \quad (3.26)$$

Figure 3.22 shows the transformation of five-phase supply to rotating dynamic reference frame. The transformation based on the equation (3.24) and (3.25). Five-phase supply consists of five-generator sine wave that have 72° phase different.

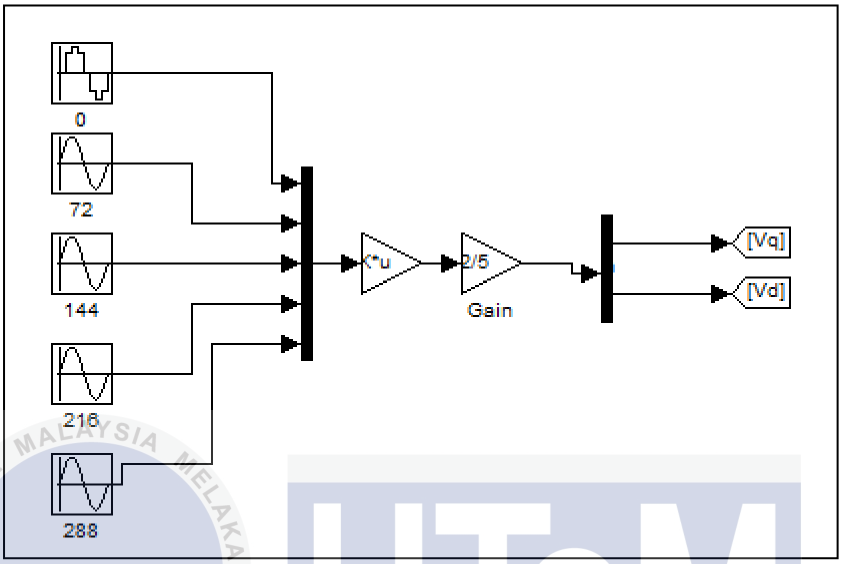

Figure 3.22: d-q transformation for five-phase supply.

The d-q dynamic equivalent of the induction motor used to model the d-q model of the induction motor. D-q model of five-phase induction motor were same with d-q model of the three-phase induction motor. The stator and rotor voltage equations in a (d, q) arbitrary reference frame can express by (p stand for d/dt):

$$V_{ds} = R_s I_{ds} - \omega_a \phi_{qs} + p\phi_{ds} \tag{3.26}$$

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

$$V_{dr} = R_r I_{dr} - (\omega_a - \omega)\phi_{qr} + p\phi_{dr} \tag{3.28}$$

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

The flux linkages of stator and rotor in an arbitrary reference frame ($\phi_{ds}, \phi_{qs}, \phi_{dr}, \phi_{qr}$) can obtain after transformation as:

$$\phi_{ds} = (L_{ls} + L_m)I_{ds} + L_m I_{dr} \tag{3.30}$$

$$\phi_{qs} = (L_{ls} + L_m)I_{qs} + L_m I_{qr} \tag{3.31}$$

$$\phi_{dr} = (L_{lr} + L_m)I_{dr} + L_m I_{ds} \tag{3.32}$$

$$\phi_{qr} = (L_{lr} + L_m)I_{qr} + L_m I_{qs} \tag{3.33}$$

The torque and speed equation:

$$T_e = PL_m(I_{dr}I_{qs} - I_{qr}I_{ds}) \quad (3.34)$$

$$\omega_r = \int \frac{P}{2J}(T_e - T_L)\, dt \quad (3.35)$$

The mathematical model of five-phase induction motor started with d-q model. The d-q model separated to two models which one generate flux linkage and from the flux linkage, another block generated the stator and rotor current. The d-q model separated into two blocks to easy implementation of the equation used. For the first block, the input is the $V_{ds}, V_{qs}, I_{ds}, I_{qr}, W_r, I_{dr}, I_{qr}$ and for the output is $\emptyset_{ds}, \emptyset_{qs}, \emptyset_{dr}, \emptyset_{qr}$. Figure 3.23 shows the first block of d-q model.

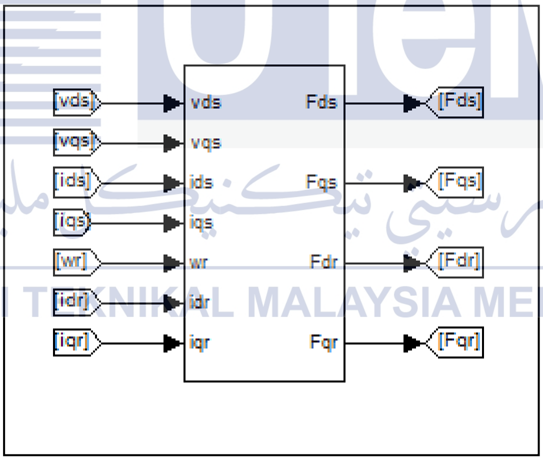

Figure 3.23: First block for d-q model of five-phase induction motor.

Figure 3.24 shows the component inside the first block of d-q model. This block based on the equation (3.26) until (3.29). The equation rearranged to make the flux linkage as the output. This block consists of several gain block, sum block and integral block.

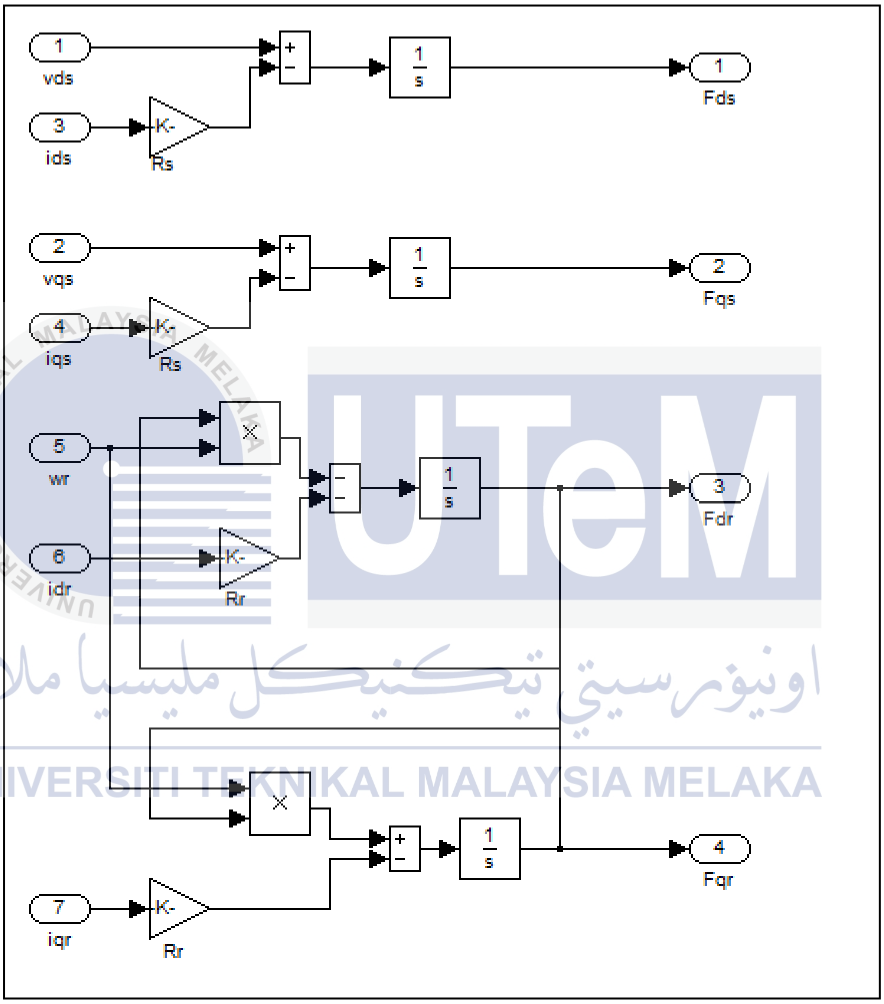

Figure 3.24: Component inside the first block of d-q model of five-phase induction motor.

The second block for d-q model has the output of the first block as the input. The input of this block is $\emptyset_{ds}, \emptyset_{qs}, \emptyset_{dr}, \emptyset_{qr}$ and the output is $I_{ds}, I_{qs}, I_{dr}, I_{qr}$. Figure 3.25 shows the second block of d-q model.

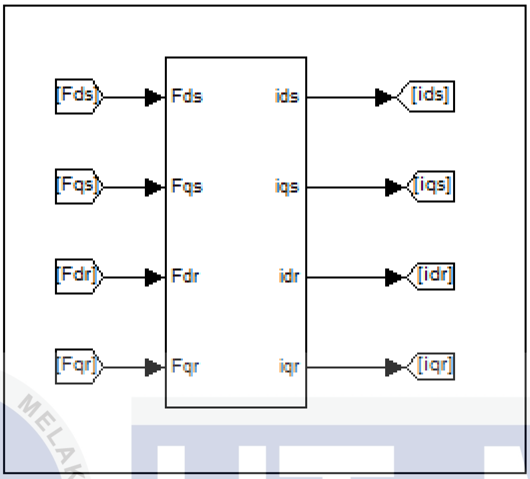

Figure 3.25: Second block of d-q model of five-phase induction motor.

Figure 3.26 shows the component inside the second block of d-q model of five-phase induction motor. This block arranged based on the equation (3.30) and (3.33). The equations rearranged to make the stator and rotor current as the output. This block built used the several gain blocks, sum block and integral block. The integral block used most of the time instead of differential block. The differential blocks not usually use because some of the signal have discontinuities or ripples and will give spikes when differentiated.

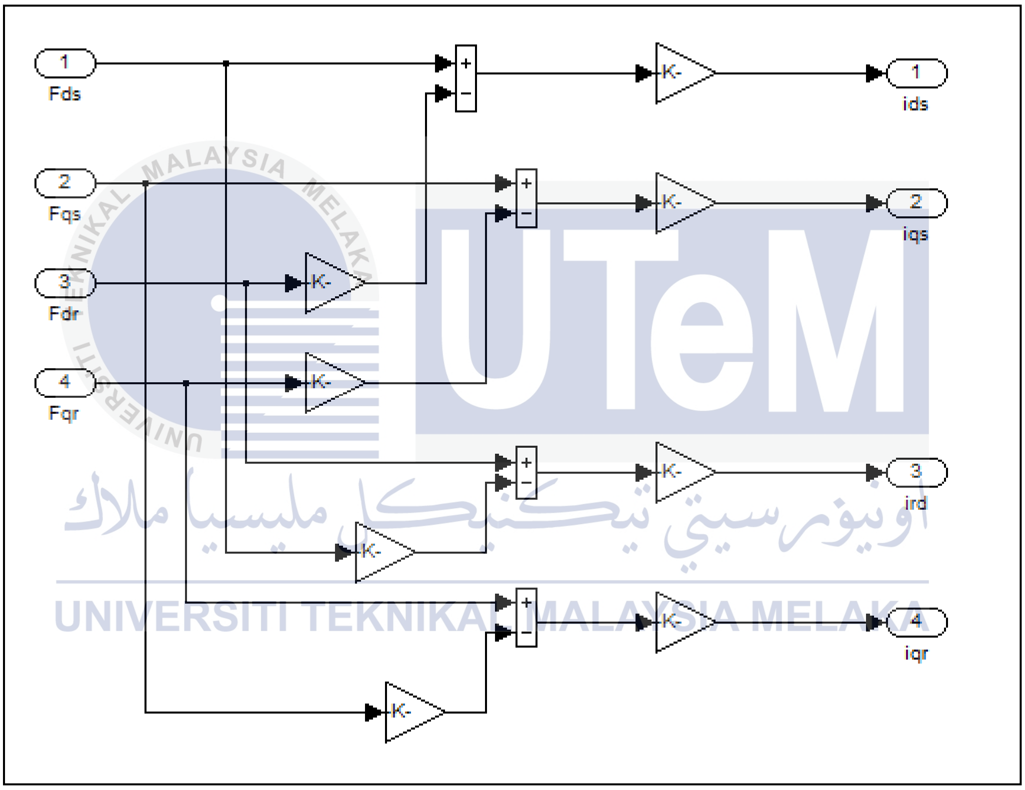

Figure 3.26: Structure inside d-q model of five-phase induction motor.

The outputs of the previous block used as input for the next block which mechanical equation block. This mechanical block generated torque and speed of the motor. Equation (3.34) and (3.35) used for built this block. Figure 3.27 shows the mechanical block that generates torque and speed of the motor.

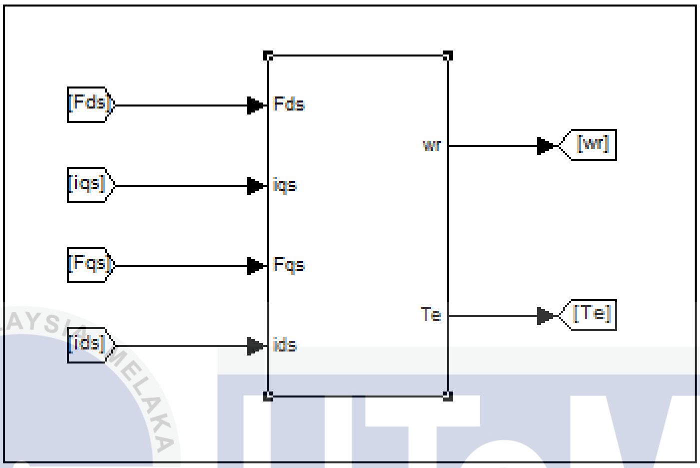

Figure 3.27: Mechanical equation block.

