MODELING AND SIMULATION OF SPACE VECTOR PULSE WIDTH MODULATION FOR THREE PHASE VOLTAGE SOURCE INVERTER

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June 2014

" I hereby declare that I have read through this report entitle "Modeling and Simulation of Space Vector Pulse Width Modulation for Three Phase Voltage Source Inverter" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Power Electronic and Drive) "

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

(Power Electronic and Drive)

Faculty of Electrical Engineering

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2013/2014

I declare that this report entitle "Modeling and Simulation of Space Vector Pulse Width Modulation for Three Phase Voltage Source Inverter " 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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ABSTRACT

Various Pulse Width Modulation(PWM) techniques are developed for industrial application [3] to increase performance of industrial power inverter in term of efficiency and output voltage. The research has produce the advancement of Voltage Source Inverter to be flexible AC drive control to obtain variable magnitude and frequency. The most popular technique in controlling voltage source inverter is Space Vector Pulse Width Modulation. Research findings declare that the efficiency of SVPWM technique can be improve by implementing Discontinous Space Vector Pulse Width Modulation (DSVPWM) technique. SVPWM technique has lower efficiency due to high switching losses as this technique uses all three phases quantities while DSVPWM only use two out three phase quantities. Thus, this thesis performed comparative studies of SVPWM and DSVPWM techniques utilizing MATLAB tools. The objectives of this research to analyse the implementation of SVPWM and DSVPWM by using MATLAB/Simulink, to analyse efficiency improvement of DSVPWM over SVPWM as well as to analyse Total Harmonis Distortion for both technique. The research methode is simplified into implementing procedure for modeling and simulating the both technique. Both of the techniques following the implementing procedure but the only difference is at the last three step. The results obtained proved that DSVPWM improved efficeincy of SVPWM but does not improve Total Harmonic Distortion. THD of voltage for both technique is quite similar but in term of THD of current,DSVPWM has slightly higher than SVPWM.

ABSTRAK

Terdapat pelbagai teknik Permodulan Lebar Denyutan (PWM) yang dibina untuk aplikasi industri [3]bagi meningkatkan prestasi penyongsang kuasa perindustrian . Penyelidikan telah menghasilkan pembaharuan kepada penyosang jenis voltan sumber iaitu dengan menghasilkan voltan berubah-ubah dan kekerapan masa berubah-ubah. Teknik yang paling popular digunakan untuk mengawal penyongsang jenis voltan sumber adalah Modulasi Ruang Vektor Lebar Denyutan.Hasil kajian mendapati bahawa kecekapan teknik SVPWM boleh ditingkatkan dengan melaksanakan teknik Modulasi Ruang Vektor Lebar Denyutan Tidak Berterusan (DSVPWM). Oleh itu , tesis ini memaparkan kajian perbandingan antara SVPWM dan DSVPWM teknik menggunakan siasatan alatan MATLAB. Objektive kajian yang dijalankan adalah untuk menganalisis pelaksanaan SVPWM dan DSVPWM dengan menggunakan MATLAB / Simulink , untuk menganalisis peningkatan kecekapan DSVPWM lebih SVPWM dan juga untuk menganalisis Jumlah Penyelewengan Harmonis untuk kedua-dua teknik.Kaedah penyelidikan dipermudahkan dengan melaksanakan prosedur untuk pemodelan dan prosedur simulasi bagi kedua-dua teknik. Proses perlaksaanaan kedua-dua teknik tersebut melalui prosedur sama tetapi perbezaan bermula pada langkah tiga terakhir. Keputusan yang diperolehi membuktikan bahawa DSVPWM membaiki kecekapan SVPWM tetapi tidak memperbaiki Jumlah Penyelewengan harmonik . Jumlah Penyelewengan Harmonic bagi voltan untuk kedua-dua teknik ini agak sama tetapi dari segi Jmlah Penyelewengan Harmonic bagi arus, DSVPWM lebih tinggi sedikit daripada SVPWM .

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MI	Modulation Index
SVPWM	Space Vector Pulse Width Modulation
DSVPWM	Discontinuous Space Vector Pulse Width Modulation
VSI	Voltage Source Inverter
CSI	Current Source Inverter
DC	Direct Current
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion
IGBT	Insulated-gate bipolar transistor
UPS	Uninterrupted Power Supply
IEGTs	Injection Enhanced Gate Transistor
AFD	Adjustable Frequency Drives
HVDC	High Voltage Direct Current

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CHAPTER 1

INTRODUCTION

1.1 Research Overview

For this project, discontinuous space vector pulse width modulation (DSVPWM) technique is used to improve the efficiency of space vector pulse width modulation (SVPWM) for voltage source inverter (VSI). SVPWM technique is depends on the representation of the inverter output as space vector. Space vector represent the output voltages of the inverter is realized for the implementation of SVPWM [1]. This PWM technique is the most popular technique in controlling voltage source inverter. This report is intended to introduce information about implementation of DSVPWM technique in order to improve the efficiency of SVPWM technique. Description of implementation steps and simulation findings is explained in this report.

1.2 Research Motivation

In the age of globalization era, the great demand in high efficiency industrial applications lead to development of high performance drives technology. The demand urged the researchers to undertake research extensively. The researches discover a technique to improve efficiency of voltage source inverter. Conventionally, space vector pulse width modulation (SVPWM) is the best technique used to control voltage source inverter. A new technique known as discontinuous pulse width modulation (DSVPWM) propose to improve SVPWM technique. The propose technique also famous as two-phase SVPWM. The analysis of these two techniques is focus on efficiency improvement and total harmonic distortion.

1.3 Problem Statement

Space pulse width modulation simultaneously symbolizes three-phase quantities as one rotating vector. This technique is popular due to higher output voltage when compared with Sinusoidal Pulse Width Modulation as well as easy digital realization. Regardless of these two advantages, SVPWM is analyses in term of its efficiency. The researchers found that the efficiency of this technique can be improved by implementing a technique call discontinuous pulse width modulation. In this technique, only two out of three-phases quantities used in a rotating vector. One of the phases is tied to positive or negative DC bus which represents zero voltage vector (000) elimination and zero voltage vector (111) elimination respectively.

1.4Objectives

i. To simulate and explain space vector pulse width modulation (SVPWM) and discontinuous space vector pulse width modulation (DSVPWM) technique for three phase voltage source inverter by using MATLAB/SIMULINK.

ii. To analyses the improvement in efficiency of discontinuous space vector pulse width modulation (DSVPWM) over space vector pulse width modulation (SVPWM).

iii. To analyses the Total Harmonic Distortion (THD) for both space vector pulse width modulation (SVPWM) and discontinuous space vector pulse width modulation.

1.4 Scope of Research

There are two approaches in implementation of DSVPWM which is zero voltage (000) eliminated and zero voltage (111) eliminated. Only zero voltage (000) eliminated approach enclosed in this research project. This research project also analyses Total Harmonic Distortion for both SVPWM and DSVPWM technique. This research project focus on the implementation of SVPWM and DSVPWM technique for three-phase voltage source inverter using the software MATLAB/SIMULINK includes:

i. Focus on development of MATLAB/SIMULINK model of SVPWM and DSVPWM step by step.

ii. Investigation on the improvement of SVPWM's efficiency by using DSVPWM technique.