Figure 3.28 shows the structure inside of mechanical equation block. This block consists product block, sum block, and gain block.

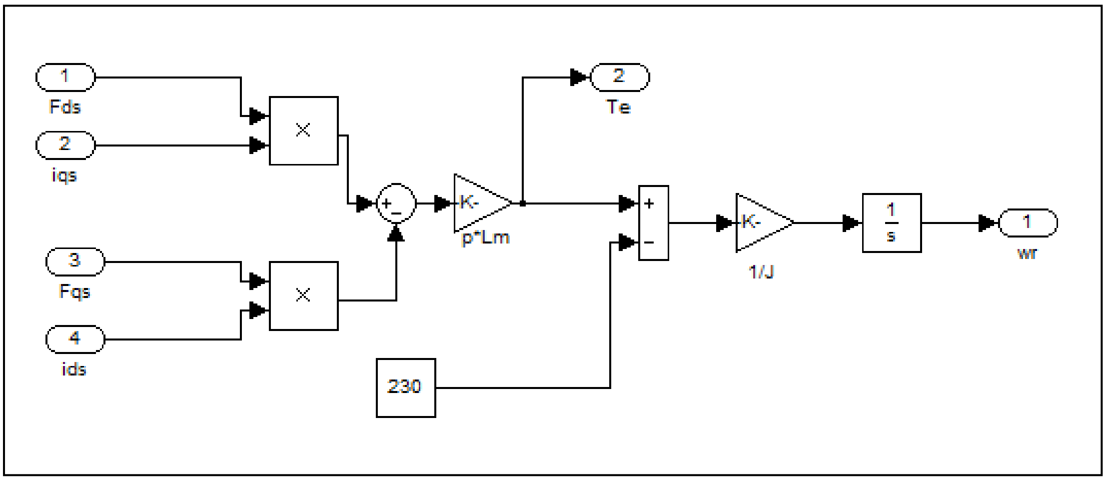

Figure 3.28: Component arrangement inside the mechanical equation block.

3.6 Modelling of the drive system.

After the modelling of inverter, space vector modulation and five-phase induction motor done, the parts connected together. The inverter used the direct current supply. Then the space vector output of gate connected to the inverter block and the inverter connected to the five-phase induction motor. The output of the five-phase induction motor measured using the scope. Space vector block supplied with the five-phase supply.

The leg voltage of the inverter need to transform into the phase voltage before it can connect to the five-phase induction motor. Before the leg voltage transformed into the phase voltage, it transformed into the line voltage first. Equation below shows the relation of the leg inverter voltage and line voltage of the inverter. Line voltage is the different voltage between two-leg inverter voltages.

$$\begin{aligned} v_{EA} &= v_E - v_A \\ v_{AB} &= v_A - v_B \\ v_{BC} &= v_B - v_C \\ V_{CD} &= v_C - v_D \\ v_{DE} &= v_D - v_E \end{aligned} \quad (3.36)$$

The relation of phase voltage and the line voltage of the inverter shows in the equation below. When the equation (3.36) replaces the value in the equation (3.37), it gives the equation (3.1). Equation below used in the phase voltage generate block.

$$
\begin{aligned}
v_a &= \frac{1}{5}(v_{AB} - v_{CD} - 2v_{DE} - 3v_{EA}) \\
v_b &= \frac{1}{5}(v_{BC} - v_{DE} - 2v_{EA} - 3v_{AB}) \\
v_c &= \frac{1}{5}(v_{CD} - v_{EA} - 2v_{AB} - 3v_{BC}) \\
v_d &= \frac{1}{5}(v_{DE} - v_{AB} - 2v_{BC} - 3v_{CD}) \\
v_e &= \frac{1}{5}(v_{EA} - v_{BC} - 2v_{CD} - 3v_{DE})
\end{aligned}
\quad (3.37)
$$

The output of this inverter will connect to the five-phase induction motor through the phase voltage. Equation (3.1) uses to convert the leg voltage to the phase voltage to connect to the five-phase induction motor. The input is the voltage from the inverter. When compare to two lines the leg, voltage becomes the line voltage. The leg voltages then convert into the phase voltage. The leg voltage passed through the current measurement and voltage measurement. The output of this block is the line voltage and the phase voltage.

Figure 3.29 shows the transformation of the leg voltage into the phase voltage. This block consists of current measurement, voltage measurement, sum block and gain block. The current measurement block used to measure the instantaneous current flowing in any electrical block or connection line. The voltage measurement block measures the instantaneous voltage between two electric nodes. The Simulink output provides a Simulink signal that can be use by other Simulink block.

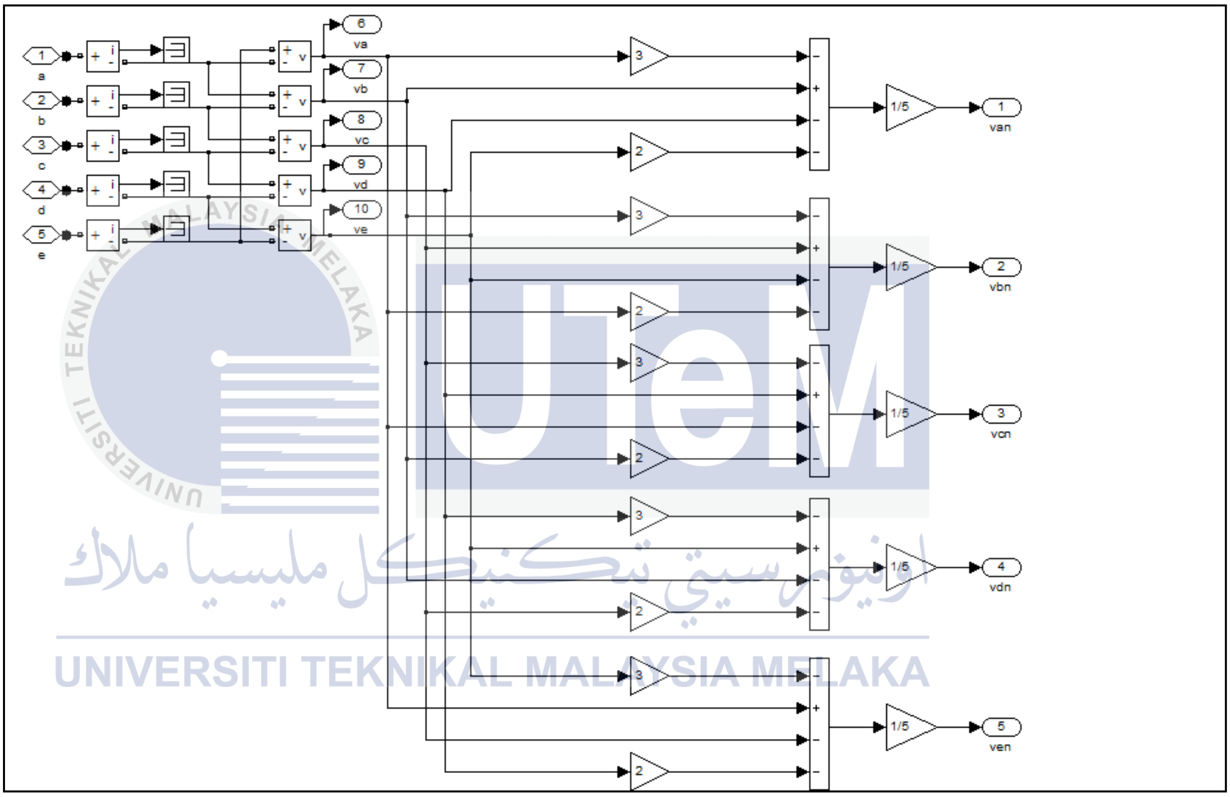

Figure 3.29: Leg voltage transform into the phase voltage.

The drive system consists of space vector block, five-phase inverter block and the five-phase induction motor block. Figure 3.30 shows the arrangement of block in the drive system.

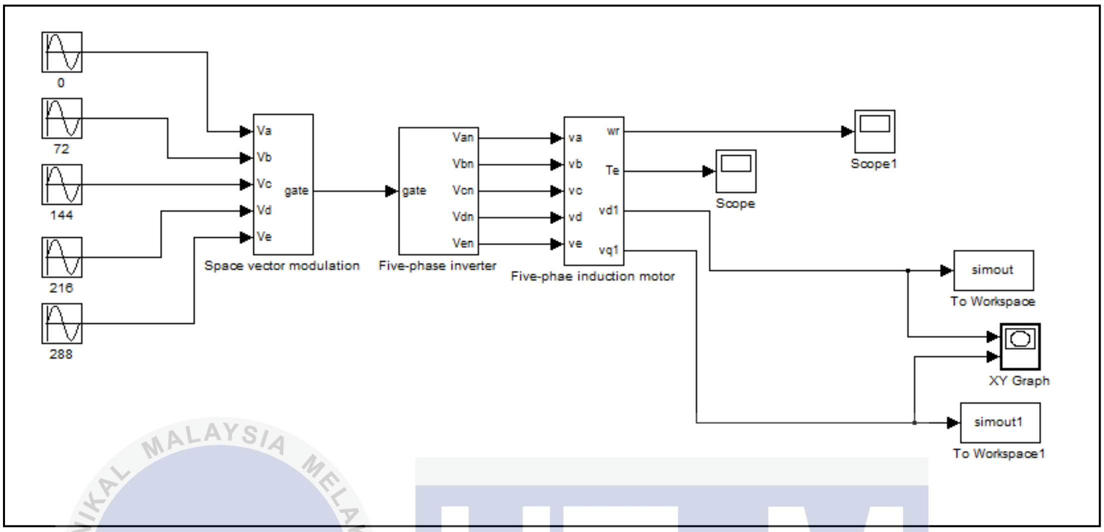

Figure3.30: Arrangement of drive system for five-phase induction motor.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Space Vector Modulation Scheme.

The five-phase space vector modulation starts with the production of the five-phase supply. Five-phase supplies have different phase value, which is 72° or $\frac{2\pi}{5}$ apart. Figure 4.1 shows the waveform of the five-phase supply. The first waveform has phase shifting by 0, the second waveform has phase shifting by $\frac{2\pi}{5}$, the third waveform has phase shifting by $\frac{4\pi}{5}$, the forth waveform has phase shifting by $\frac{6\pi}{5}$ and the phase shifting for the fifth waveform is $\frac{8\pi}{5}$. Each waveform period is $0.01s$, which means the frequency of the supply was $100\ Hz$. The amplitude of the waveform is $10V$.

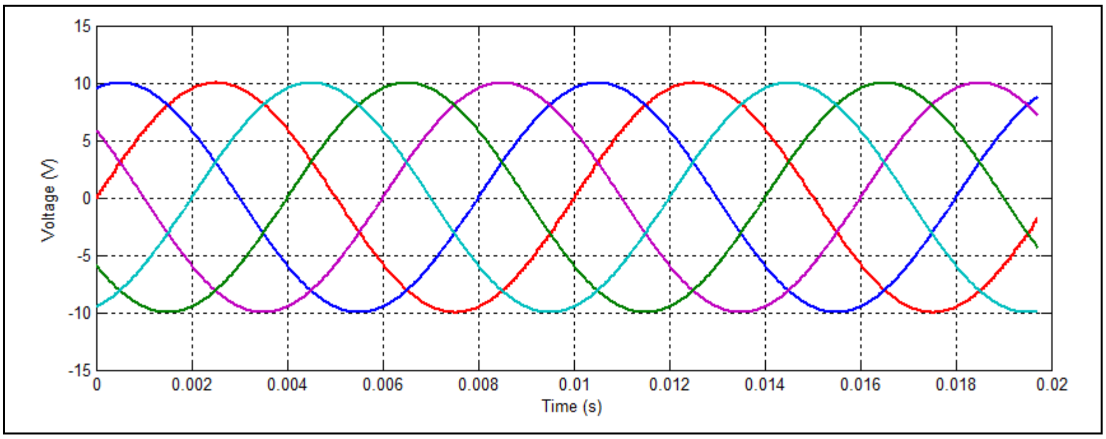

Figure 4.1: Waveform of five-phase supply for the space vector modulation.

The five-phase supply then transformed into the d-q voltage by the d-q voltage transformation block as explained in Chapter 3. From the five waveform, the transformation five out two waveform. The two waveforms were 180° apart and have the same frequency with the five-phase supply. Figure 4.2 shows the waveform of d-q voltage. The amplitude of the d-q model similar with the five-phase supply which is $10V$.

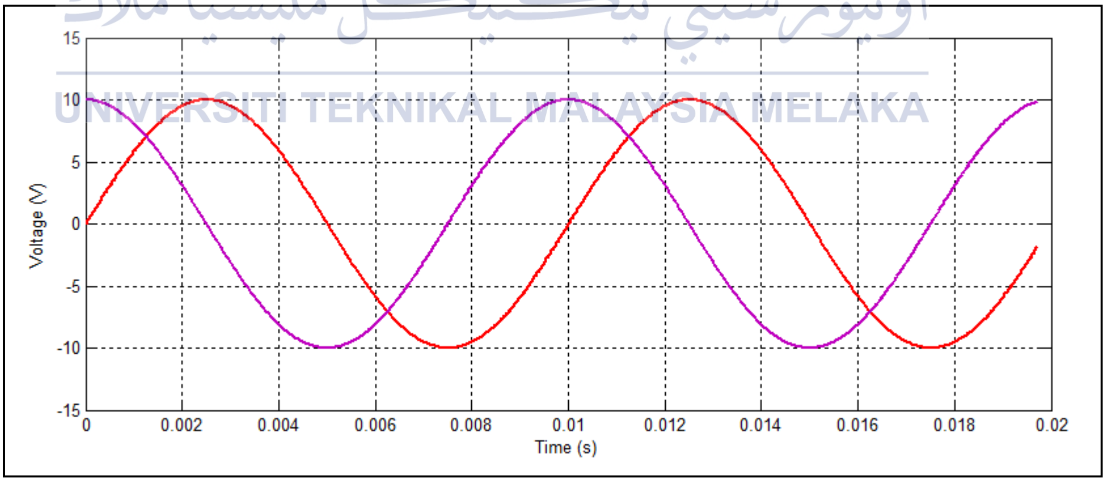

Figure 4.2: Waveform of d-q voltage of the space vector.

After transformed the five-phase supply into the d-q voltage, the output waveform split into real and imaginary value, which gives the magnitude and angle of the waveform. Figure 4.3 shows the waveform of the magnitude that act as the reference voltage for the space vector block. The magnitude for the reference voltage is $10V$.

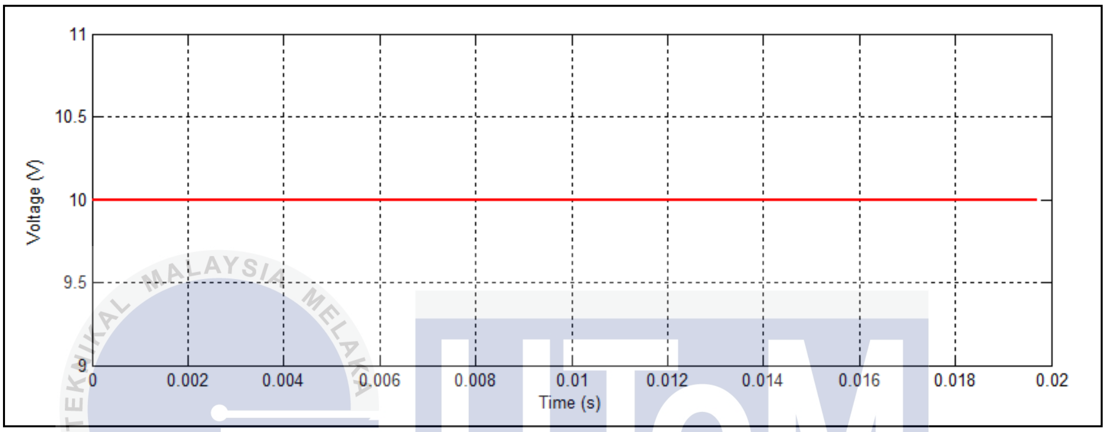

Figure 4.3: Voltage reference for the space vector block.

Figure 4.4 show the angle of the d-q voltage waveform. The frequency of the waveform similar with the frequency of the d-q voltage which is $100Hz$. The angle waveform is the triangle waveform. This shows that the angle is repeating from 0° to 360° and the process repeated.

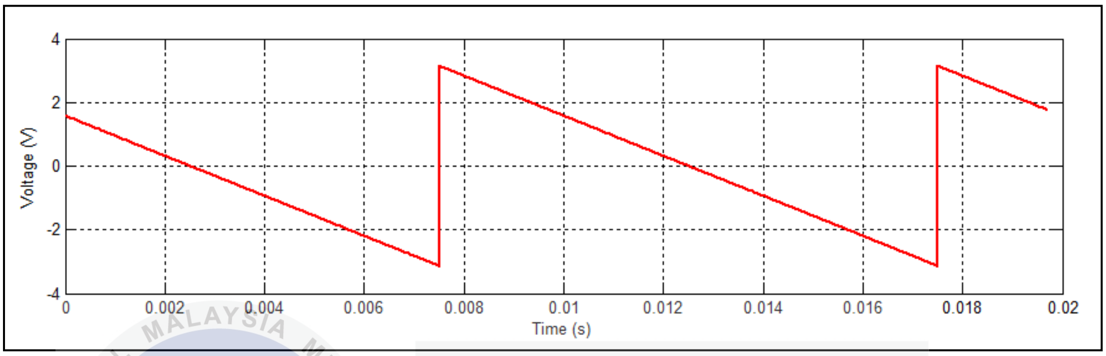

Figure 4.4: Waveform angle of the d-q voltage.

The angle waveform is the input for the angle to sector block mention is Chapter 3. The angle waveform divided into ten, which mean ten sector of the five-phase space vector. 360° of the angle divided into ten sector, which each sector is 36°. Figure 4.5 shows the waveform of the sector for the space vector. This waveform is the output of the angle to sector transformation block. Each sector period is $0.001s$.

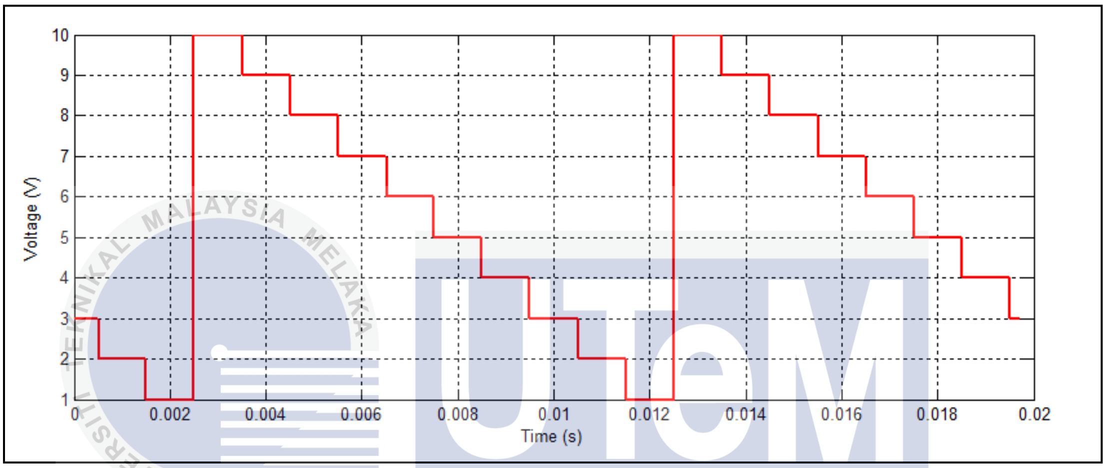

Figure 4.5: Sector waveform for the five-phase space vector block.

After the sector, waveform is form. The next block is T_a and T_b generator block. Using the equation and block mention previously, the T_a waveform that formed from the block shown in figure 4.6. The frequency for T_a similar with sector waveform which is $0.001s$. The amplitude for T_a is $0.00004V$.

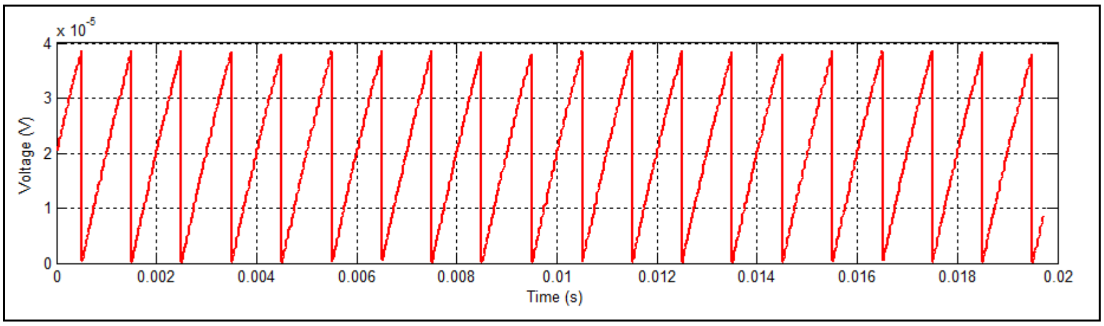

Figure 4.6: T_a waveform for five-phase space vector block.

Block that generate T_a also generate T_b with the same frequency and amplitude but different direction. This shows that the length of T_a and T_b are the same but the position of them are different. Figure 4.7 shows the waveform of T_b.

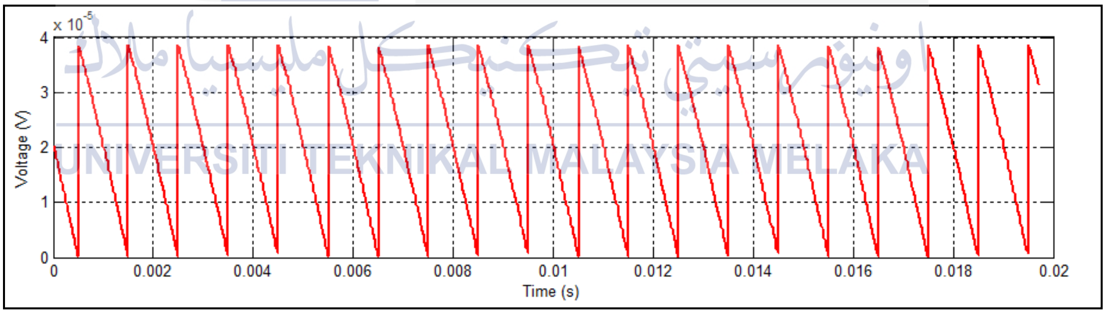

Figure 4.7: T_b waveform for five-phase space vector block.

The combination of medium and large vector used to gain the sinusoidal output waveform of the phase voltage of the inverter. This can eliminate the possible low order harmonics. T_{al}, T_{bl} is the time that represented the large vector and T_{am}, T_{bm} is represented the medium vector.

Next block is generating the $T_{al}, T_{bl}, T_{am}, T_{bm}$ based on the previous output which is reference voltage, angle, sector, T_a and T_b. Figures below show the output waveform from this block. Figure 4.8 shows the waveform of T_{al} that has the magnitude half from the T_a. This shows that the length of T_{al} is short by half of the T_a length. This waveform has similar frequency with the frequency of T_a waveform.

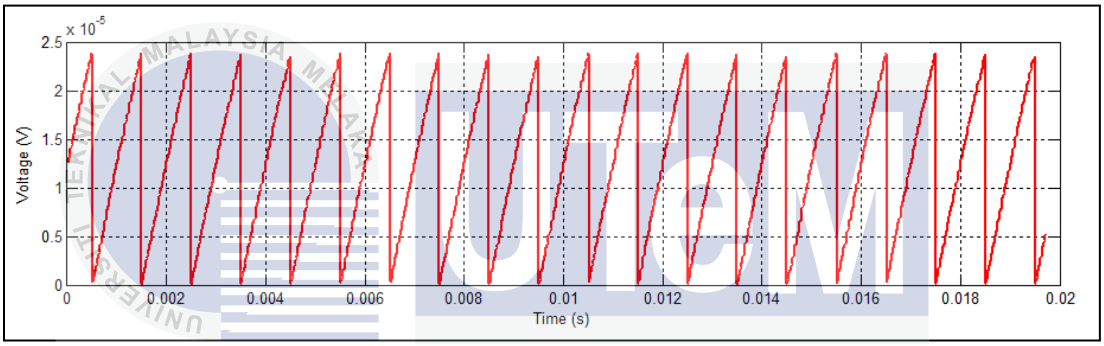

Figure 4.8: T_{al} waveform generate from previous waveform.

Figure 4.9 shows the waveform of T_{bl}. This waveform has magnitude same with the magnitude T_{al} but different direction. This shows that the length of T_{al} and T_{bl} are the same but have different position.

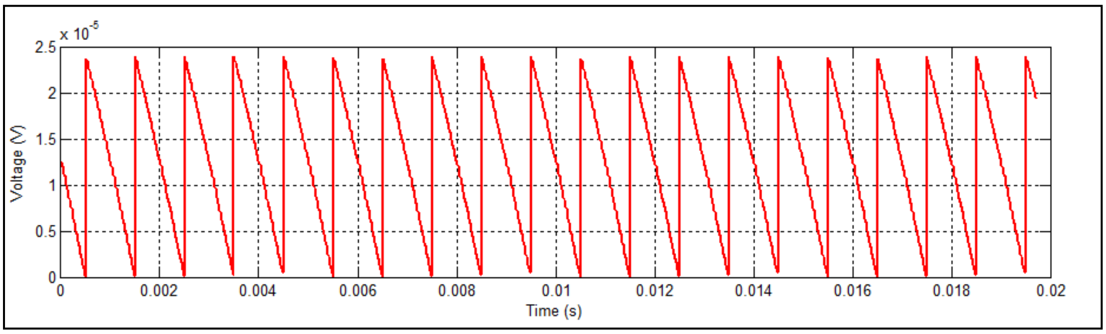

Figure 4.9: T_{bl} waveform generate from previous waveform.

Figure 4.10 shows the waveform of T_{am}. This waveform has magnitude half from the magnitude of T_{al} same different direction. This shows that the length of T_{am} half of the T_{al} length. The frequency of this waveform is same with previous waveform.