1.6 Report Outlines

Chapter 1 Introduction

In this chapter, the brief idea about the project is discuss in overview. The idea is then elaborated in research motivation, objectives, scope as well as contribution of research.

Chapter 2 Literature Review

The review of basic principle PWM technique and the topologies of voltage source inverter are explained in detail. Besides, this chapter summed up the research information in related previous work and summary of review. The software used for simulation is described.

Chapter 3 Methodology

The overall flow of the project is explain and illustrated in flow chart. In addition, the detail of involved step is provided in analogical approach.

Chapter 4 Results and Analysis

The results, analysis and discussion of three-phase VSI using SPWM will be discuss in this chapter.

Chapter 5 Conclusion

Summation of ideas in the report will be concluded.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will justify and discusses the source or articles that are associated with the project. It consists of the theoretical information about the technique used. The derivation of Space Vector Pulse Width Modulation (SVPWM) is additionally express in this chapter.

2.2 Voltage source inverter (VSI)

A power inverter is an electronic device that converts Direct Current to Alternating current. It converts the DC power obtained from power supply or batteries and rectifier to AC power at the desired output voltage and frequency. There are two dominant types of inverter known as voltage source inverter (VSI) and current source inverter (CSI)[7]. In industrial market, voltage source inverter (VSI) design has greater advantages over current source inverter (CSI) as it is competent for running motor without reducing the power rating of the motor. Basically, a voltage source inverter (VSI) is one in which has small or negligible impedance at the DC source.

Voltage source inverter made up of power transistors and their controlled turn ON and turn OFF is generated from self-commutation with base signals. Each power switch of the inverter is insulated gate bipolar transistor (IGBT) with anti-parallel diodes. There are other possible choices of transistor to replace IGBT such as insulated gate commutated thyristors (IGCTs) and injection enhanced gate transistors (IEGTs) but IGBT is widely used in VSI drives market. The IGBT switches create a PWM voltage output that regulates the voltage and frequency to the motor [2].

Inverters industrial applications are for adjustable frequency drives (AFDs), HVDC transmission line, uninterruptable power supply (UPS) and electric vehicles [7]. Adjustable frequency drives (AFDs) consist of converter, DC link, inverter and motor as shown in Figure 2.1. Diode rectifiers are usually used as converter to converts line AC voltage between 50Hz-60Hz to DC voltage. The DC link transmits the DC voltage to the inverter. By storing energy, it provides ride-through capability as well as some isolation from utility. Motor as the AC loads requires adjustable voltage and frequency at their input terminals. Thus, they are fed by inverters as to fulfill the requirement load.

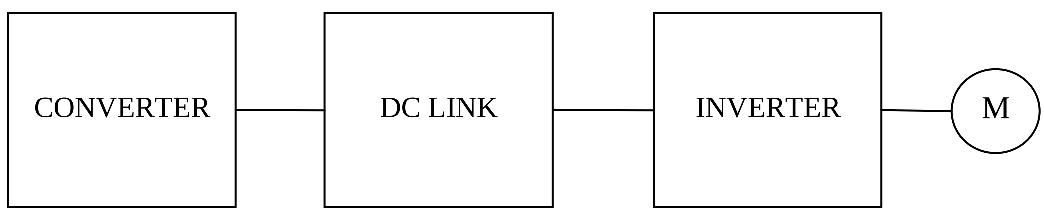


Figure 2.1: Block diagram of adjustable frequency drive (AFD)

2.2.1 Three-Phase Voltage Source Inverter

As shown in Figure 2.2, three- phase voltage source inverter (VSI) is composed with DC supply and pair of switch in each leg. Each switch is made up of fully controllable semiconductor, IGBT and diode. Upper and lower switch in each leg are complimentary in operation. If the lower switch is ON, the upper switch must be OFF in order to protect the circuit. The DC voltage at the input terminal is assumed as being constant. Symbols of (a, b, c) are donated as the inverter outputs, while (A, B, C) refer to the points connection of the outputs legs. The three-phase voltage source inverter (VSI) is developed assuming the commutation is ideal and zero forward voltage drop, six-step mode and phase delay between firing of two switches in any subsequent two phases is equal to $360°/3 = 120°$.

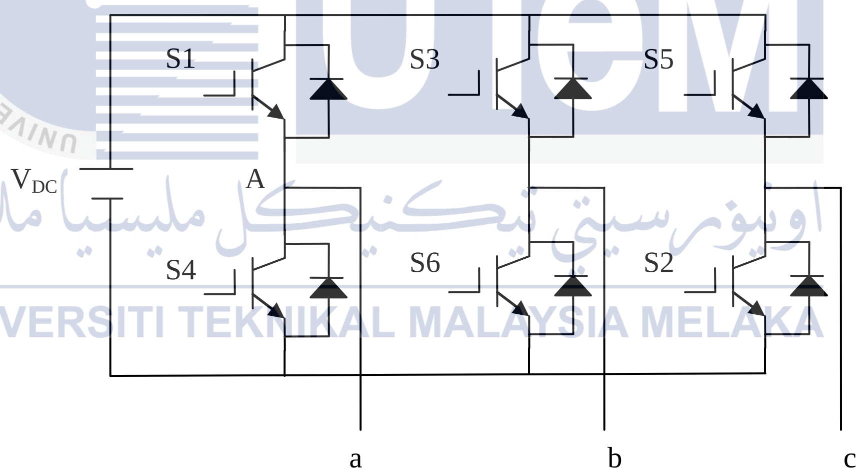


Figure 2.2: Power circuit topology of a three-phase voltage source inverter

The driving control gate for six-step mode operation of inverter in Figure 2.2 is illustrated in Figure 2.3. This driving control gate generates signal to inverter. One complete cycle is divided into six operation mode. Each of operation modes carries $360°/6 = 60°$. At any instant time, three switches are ON and three switches are OFF. From the illustration in Figure 2.3, the switching signal generated by (S1, S3, S5) is complement to the switching signal generated by (S4, S6, S2) respectively. The six-step mode operate in the principles of two conducting switches from the upper three that are ON and one conducting switch from the lower three is OFF or vice versa. The mode of operation is summarized in Table 2.1.