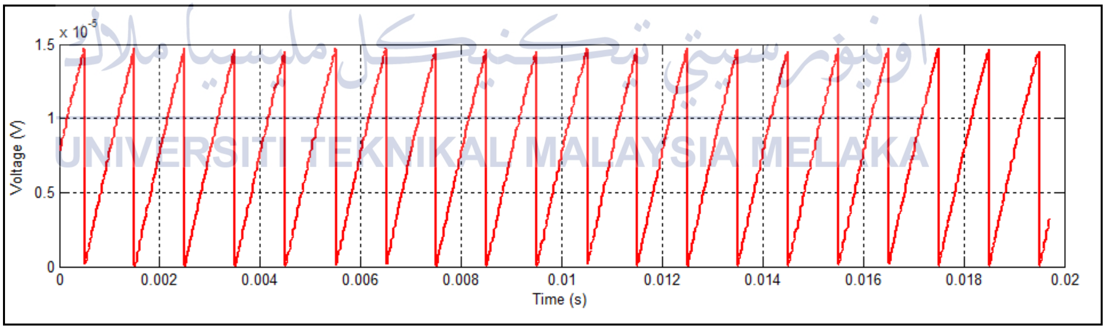

Figure 4.10: T_{am} waveform generate from previous waveform.

Figure 4.11 shows the waveform of T_{bm}. This waveform has same magnitude with T_{am} but different direction. This shows that the length of T_{am} equal to T_{bm} length but have different position. The frequency of this waveform is same with previous waveform.

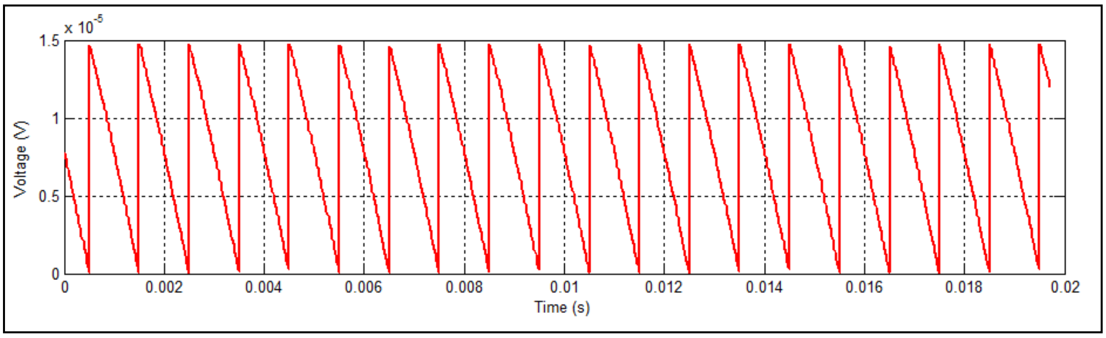

Figure 4.11: T_{bm} waveform generate from previous waveform.

Figure 4.12 shows the waveform of T_0. T_0 generate through subtraction of $T_{al}, T_{bl}, T_{am}, T_{bm}$ from T_s. The frequency of this waveform is same with the previous waveform.

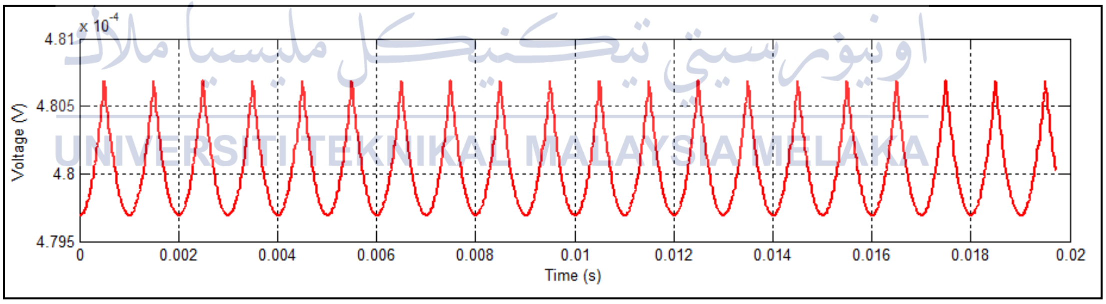

Figure 4.12: T_0 waveform generate from the previous waveform.

After generation of $T_{al}, T_{bl}, T_{am}, T_{bm}$ done, next block generate T_1, T_2, T_3, T_4, T_5 for switching upper part of the inverter. Using the equation and block mention earlier, the switching pattern waveforms produced with refer to medium and large vector of the space vector. Space vector modulation not confined to the limits of the bus voltage and the centre voltages that give below waveform. Space vector modulation utilizes about fifteen percent more of the available bus voltage similar to third harmonic injected sinusoidal PWM.

Space vector controls allows for different switching combination using $T_{al}, T_{bl}, T_{am}, T_{bm}$ based on the choice of the null vectors which are applied for duration of time T_0. Applying either one or both zero vector result in different switching pattern to generate less total harmonic distortion or reduce linear switching power losses in the switching devices. Different sequence of $T_{al}, T_{bl}, T_{am}, T_{bm}$ and T_0 give different effect on the inverter circuit. This model of space vector modulation used alternate reverse switching modes by alternating zeroes for each sequence and reverse sequence after each zero vector.

Figure 4.13 until 4.18 below show the switching scheme waveform for T_1, T_2, T_3, T_4, T_5. The frequency of this waveform is similar to frequency of previous waveform. Each figure has same shape waveform but by different phase shifting 72° apart.

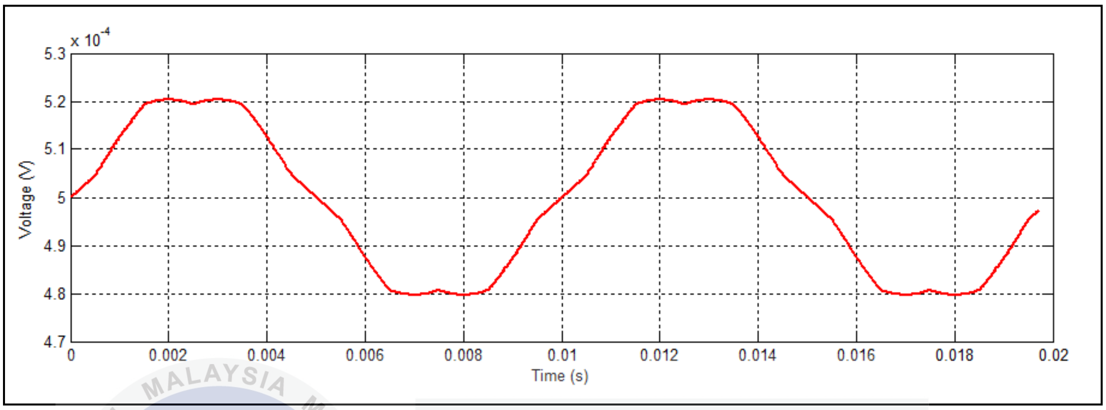

Figure 4.13: Switching pattern waveform for T_1.

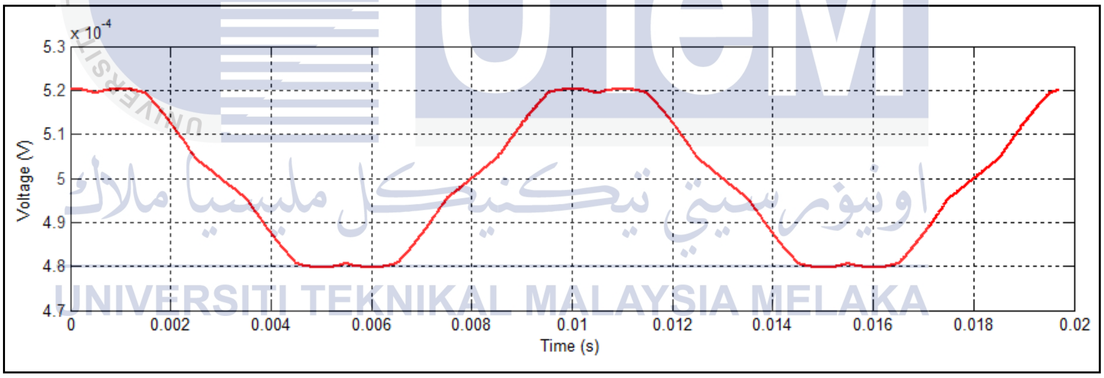

Figure 4.14: Switching pattern waveform for T_2.

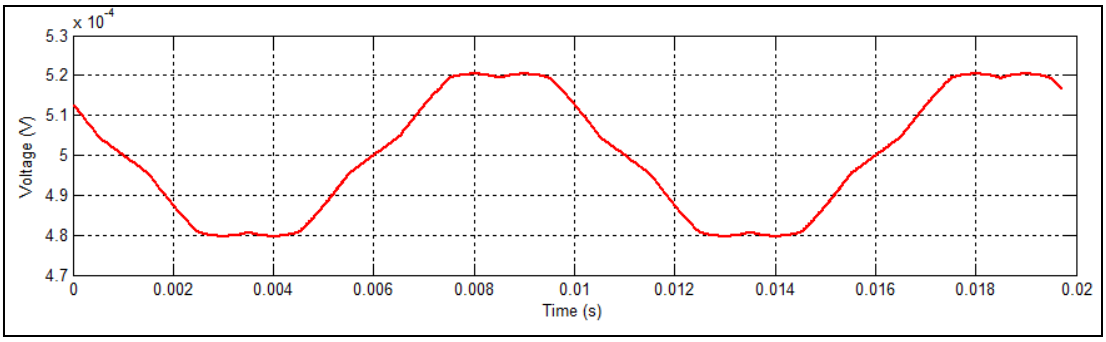

Figure 4.15: Switching pattern waveform for T_3.

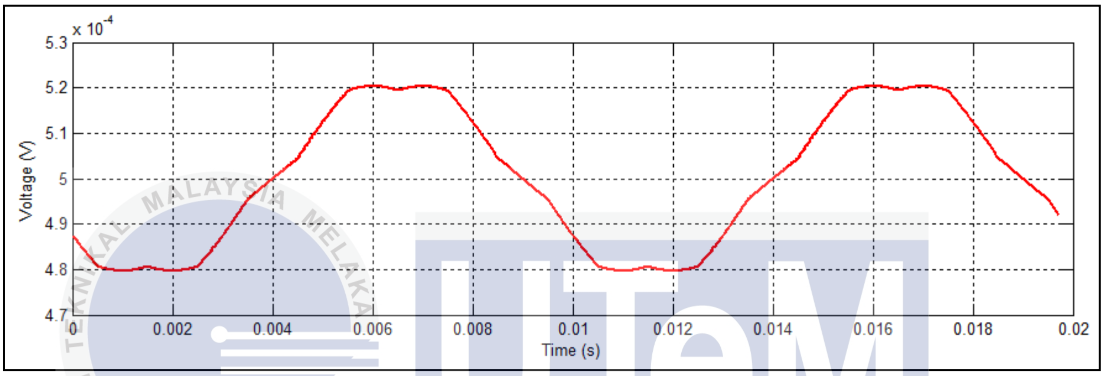

Figure 4.16: Switching pattern waveform for T_4.

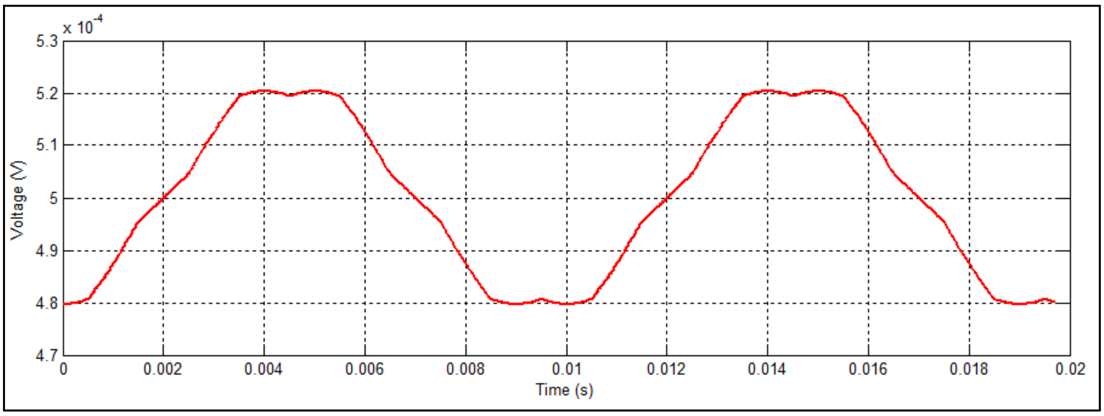

Figure 4.17: Switching pattern waveform for T_5.