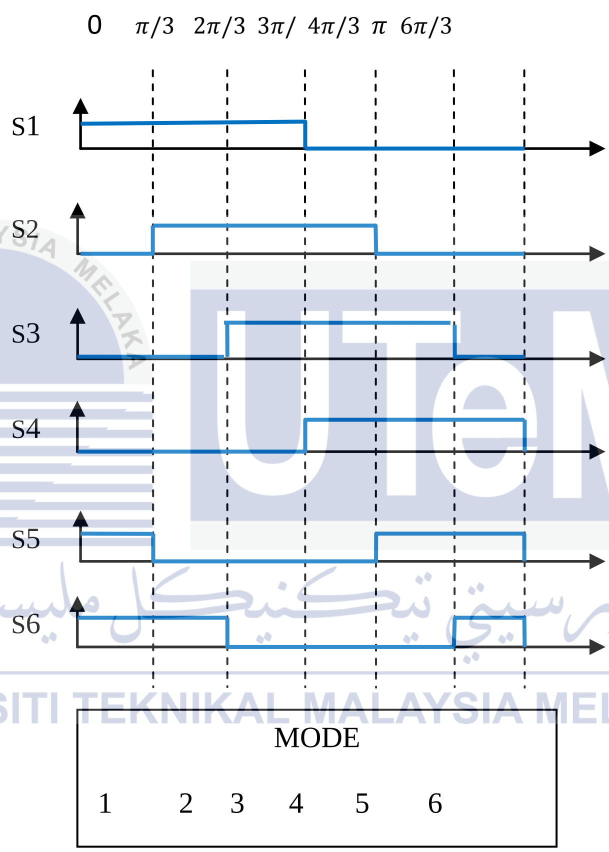


Figure 2.3: Driving switching signal of a three-phase VSI in six-step mode operation

Table 2.1: Leg voltage of three-phase VSI during six step mode operation

SWITCHING MODE	SWITCHES ON	LEG VOLATAGE V_A	LEG VOLATAGE V_B	LEG VOLATAGE V_C
1	S5,S6,S1	V_{DC}	0	V_{DC}
2	S6,S1,S2	V_{DC}	0	0
3	S1,S2,S3	V_{DC}	V_{DC}	0
4	S2,S3,S4	0	V_{DC}	0
5	S3,S4,S5	0	V_{DC}	V_{DC}
6	S4,S5,S6	0	0	V_{DC}

The three-phase inverter is assumed to be a star connected and the phase-to-neutral load and the leg voltages express as equation (2.1). The associated waveforms for phase-to-neutral load voltages are shown in Figure 2.4.

$$VA(t) = va(t) + vnN(t)$$

$$VB(t) = vb(t) + vnN(t) \qquad (2.1)$$

$$VC(t) = vc(t) + vnN(t)$$

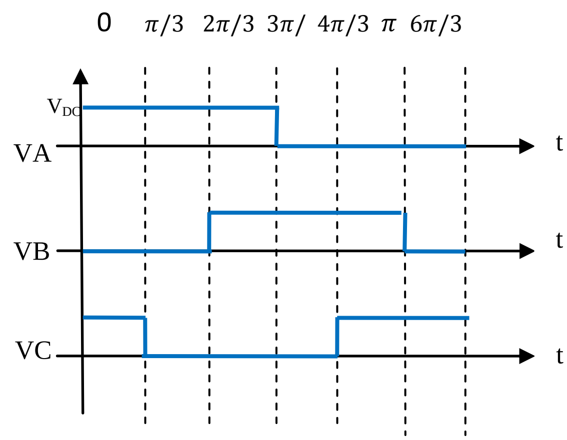


Figure 2.4: Phase-to-Neutral Load Voltage of three-phase VSI

By substituting equation (2.2) into equation (2.1), the phase voltage expressions are obtained in the equation (2.3) respective waveforms is illustrated in Figure 2.5.

$$VnN(t) = \frac{1}{3}[VA(t) + VB(t) + VC(t)] \qquad (2.2)$$

$$van(t) = \frac{2}{3}VA(t) - \frac{1}{3}[VB(t) + VC(t)]$$

$$vbn(t) = \frac{2}{3}VB(t) - \frac{1}{3}[VA(t) + VC(t)] \qquad (2.3)$$

$$vcn(t) = \frac{2}{3}VC(t) - \frac{1}{3}[VB(t) + VA(t)]$$

In term of switching function definition, equation (2.3) is express in equation (2.4)

$$van(t) = \frac{Vdc}{3}[2SA - SB - SC]$$

$$vbn(t) = \frac{Vdc}{3}[2SB - SA - SC] \qquad (2.4)$$

$$vcn(t) = \frac{Vdc}{3}[2SC - SB - SA]$$

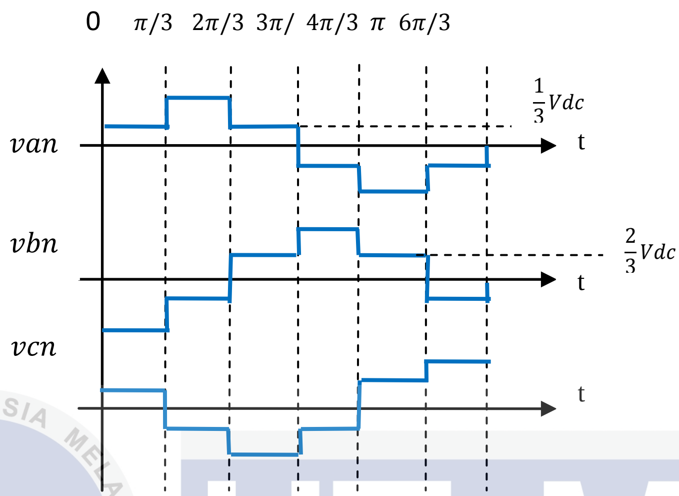


Figure 2.5: Phase voltage of three-phase VSI

Line voltages are obtained by using equation express in (2.5) and Figure 2.6 pictured their corresponding output waveform.

$$vab = VA - VB$$

$$vbc = VB - VC \quad (2.5)$$

$$vca = VC - VA$$

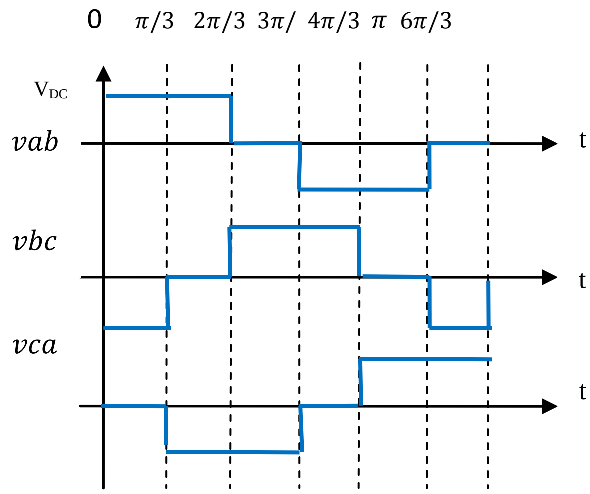


Figure 2.6: Line-to-line Voltage of three-phase VSI

2.3 Pulse Width Modulation

The pulse width modulation (PWM) is a modulation technique that harmonizes the width of pulse, formally the pulse duration based on modulator signal information [6]. The main purpose of modulation techniques is to gain the maximum voltage with the lowest THD in the output voltage. In general, the PWM technique originally implemented with analog technology using discrete electronic components. Sinusoidal carrier-based PWM (SPWM) is the basic PWM technique and space vector PWM is the modern PWM technique evolvement of SPVWM. SPWM technique is based on the comparison between high frequency carrier-wave with the sinusoidal modulating signal to generate the appropriate gate signals for the inverters [4].Meanwhile, the gating time for each power switch is directly calculated from the analytical times equations in SVPWM [4]. The power switches are then switched according to the predefined switching patterns. The SVPWM technique has higher desired output compared to the SPWM.

2.3.1 Principle of Space Vector Pulse Width Modulation(SVPWM)

Space vector modulation is an algorithm for the control of Pulse Width Modulation. In variable speed drive Ac motor as the load required three-phase line to neutral sine wave that can be represented as 120° phase shifted vectors (Va, Vb, Vc)[8] as illustrated in Figure 2.7. The sum of this three phase voltage vector in balanced load is zero and the single space reference V* refer to the three-phase load voltages. Motor frequency and voltage are controllable with space vector modulation strategy by controlling the V*'s amplitude and frequency.

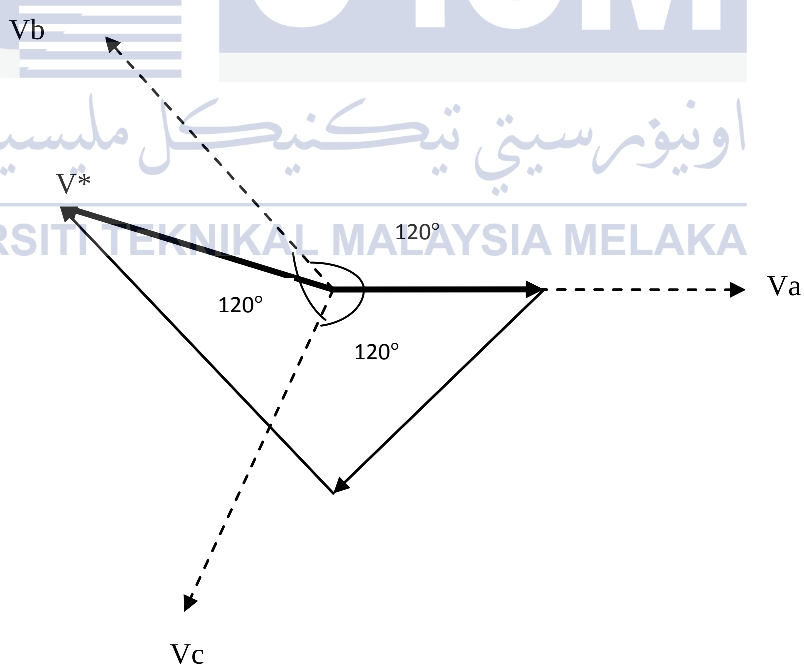


Figure 2.7: Three-phase voltage vectors and resultant space voltage vector [5]

Induction motor as the load is considered Y connected and its three-phase stator current as used as phase stator current vector[8] (ia, ib, ic) as illustrated in Figure 2.8.The phase stator current can be added in vector as express in equation (2.13).

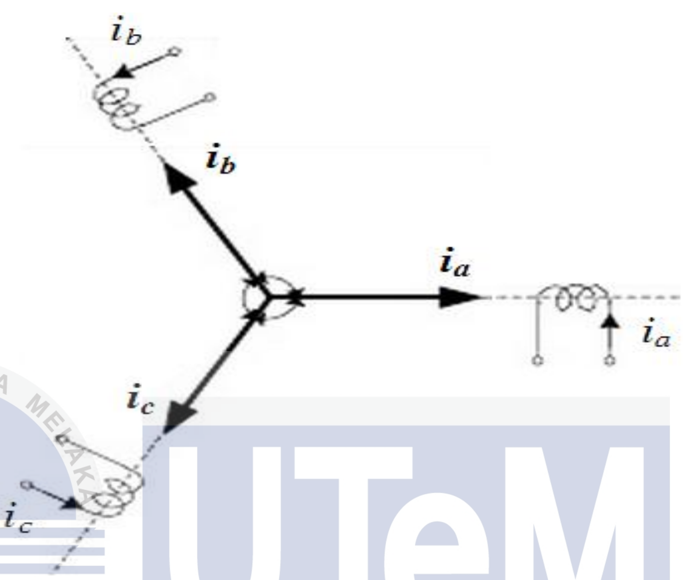


Figure 2.8: The vector of three-phase stator current [5]

$$\text{is} = \frac{2}{3}(\text{ia} + \text{ib} + \text{ic}) \tag{2.13}$$

$$\text{is} = \text{is } e^{j\theta} \tag{2.14}$$

$$\text{is} = \text{is } e^{j\omega t} \tag{2.15}$$

Equation (2.13) shows that i_s is the sum of phase stator current and equation (2.14) described i_s in complex number as it is an instantaneous quantity not in phase quantity. When stator current, i_s is in steady state, it is expressed as equation (2.15). By using Euler theorem, three-phase stator current are signify as

$$\text{ia} = \text{ia } e^{j0°} = \text{ia} \tag{2.16}$$

$$\text{ib} = \text{ib } e^{j120°} = a\text{ib} \tag{2.17}$$

$$\text{ic} = \text{ic } e^{j240°} = a^2\text{ic} \tag{2.18}$$

By substitute equation (2.18) into equation (2.13), the following equation is obtained,

$$\mathrm{is} = \frac{2}{3}(\mathrm{ia} + \mathrm{aib} + \mathrm{a}^2\mathrm{ic}) \quad (2.19)$$

Park transformation is used to transform from three-phase vectors to d-q axis in order to determine space reference vector of three-phase voltage and current. The rectangular coordinate in Figure 2.9 (a) shows how complex vector can be transform into real and imaginary components [5].

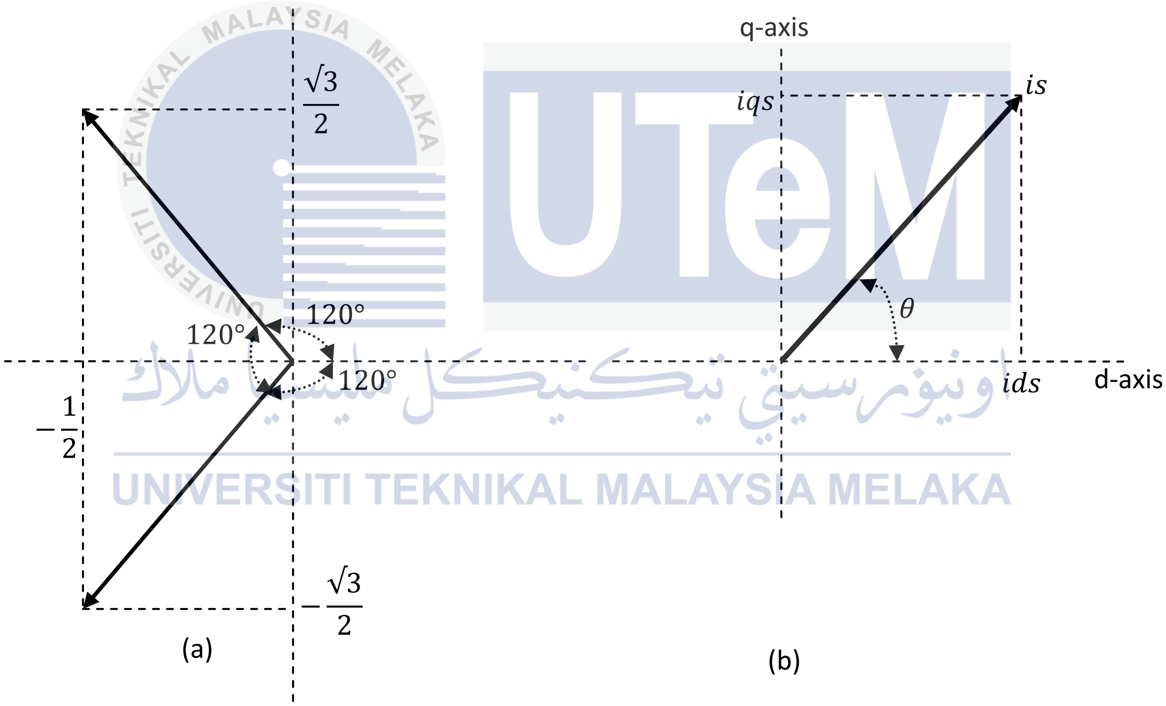


Figure 2.9: the complex vector, (a) in rectangular coordinate (b) space reference vector.