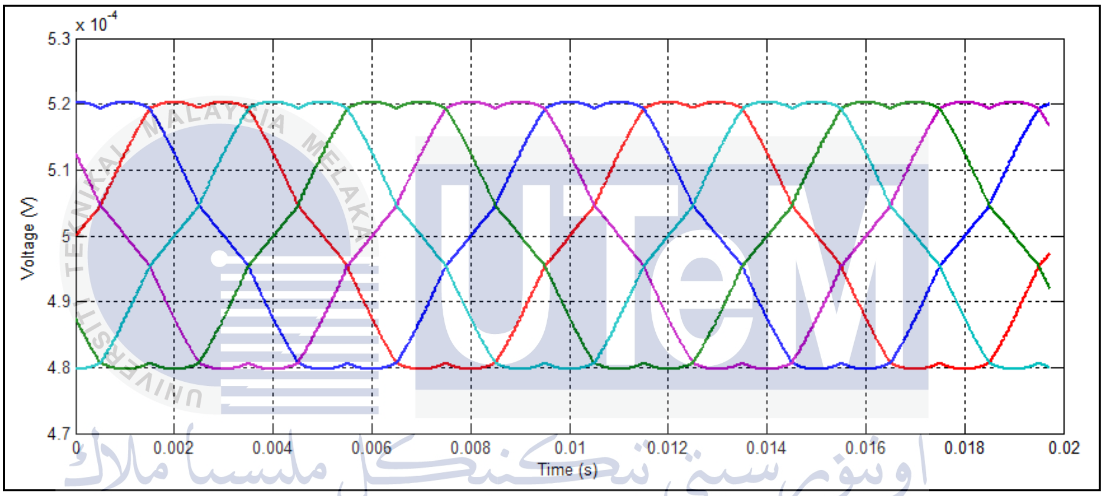

Figure 4.18: Switching pattern waveform for T_1, T_2, T_3, T_4, T_5.

The switching pattern for T_1, T_2, T_3, T_4, T_5 then compare to the triangle waveform to get the switching waveform for the inverter. The triangle waveform generate using the repeating sequence block and the frequency is $10kHz$. The amplitude of the triangle waveform is $0.001V$. Figure 4.19 shows the triangle waveforms generate by repeating sequence block.

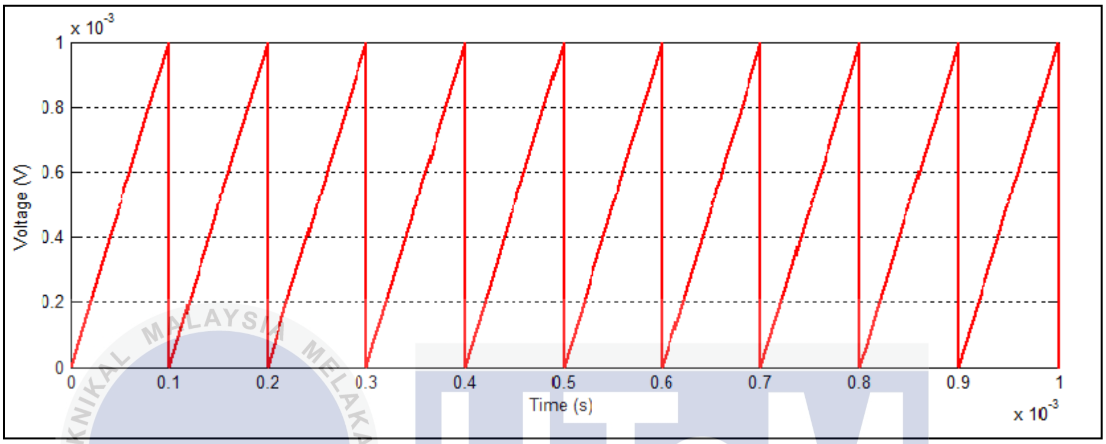

Figure 4.19: Triangles waveforms generate by repeating sequence block.

The switching pattern waveform then compare to the triangle waveform to generate the switching for the inverter. Based on the T_1, T_2, T_3, T_4, T_5, that is only for the upper part of the inverter. For the lower part of the inverter, the waveform has reverse. The switching signal for ten MOSFET generate based on the previous waveform. Each MOSFET have different switching signal that represented by $S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}$.

Figure 4.20 until 4.29 show the switching signal for each MOSFET. The frequency of this waveform is $10kHz$.

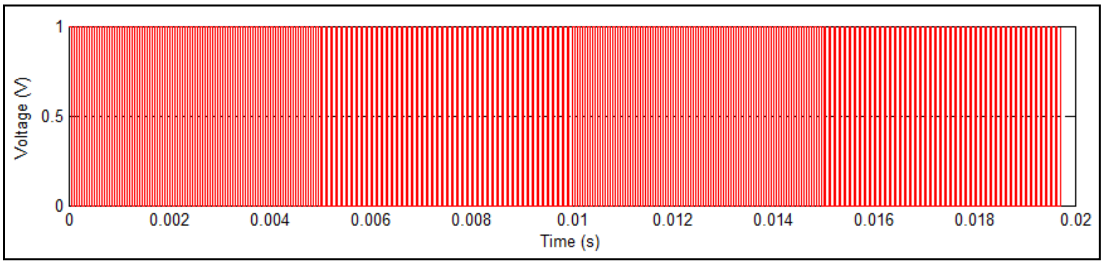

Figure 4.20: Switching signal for S_1 of the inverter.

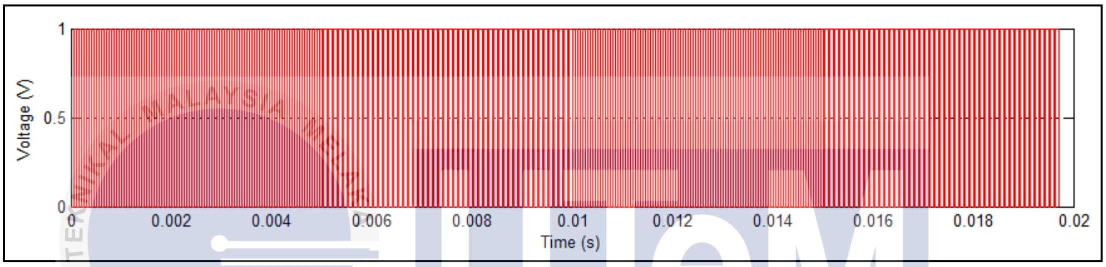

Figure 4.21: Switching signal for S_2 of the inverter.

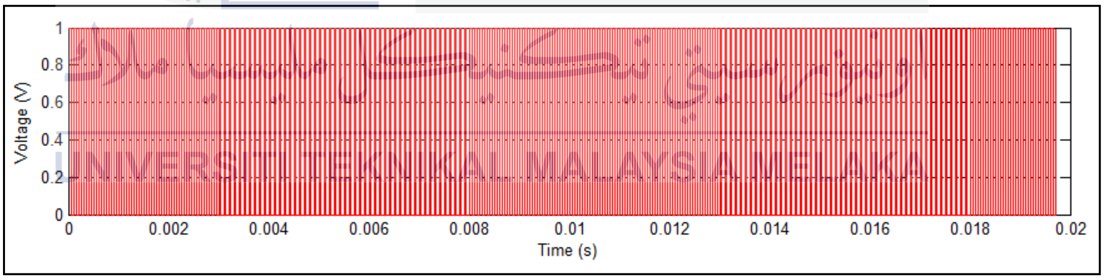

Figure 4.22: Switching signal for S_3 of the inverter.

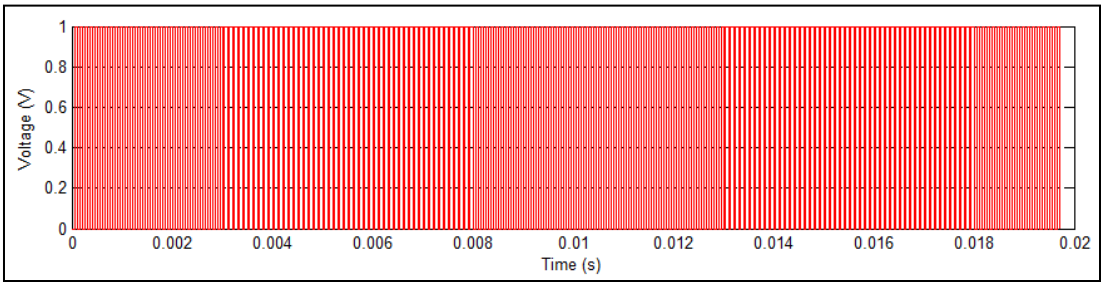

Figure 4.23: Switching signal for S_4 of the inverter.

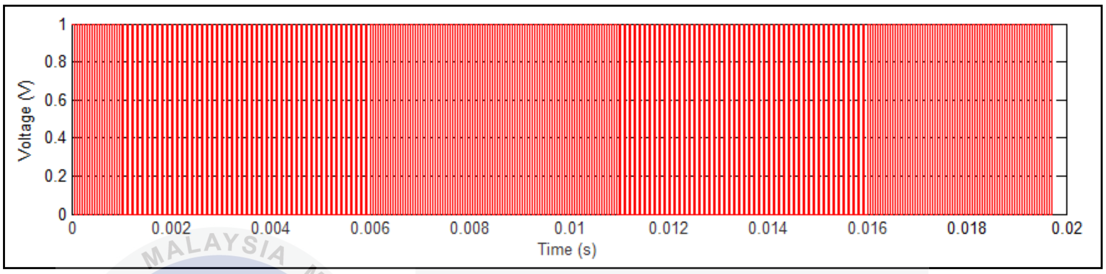

Figure 4.24: Switching signal for S_5 of the inverter.

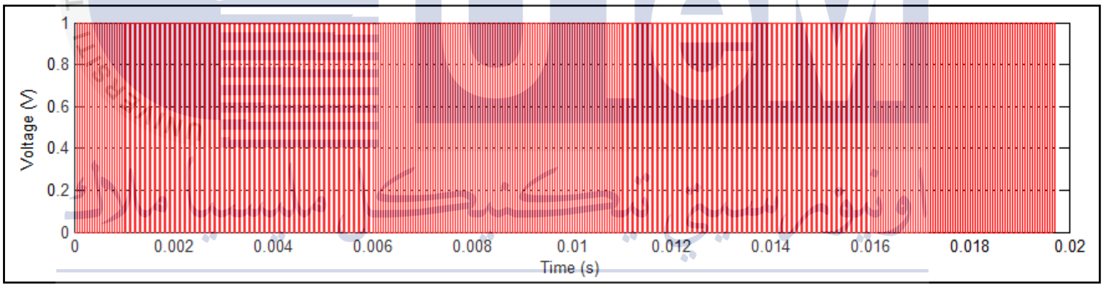

Figure 4.25: Switching signal for S_6 of the inverter.

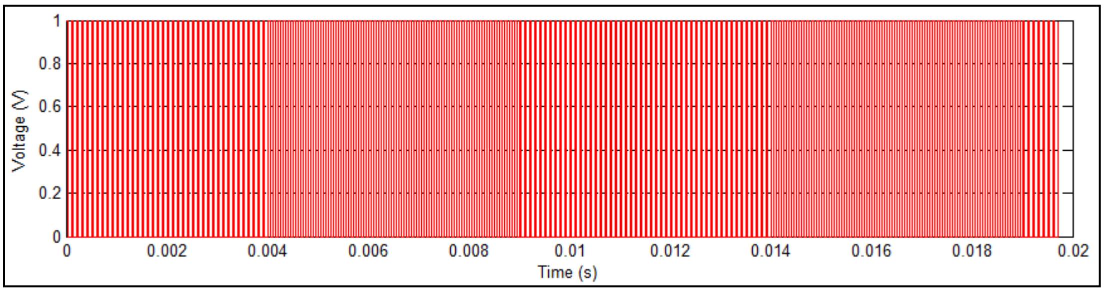

Figure 4.26: Switching signal for S_7 of the inverter.

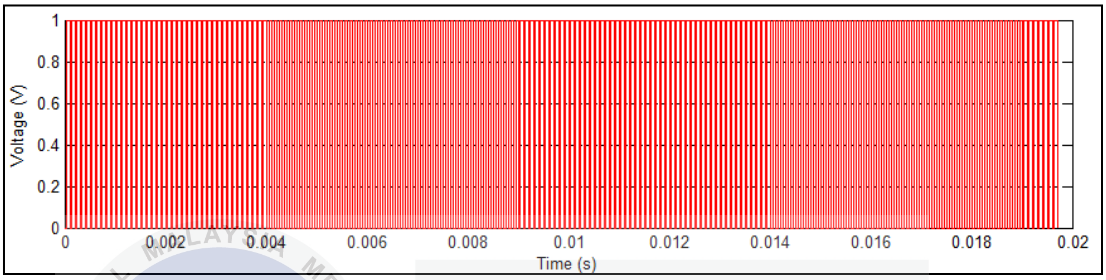

Figure 4.27: Switching signal for S_8 of the inverter.

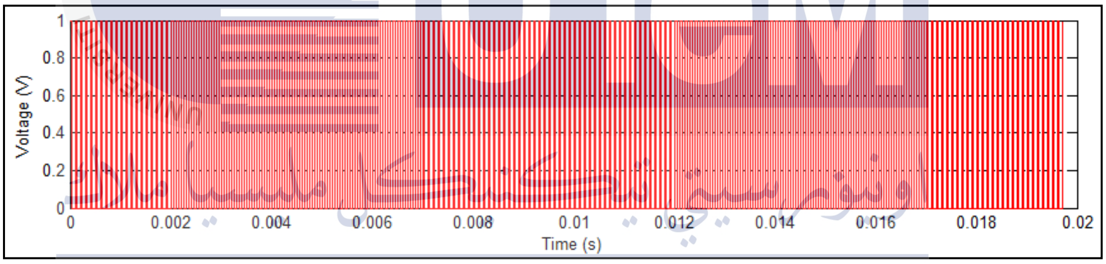

Figure 4.28: Switching signal for S_9 of the inverter.

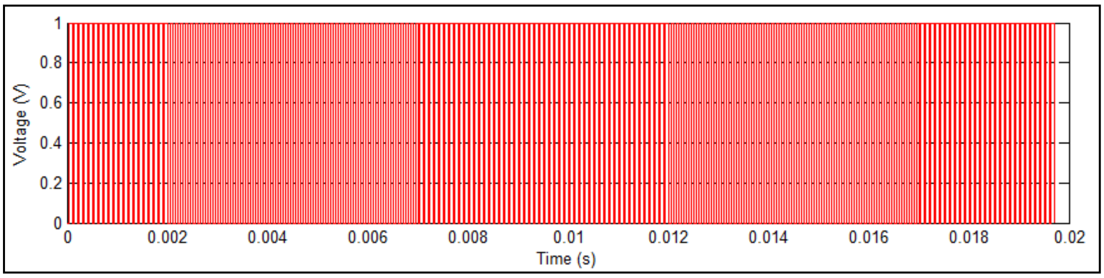

Figure 4.29: Switching signal for S_{10} of the inverter.

4.2 Five-phase Voltage Source Inverter

The switching signals for the inverter operate the MOSFEt. The space vector drive using the medium and large vector give the output of five-phase inverter closed to sinusoidal waveform. For medium vector which state 11 until 20 of the space vector give the output of phase voltage equal $\frac{4}{5}V_{DC}$ and $\frac{1}{5}V_{DC}$. For large vector that is state 21 until 30, give the output of phase voltage equal to $\frac{2}{5}V_{DC}$ and $\frac{3}{5}V_{DC}$. The combination of used medium and large vector gives the output phase voltage for each phase equal to $\frac{1}{5}V_{DC}\frac{2}{5}V_{DC},\frac{3}{5}V_{DC},\frac{4}{5}V_{DC}$.

The output phase voltage of the five-phase voltage source inverter designed to close to sinusoidal waveform for better performance of the five-phase induction motor. Figure 4.30 until 4.34 show the phase voltage of the five-phase inverter.

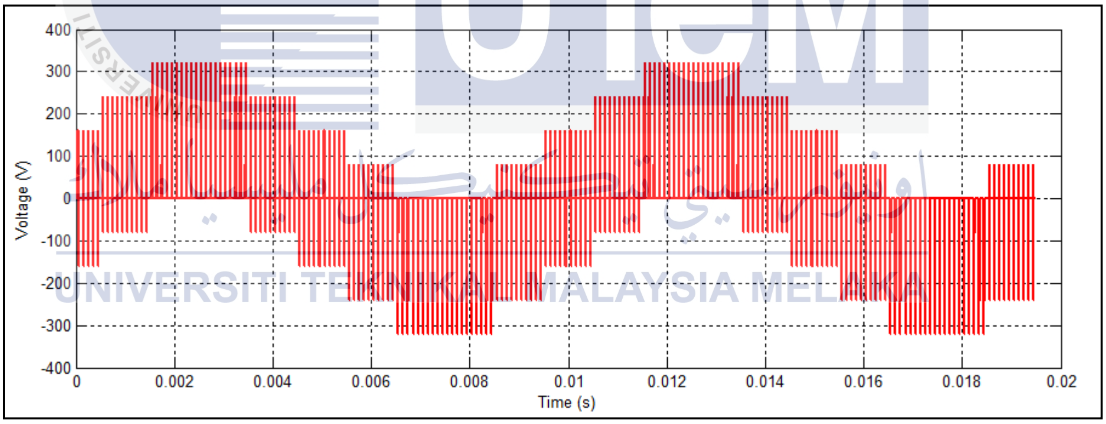

Figure 4.30: Phase voltage for phase a of the voltage source inverter.

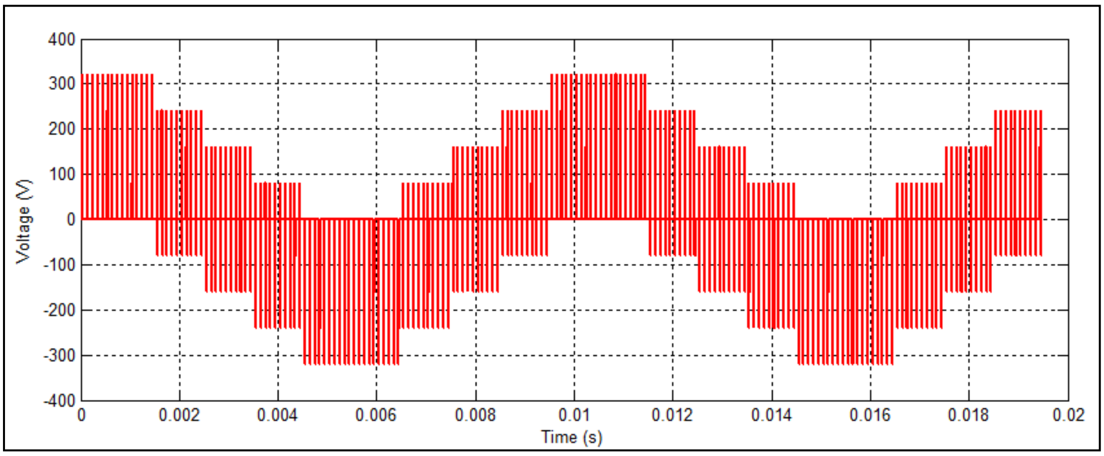

Figure 4.31: Phase voltage for phase b of the voltage source inverter.

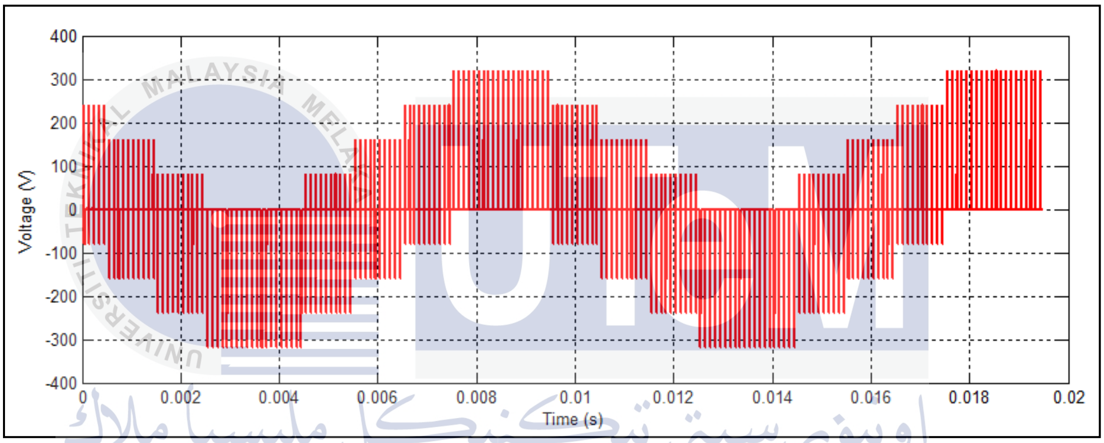

Figure 4.32: Phase voltage for phase c of the voltage source inverter.

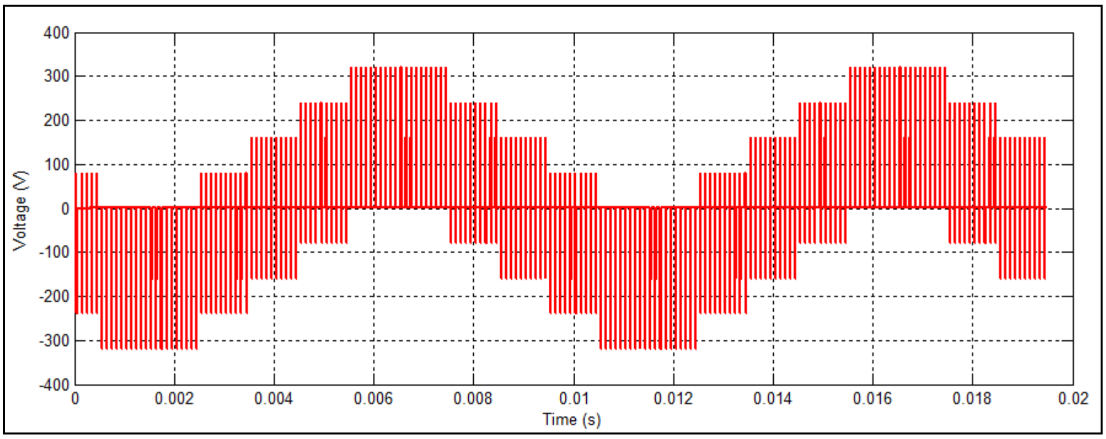

Figure 4.33: Phase voltage for phase d of the voltage source inverter.

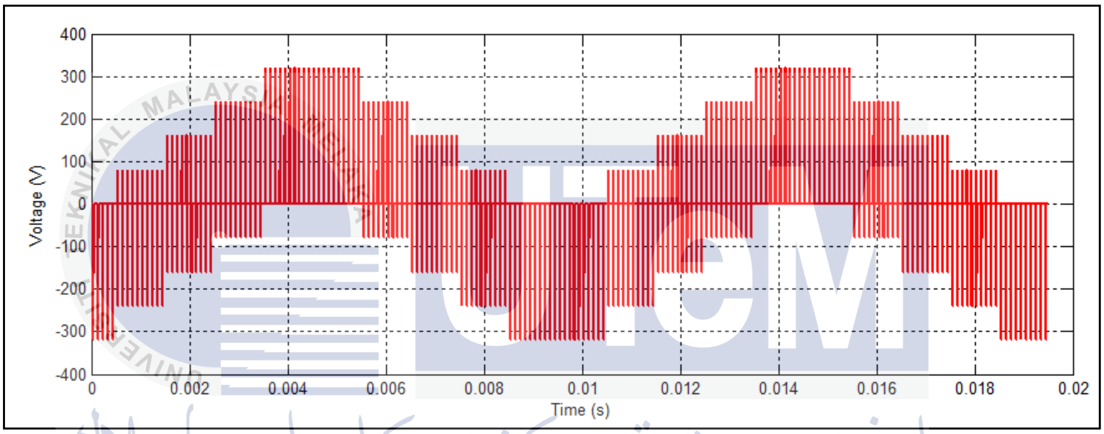

Figure 4.34: Phase voltage for phase e of the voltage source inverter.

Figure 4.35 shows the phase to neutral voltage space vector for state 1 until 32. State 31 and 32 is at the origin.

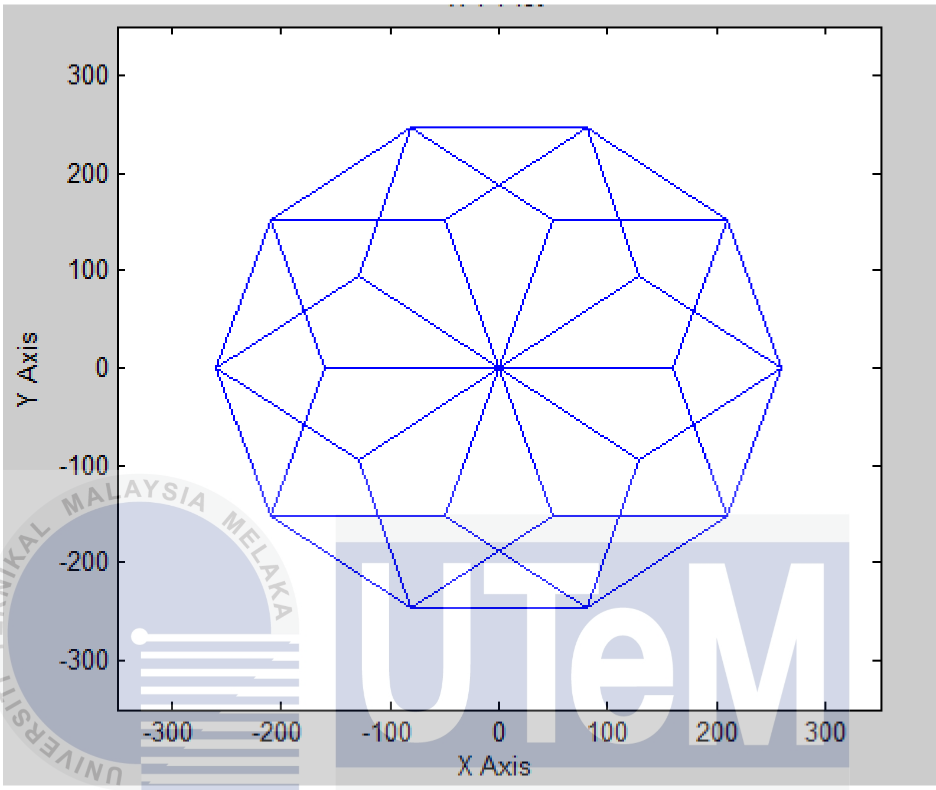

Figure 4.35: Phase to neutral voltage space for states 1 until 32 vector on d-q plane.