From equation (2.15), by implementing Euler theorem the real and imaginary components can be acquire as equation (2.20) and equation (2.21).Equation (2.23) is acquired by separating real and imaginary term and thus the space vector can be obtained using Pythagoras Theorem as represented in Figure 2.9 (b).

$$a = e^{j120°} = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \tag{2.20}$$

$$a = e^{j240°} = -\frac{1}{2} - j\frac{\sqrt{3}}{2} \tag{2.21}$$

$$\begin{aligned} is &= \left(\frac{2}{3}ia - \frac{2}{3}ib - \frac{2}{3}ic\right) + j\frac{1}{\sqrt{3}}(ib - ic) \\ &= ids + jiqs \end{aligned} \tag{2.22}$$

By referring to Figure 2.2 six IGBT are donated as S1, S2, S3, S4, S5, and S6 the voltage vector for the three-phase balanced load at terminal a, b and c donated as Va,Vb and Vc.

$$v = \frac{2}{3}(va + avb + a^2vc) \tag{2.23}$$

with $a = e^{j120°}$ and $a = e^{j240°}$

For the operation of three-phase inverter is designed to be at any instant time, only one switch of a half bridge is turn on and the other half bridge is off. This designed is created to ensure the security of the circuit. Based on the design mentioned, that is mean at each step, three independent PWMs are generated to switch on the involved three half bridge resulting to eight distinct switching state of VSI. Figure 2.10 pictorial the switching state that be represented in hexagon, V_0(000) and V_7(111)are inactive state while V_1 to V_6 are active switching state. The hexagon consists of six sectors which each sector has the same size of

60° and confined with two active vectors. The locus of the circle is projected by the space vector V* depends on V0, V1,…,V7 mathematically represented by equation (2.10).

$$V *= \sum_{n=1,2\ldots7}^{n=7}\left[\frac{tn}{Ts} X\, vn\right] \tag{2.24}$$

Ts donated the sampling time

As time, t increases, the reference space voltage vector rotates and moves through the different sectors of the complex plane. 2fs is the fixed input sampling for modulation vector *V** in each PWM cycle. Figure 2.10 shows the reference vector *V** is in sector 1 and confined with two active voltage vector V_1 and V_2 .As *V** is lies in sector 1, it can be illustrated as shown in Figure 2.11.

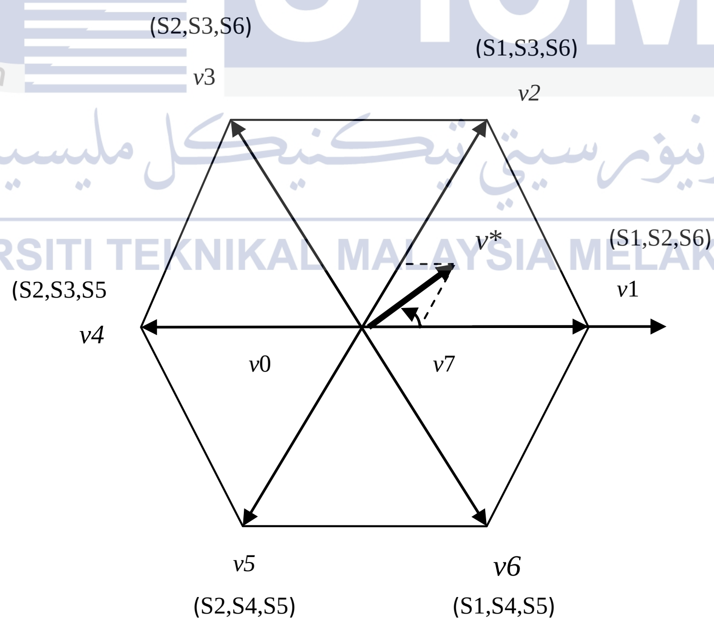


Figure 2.10: Space Vector Hexagon

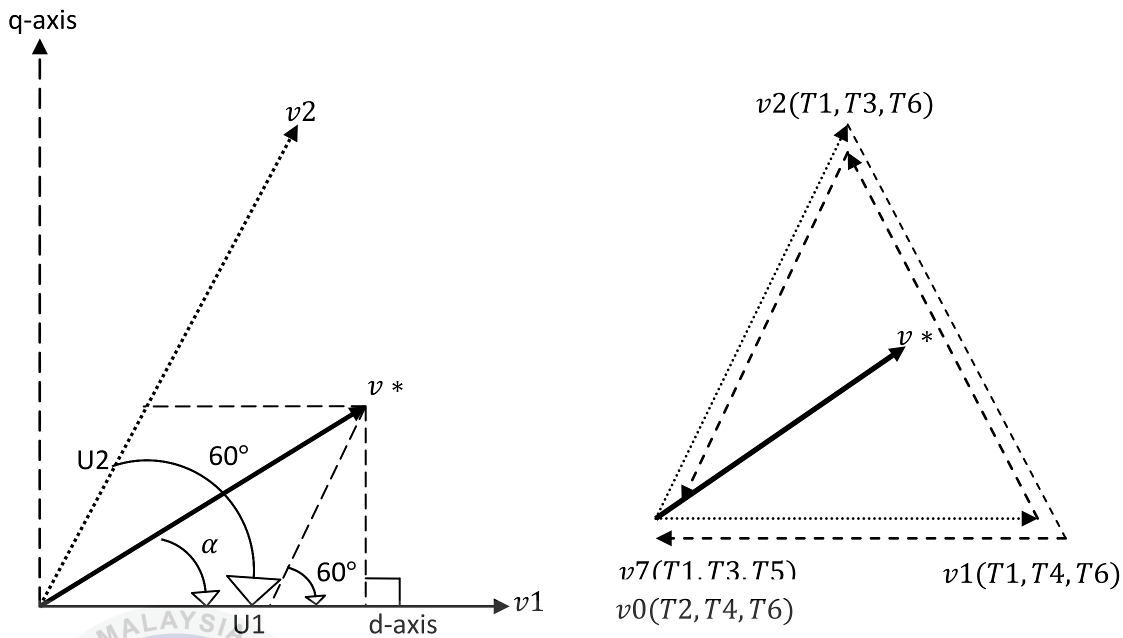


Figure 2.11: Voltage *V** at sector 1

V* can be determine as

$$V^* = \frac{t1}{Ts} + \frac{Ta}{Ts}\,\frac{T2}{Ts} + \frac{Tb}{Ts}\,\frac{T0}{Ts} + \frac{T0}{Ts}\,v0 \qquad (2.25)$$

where $Ts = t_1 + t_2 + t_c$

Considering V_0 is zero,

$$V^* = \frac{Ta}{Ts}\,V1 + \frac{Tb}{Ts}\,V2 = U1 + U2 \qquad (2.26)$$

By applying trigonometric the voltage vector Ua and Ub are obtained

$$U_1 = |v*|\cos\alpha - \frac{1}{\sqrt{3}}|v*|\sin\alpha \qquad (2.27)$$

$$U_2 = \frac{2}{\sqrt{3}} |v *| \sin \alpha \tag{2.28}$$

The amount of time V_1 and V_2 is calculated by using the component U_1 and U_2 and by considering equation (2.29)

$$|v1| = |v2| = \frac{2}{3} V_D \tag{2.29}$$

The time t1 and t2 are obtained using equation (2.25) to (2.28).