The line voltages of the leg inverter are either equal to V_{DC} or 0. When the upper diode are switch on and the lower diode are switch off, then the leg inverter voltage equal to V_{DC}. When the upper diode are switch off and the lower diode are switch on, the leg inverter voltage equal to 0. For each switching state, there will be the leg inverter voltage equal to V_{DC} and 0. Figure 4.36 until 4.40 show the line voltage of the five-phase inverter.

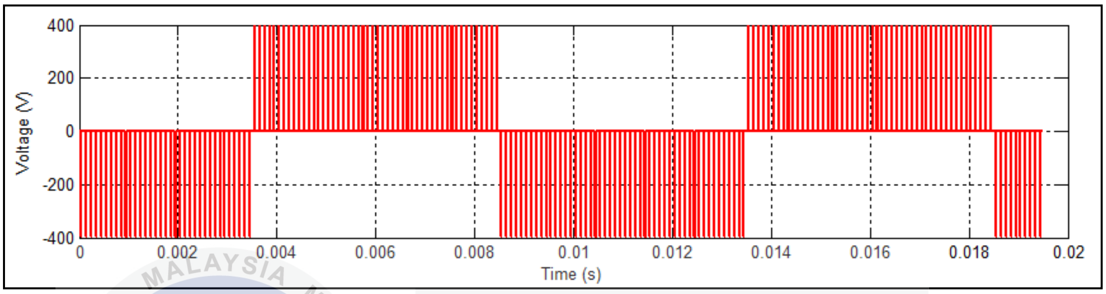

Figure 4.36: Line voltage for leg inverter A.

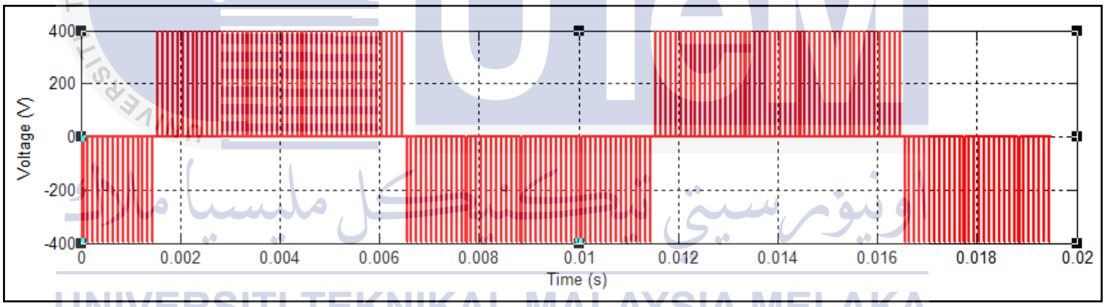

Figure 4.37: Line voltage for leg inverter B.

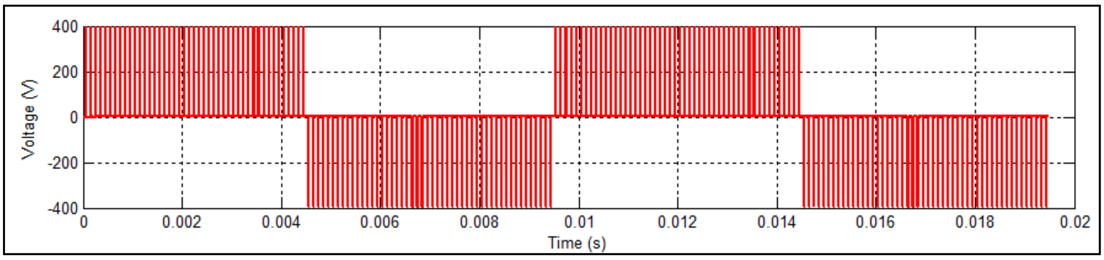

Figure 4.38: Line voltage for leg inverter C.

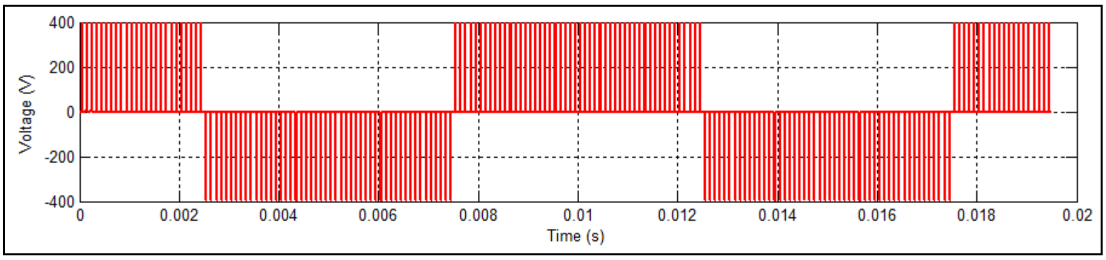

Figure 4.39: Line voltage for leg inverter D.

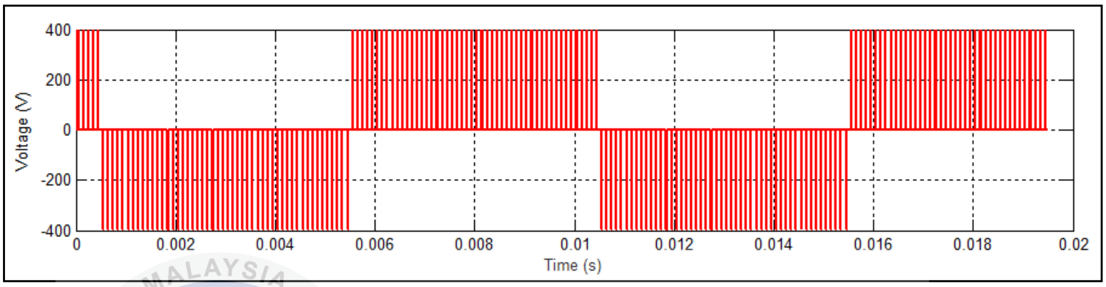

Figure 4.40: Line voltage for leg inverter E.

4.3 Five-phase Induction Motor

Five-phase induction motor have five-phase supply source. For induction motor that drive by the inverter approach by space vector method, the source for the five-phase induction is the phase voltage of the voltage source inverter. The phase voltage from the five-phase voltage source inverter have transformed into d-q voltage. The d-q voltage waveform closely similar with the phase voltage waveform but consists of two variables. The frequency of this waveform is similar to the phase voltage waveform of the five-phase voltage source inverter. Figure 4.41 shows the d-q voltage for the five-phase induction motor.

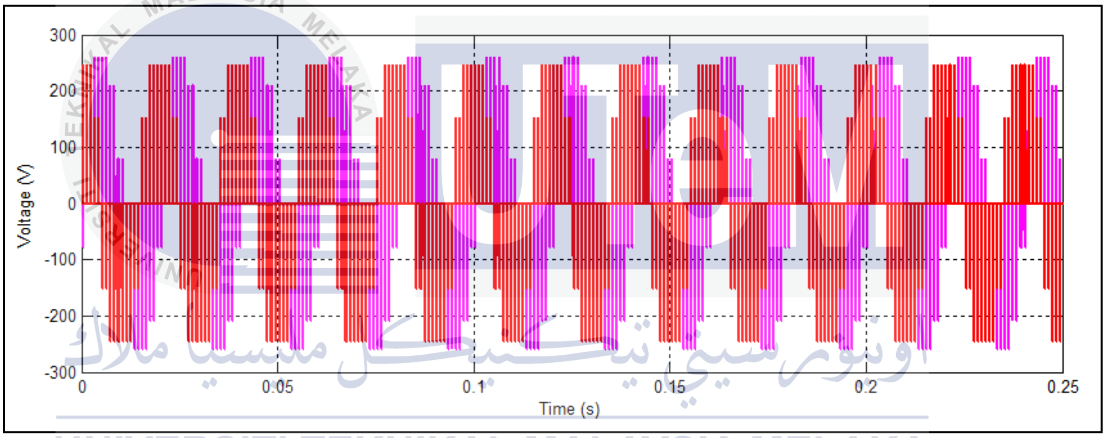

Figure 4.41: d-q voltage for the five-phase induction motor.

Using equation and block mention in Chapter 3, the d-q voltage need to transformed into d-q stator current. d-q stator current is the current in the d and q axis of the motor. The d-q stator current is stable which mean the current flowing to the stator of the motor is consistent. At early stage, the current a little bit high because to start the rotor to rotate from zero to constant speed. After early stage, the current flowing is consistent in order to rotate the rotor at constant speed just to against the resistance inside the motor. Figure 4.42 shows the d-q current for five-phase induction motor.

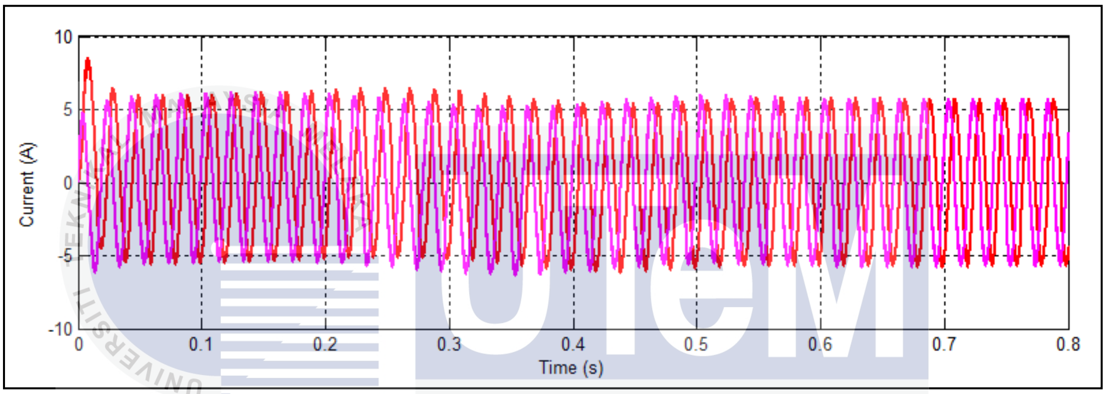

Figure 4.42: d-q stator current of the five-phase induction motor.

The d-q stator current have transformed into the phase stator current by the block transformation. The waveform of the phase stator current is close like the waveform of d-q stator current. Figure 4.43 until 4.47 shows the phase stator current for phase a,b,c,d, and e.

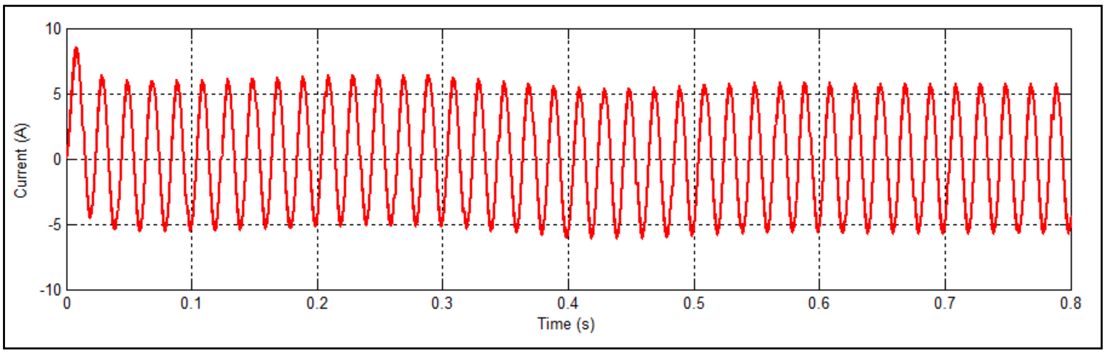

Figure 4.43: Stator phase current of the five-phase induction motor for phase a.

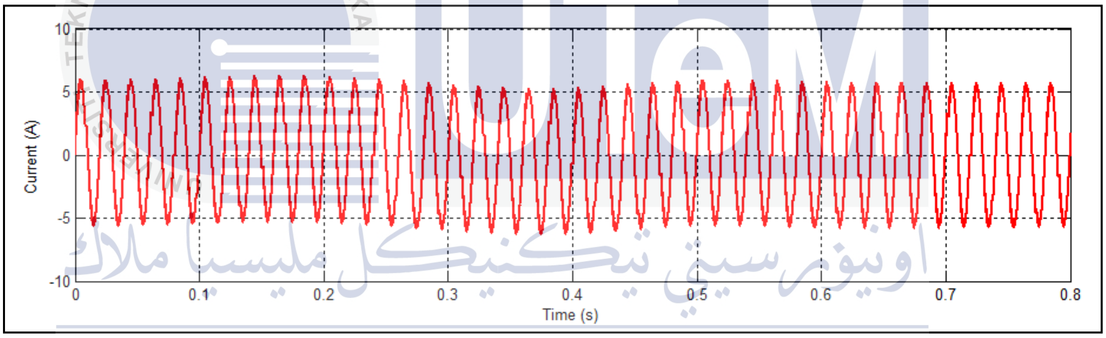

Figure 4.44: Stator phase current of the five-phase induction motor for phase b.