$$t_1 = t_a = \frac{3}{2} \frac{|v*|}{VD} \left(\cos \alpha - \frac{1}{\sqrt{3}} \sin \alpha\right) T_s \tag{2.30}$$

$$t_2 = t_b = \sqrt{3} \frac{|v*|}{VD} (\sin \alpha)\, T_s \tag{2.31}$$

$$t_0 = Ts - t_1 - t_2 \tag{2.32}$$

By locating zero voltage vector and V_7 as the last vector in switching sequence within the sampling interval and by spotting V_0 as the last vector in reversion of switching sequence with respect to the sequence of previous sampling interval, the optimization switching sequence is obtained[5] as shows in Figure 2.12.

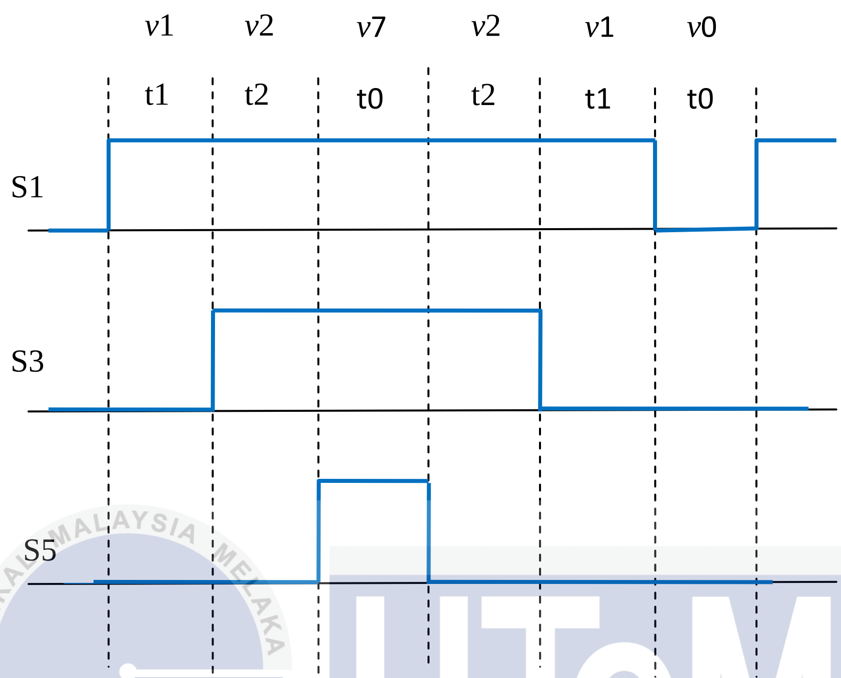


Figure 2.12: the optimization of switching sequence

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explains about the project direction from the beginning until the end of the project. Every procedure that has been taken during the project implementation is explains in details. This chapter also discusses MATLAB/Simulink software implementation of SVPWM and DSVPWM. In addition, the detailed subsystems of Simulink models are included as well as an explanation of the purpose of every subsystem.

3.2 Research Methodology

Flow chart shown in Figure 3.1 explains about the project path from the beginning until the end of the project. The details of the project flow are explained step by step.

Step 1: Comprehensive Study

A comprehensive study had been carried out on several PWM schemes for VSI, topology of space vector pulse width modulation (SVPWM) and topology of DSVPWM for three-phase voltage source inverter VSI as well as implementation of MATLAB/SIMULINK. The study focus on step by step simulation of space vector pulse width modulation (SVPWM) and discontinuous space vector pulse width modulation (DSVPWM) for three phase voltage source inverter. In order to get familiar with MATLAB/SIMULINK, some simulation practice has been carried out based on MATLAB simulation manual.

Step 2: Designing Stage

Based on the information collected, SVPWM control technique for three-phase VSI has been designed. The design starts with establishment of three phase sinusoidal voltage that be transformed into two-phase quantity in stationary frame. Next, design the sector identification and alpha beta voltage vectors, on times calculation, duty ratios calculation, PWM generation and mapping vectors. The same procedure used to design discontinuous space vector modulation. The only difference on the design of DSVPWM is at the on duty ratios calculation, PWM calculation and mapping vectors. Next, the output of mapping sector is connected to voltage source inverter.

Step 3: Analyzing Stage

The results of SVPWM and DSVPWM for three-phase VSI is analyze in term of switching pattern, phase voltage, phase current, efficiency, harmonic spectrum and THD.

Step 4: Verification Results of SVPWM and DSVPWM for three-phase VSI

The obtained results are verified and evaluated to determine whether the objectives are achieved or not. The results obtained must meet the objectives and theory as follows:

1. Efficiency of DSVPWM must be greater than the efficiency of SVPWM
2. Total Harmonic Distortion for both SVPWM and DSVPWM need to be slightly the same.
3. Switching pattern of each sector for SVPWM and DSVPWM similar to the theory.

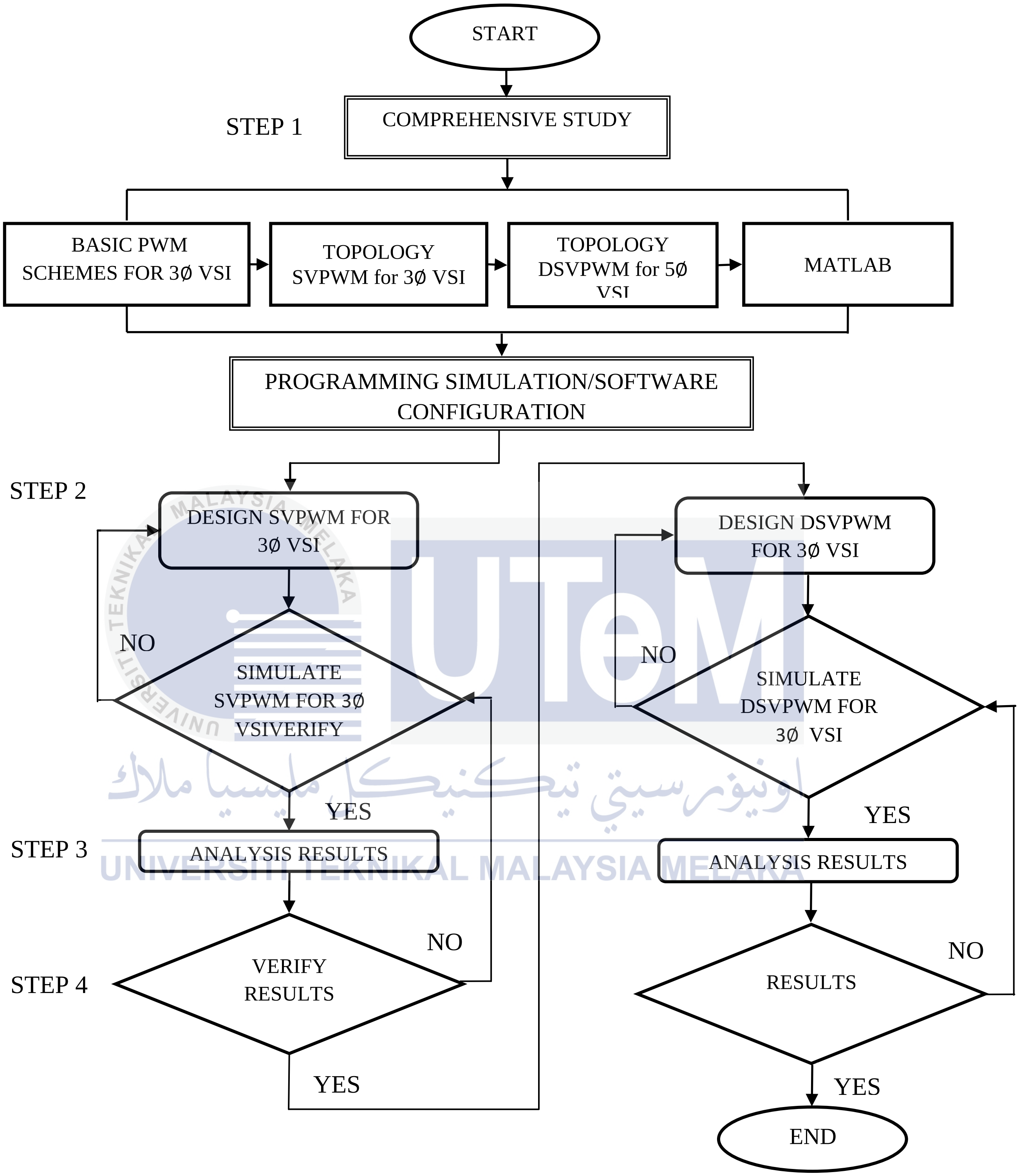


Figure 3.1: Flow chart of overall process

3.3 Analytical Approach

3.3.1 Implementation Procedure of SVPWM and DSVPWM

Two-level three-phase inverter has eight possible inverter switching states that can generate eight space vectors [3]. Vector V1 to V6 represents non-zero vectors and V_0 and V_1 represents zero vectors. These vectors are applied during the switching times t_a, t_b, and t_z . The reference voltage vector must be limited to the imprinted circle inside the hexagon in order to generate a rotating space vector with constant amplitude. The simulation model is constructed step by step using flow diagram describe in Figure 3.2(a) and Figure 3.2(b). By pursuing the same procedure, discontinuous space vector pulse width modulation can be implemented. The only difference is at the step 6, step 7 and step 8.The concept of DSVPWM is based on the inference that only two phases are switched. The other phase is either tied by 60° to the lower (negative) or upper (positive) DC bus. If the leg voltage of the equivalent one phase is tied to lower DC bus, the zero voltage (111) is eliminated. The zero voltage (000) is eliminated when the leg voltage of the corresponding one phase is tied to the upper DC bus. The switching pattern for leg voltage tied to upper DC bus is portrayed in Figure 1.4.

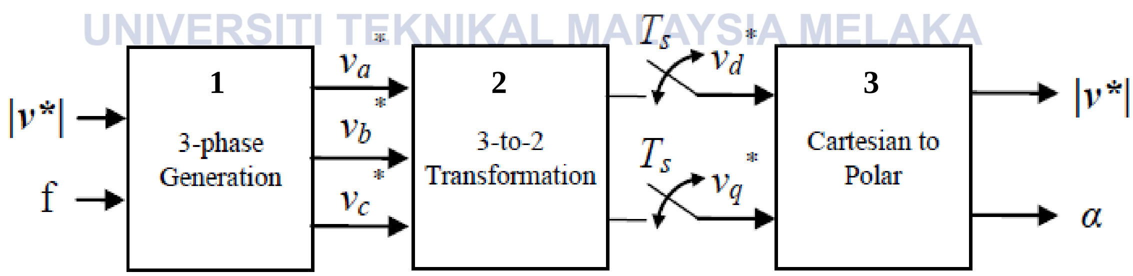


Figure 3.2: (a)Flow diagram for Space Vector Modulator Implementation

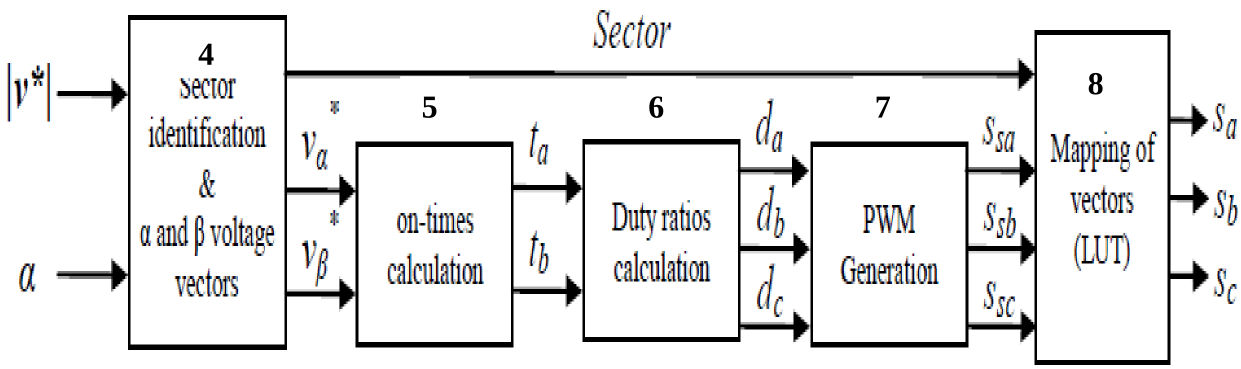


Figure 3.2: (b) Flow diagram for Space Vector Modulator Implementation

Step 1: Three-phase Generation

This block is used to establish three-phase sinusoidal input voltages, V_{an}, V_{bn} and V_{cn} with variable and amplitude. The three signals are delayed by 120° from each other [3]. These three-phase abc voltages are describe in equation (3.1), equation (3.2) and equation (3.3). Based on these equations, simulation subsystem for this block is constructed.

$$V_{an} = V_m \sin \omega t \tag{3.1}$$

$$V_{bn} = V_m \sin \omega t - \frac{2\pi}{3} \tag{3.2}$$

$$V_{cn} = V_m \sin \omega t + \frac{2\pi}{3} \tag{3.3}$$

Step 2: Three to Two Transformations

In this step, the three-phase sinusoidal input voltage is converted to two-phase voltages by applying three to two transformation equations. Equation (3.4) and equation (3.5) represents three to two phase transformation equations.

$$V_d = \frac{2}{3}(V_a - \frac{1}{2}V_b - \frac{1}{2}V_c) \quad (3.4)$$

$$V_q = \frac{1}{\sqrt{3}}(V_b - V_c) \quad (3.5)$$

Step 3: Cartesian to Polar Conversion

Cartesian plane described its variables in term of [x,y] coordinate while polar plane described its variables in term of [r,θ]. In order to have θ as the angle for each sector the output variables from three to two phase transformations need to be converted in polar form.