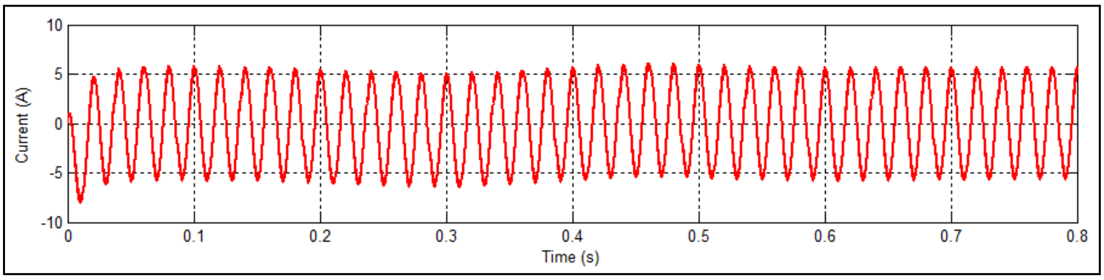

Figure 4.45: Stator phase current of the five-phase induction motor for phase c.

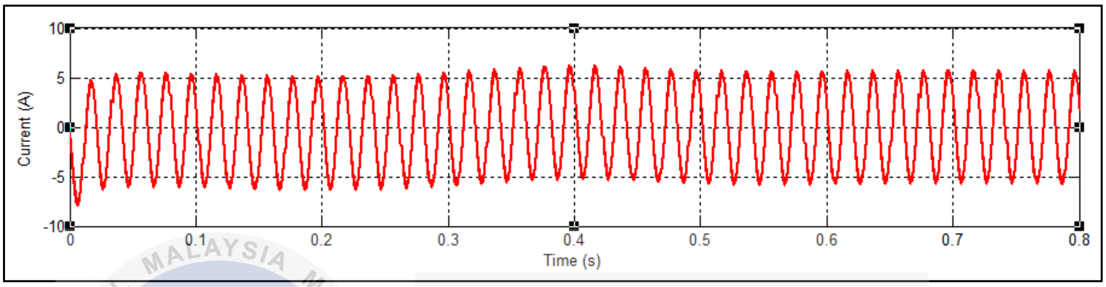

Figure 4.46: Stator phase current of the five-phase induction motor for phase d.

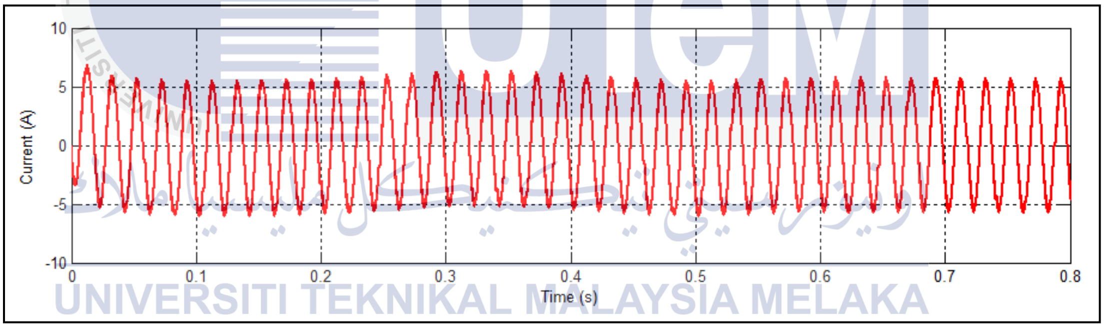

Figure 4.47: Stator phase current of the five-phase induction motor for phase e.

Torque of the motor is rotating force developed by the motor. Figure 4.48 shows the torque of the five-phase induction motor. At time 0 until 0.5s, the torque of the motor increase closes to 0.2 Nm. This starting torque show the torque that need by the motor to start rotate. From time 0.5s until 0.7s, the torque of the motor decrease and approaching to zero. For time 0.7s and more, the torque is not equal to zero but approaching to zero. This means the motor speed approaching to constant. The torque for this period is for against the resistance of the motor.

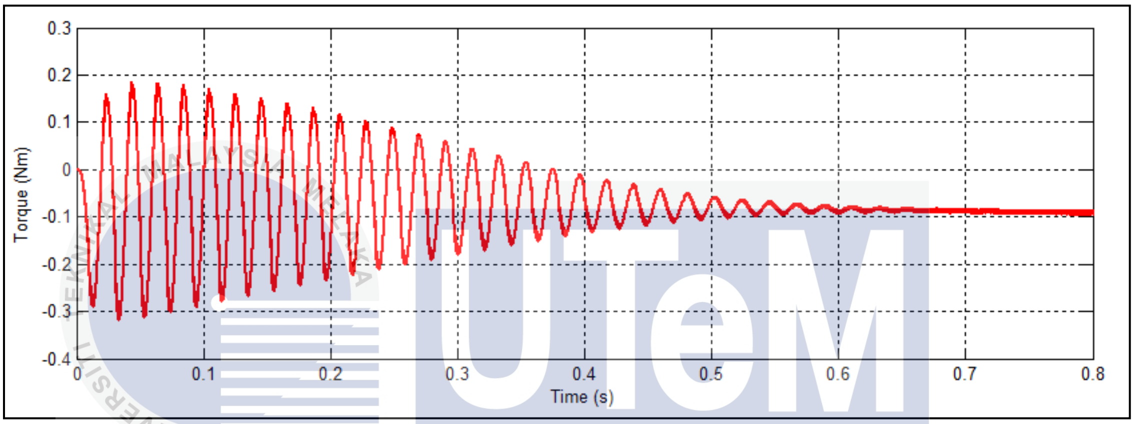

Figure 4.48: Torque of the five-phase induction motor.

Figure 4.49 show the speed of the five-phase induction motor. The waveform of the speed has increase from zero until constant speed. At time 0 until 10s, the speed of the motor from zero increase to constant speed. For time 10s and more, the speed is constant close to 1500 rpm. This motor takes 10 s to reach the constant speed.

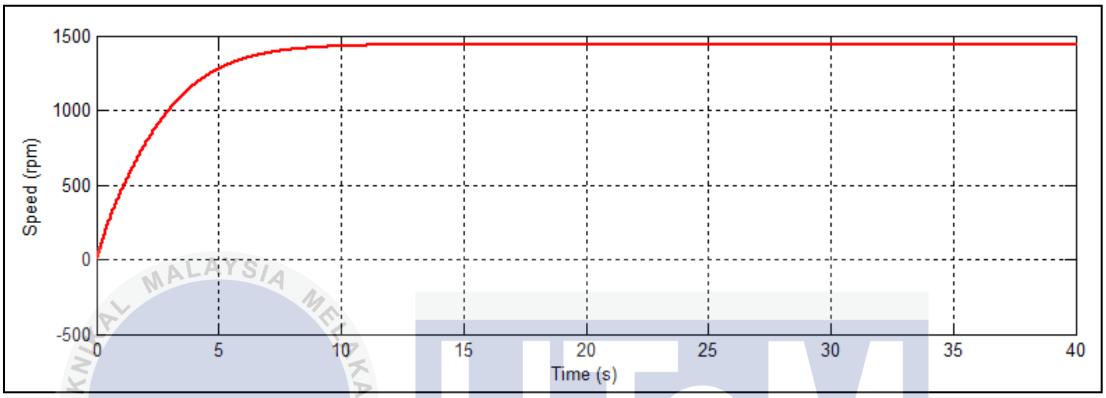

Figure 4.49: Speed waveform of the five-phase induction motor.

Parameter use for this induction motor:

Rotor resistance, $R_R = 0.2447\Omega$

Stator resistance, $R_s = 0.1589\Omega$

Mutual inductance, $L_m = 60.6639mH$

Stator leakage inductance, $L_{ls} = 62.6956mH$

Rotor leakage inductance, $L_{lr} = 63.4561mH$

Inertia, $J = 2.018\ kg.m^2$

CHAPTER 5

CONCLUSION

5.1 Conclusion

Throughout this project, student should fully understand the topic that learns in this project. Through this project, student applied the theoretical and practical related topic to this project. This project also improves important skill and knowledge on troubleshooting, analysing and simulation. This project presents a complete simulation model to simulate a five-phase induction motor drive system for space vector modulation.

The space vector modulation for five-phase yield 22 more switching state compare to three-phase space vector. Two of them yield zero output phase voltage and called zero vectors. This project used medium and large vector as reference for the space vector. The used of medium and large vector is to synthesize a sinusoidal waveform. The output phase voltages of the five-phase inverter in the simulation block give the output close to the sinusoidal waveform. This shows the effectiveness of the combination medium and large vector of space vector. This technique gives better performance in term of low harmonic especially low order voltage harmonics.

The usage of the large vector only cannot produce the sinusoidal waveform. When number of phases in the inverter increase, the available number of inverter voltage space vector can be changed. The auxiliary space vector is where the harmonic distortion created. The switching combination that gives large vector in d-q plane create small vector in x-y plane. The x-y plane components produce losses to the system due to uncontrollable harmonics. To minimize the switching losses, the resultant voltage vector on x-y component to zero.

The combination used of medium and large vector lead to reduce the low order harmonic and minimize the number of switching. Five-phase induction model were model used d-q axis equivalent circuit. This project develops the five-phase induction model in an arbitrary reference frame. This model of induction motor is easy to manipulated, versatile and easy to implement various types of control strategies. The simulation model developed using simpower system block sets of the Matlab/Simulink software. The objectives of this project achieved as the voltage and the speed of the motor is followed the implement one.

5.2 Recommendation

For future work, the simulation for the drive can be more simple and effective. Implement the close loop operation control for this project. Generate higher space vector modulation. There is part that can modify for easy troubleshooting. More analysis needs to analyse through the motor performances.

REFERENCES

[1] M.SajediHir, Y.Hoseynpoor, P.MosadeghArdabili, T.PirzadehAshraf. Modeling and Simulation of Induction Motor Drive with Space vector Modulation, *Autralian Jurnal of Basic and Applied Science,* 2011, 5(9): 2210-2216.

[2] Singh, G.K., “Multi-phase induction machine drive research – a survey”, *Electrical Power System Research*, 61, pp. 139-147, 2002.

[3] E. E. Ward and H. Harer, “Preliminary investigation of an inverter-fed 5-phase induction motor”, *Proc. IEE*, Vol. 116, No. 6, pp.980-984, 1969.

[4] S. Smith, “Development in power electronics machines and drives. IEE Power Eng. J. , 2002, 16, pp. 13-17.

[5] Levi, E., Bojoi, R., Profumo, F., Toliyat, H.A., Williamson, S., “Multiphase induction motor drives – a technology status review”, *IEE Electric Power Application*, 2007.

[6] Min-Huei Kim, Nam-Hun Kim, Won-Sik Baik. A Five-phase Induction Motor Speed Control System Excluding Effects of 3rd Current Harmonics Component, *Journal of Power Electronic*, 2011, 11(3) Vol. 11, No. 3, 2011.

[7] K. N. Pavithran, R. Parimelalagan, M. R. Krishnamurthy, “ Studies on Inverter-Fed Five-phase Induction motor Drive”, *IEE Tranc. on Power Electronics*, vol. 3, no. 2, 1988, pp. 224-235.

[8] Valentin Oleschuk, Francesco Profumo, Alberto Tenconi, Evgeni Yaroshenko. Five-phase Inverters with Synhronized PWM. *Computer as a Tool*. September 9-12, Warsaw: Eurocon, 2007. pp. 1872-1878.

[9] Ben Echikh. H., Trabelsi R., Mirnouni M.F., M’sahli F.. 5-phase AC induction motor rotor flux oriented control with space vector modulation technique. *ICEESA*. IEE, 2013. pp. 743-748.

[10] B. S. Khaldi, H. Abu-Rub, A. Iqbal, R. Kennel, M. O. Mahmoudi, D. Boukhetala. Comparison study between a simple sensorless and adaptive observer for DTC-SVM five-phase induction motor drive. *Industrial Technology (ICIT).* IEE International Conference. 2012.

[11] A. Iqbal, E. Levi. Space vector modulation schemes for a five-phase voltage source inverter. *Power Electronics and Applications*. European Conference. 2005.

[12] G. Renukadevi, K. Rajambal. Generalized d-q Model of n-Phase Induction Motor Drive, *International Journal of Electrical, Electronic Science and Engineering*, 2012, 6 (9) Vol. 6, No. 9, 2013.

[14] N. Wan, F. Mohamad, M. Ismail, "Switching technique for Multiphase Voltage Source Inverter", *IEEE Symposium on Huminities, Science and Engineering Research*, pp. 589-593, 2012.

[15] Singh, G.K., Pant V., Sigh Y.P., "Voltage Source Inverter Driven Multi-phase Induction Machine", *Computer and Electrical Engineering*, 29, pp. 813-834, 2003.

[16] K. L. Shi, T. F. Chan, Y. K. Wong, S. L. Ho, "Modelling and Simulation of the Three-phase Induction Motor Using Simulink", *Int. J. Elect. Enging. Educ.*, vol. 36, 1999, pp. 163-172.

[17] K. P Prased Rao, B. Krishna Veni, D. Ravithej. Five-phase Inverter for Five-phase Supply, *International Journal of Engineering Trends and Technology*, 2012, 3 (2) Vol. 3, No. 2, 2012.

[18] G. Renukadevi, K. Rajambal. Modelling and Analysis of Multi-phase Inverter Fed Induction Motor Drive with Different Phase Numbers, *WSEAS Transactions on System and Control*, 2013, 8 (3) Vol. 8, No. 3, 2013.