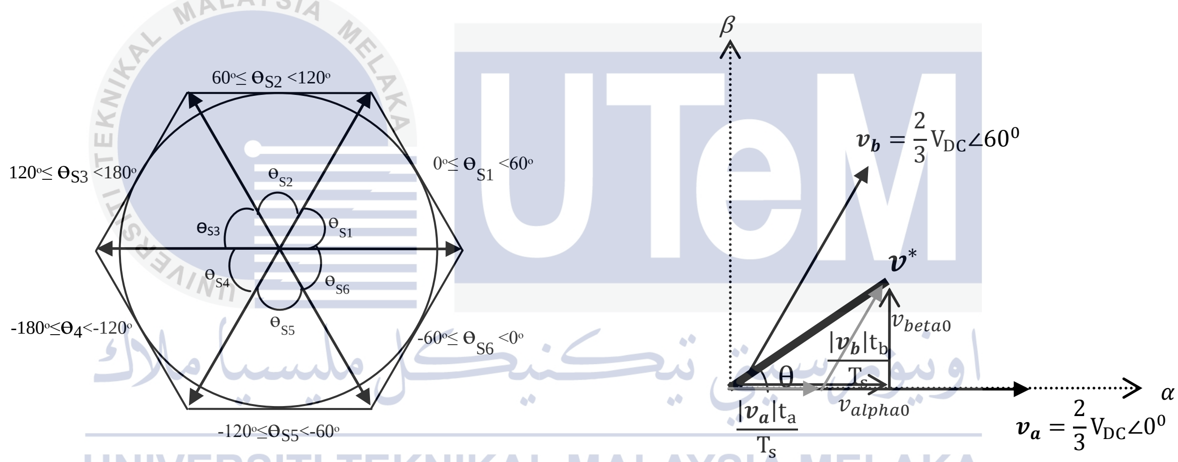
Step 4: Sector Identification and Alpha and Beta Voltage Vectors

The block of sector identification and α β voltage vectors is used to generate each sector in the hexagon as well as to produce alpha and beta voltage vectors. The hexagon consists of six distinct sector spinning over 360 degrees with each sector of 60 degrees [1]. Generation of sector in the hexagon is achieved by limiting each sector according to their respective angle's position in the hexagon. Angle for sector 1 is limited form greater and equal to 0^o until less than 60^o ($0^o \leq \theta_{S1} < 60^o$). All the sectors identification is illustrated in Figure 3.3(a). Calculations of alpha and beta voltage vectors equations are based on Figure 3.3(b). Alpha and beta voltage vectors are defined as

$$v_{alpha0} = magnitude\ of\ v^{*}\ \cos\theta \tag{3.6}$$

$$v_{beta0} = magnitude\ of\ v^{*}\ \sin\theta \tag{3.7}$$

Angle θ lies between reference voltage vector and the vector that first change its switching state.



(a) (b)

Figure 3.3:(a)Sector Identification (b)Alpha Beta Voltage Vector

Step 5: On Time Calculation

The on time calculation is used to determine the time duration, t_a and t_b. Equation (3.12) and equation (3.13) specify t_a and t_b. These equations are derived by referring to Figure 2.

$$\boldsymbol{v}^* = \frac{|\boldsymbol{v_a}|\mathrm{t_a}}{\mathrm{T_s}} + \frac{|\boldsymbol{v_b}|\mathrm{t_b}}{\mathrm{T_s}} + \frac{|\boldsymbol{v_z}|\mathrm{t_z}}{\mathrm{T_s}} \tag{3.8}$$

$$\boldsymbol{v}^* = v_{alpha0} + jv_{beta0} = \frac{|\boldsymbol{v_a}|\mathrm{t_a}}{\mathrm{T_s}} + \frac{|\boldsymbol{v_b}|\mathrm{t_b}}{\mathrm{T_s}} + \frac{|\boldsymbol{v_z}|\mathrm{t_z}}{\mathrm{T_s}} \tag{3.9}$$

Where

$$v_{alpha0} = \frac{|\boldsymbol{v_a}|\mathrm{t_a}}{\mathrm{T_s}} + \frac{|\boldsymbol{v_b}|\mathrm{t_b}}{\mathrm{T_s}}\cos(60^0) = \frac{|\boldsymbol{v_a}|\mathrm{t_a}}{\mathrm{T_s}} + 0.5\frac{|\boldsymbol{v_b}|\mathrm{t_b}}{\mathrm{T_s}} \tag{3.10}$$

$$v_{beta0} = \frac{|\boldsymbol{v_b}|\mathrm{t_b}}{\mathrm{T_s}}\sin(60^0) = \frac{\sqrt{3}}{2}\frac{|\boldsymbol{v_b}|\mathrm{t_b}}{\mathrm{T_s}} \tag{3.11}$$

Thus the on time calculations are;

$$t_a = \frac{3}{2\mathrm{V_{DC}}}\left[v_{alpha0} - \frac{v_{beta0}}{\sqrt{3}}\right].\mathrm{T_s} = \frac{3}{2\mathrm{V_{DC}}}\left[v_{alpha0} - \frac{v_{beta0}}{\sqrt{3}}\right].\mathrm{T_s} \tag{3.12}$$

$$t_b = \frac{\sqrt{3}}{\mathrm{V_{DC}}}v_{beta0}.\mathrm{T_s} \tag{3.13}$$

Step 6: Duty Ratios Calculation

Duty ratio is a ratio between ON time and OFF time. Equation 3.14 defined duty ratio in general.Duty ratio calculation block is used to calculate duty ratio for reference switching time. Figure 3.4 and Figure 3.5 illustrate relationship between duty ratio and reference switching time for SVPWM and DSVPWM. The SVPWM required three duty cycle(D1, D2 and D3) while DSVPWM only need two duty cycle (D2 and D3). Their corresponding duty ratio are described in equation (3.15), equation (3.16), equation (3.17), equation (3.18) as well as equation (3.19).

$$Duty\ Ratio = \frac{T(on)}{T(on) + T(off)} \tag{3.14}$$

Duty ratio for SVPWM

$$D1 = \frac{T - 2(t_z/4)}{T} \tag{3.15}$$

$$D2 = \frac{T - 2(\frac{t_z}{4} + \frac{t_a}{2})}{T} \tag{3.16}$$

$$D3 = \frac{T - 2(\frac{t_z}{4} + \frac{t_a}{2} + \frac{t_b}{2})}{T} \tag{3.17}$$

Duty ratio for DSVPWM

$$D2 = \frac{T - 2(\frac{t_a}{2})}{T} \tag{3.18}$$

$$D3 = \frac{T - 2(\frac{t_a}{2} + \frac{t_b}{2})}{T} \tag{3.19}$$

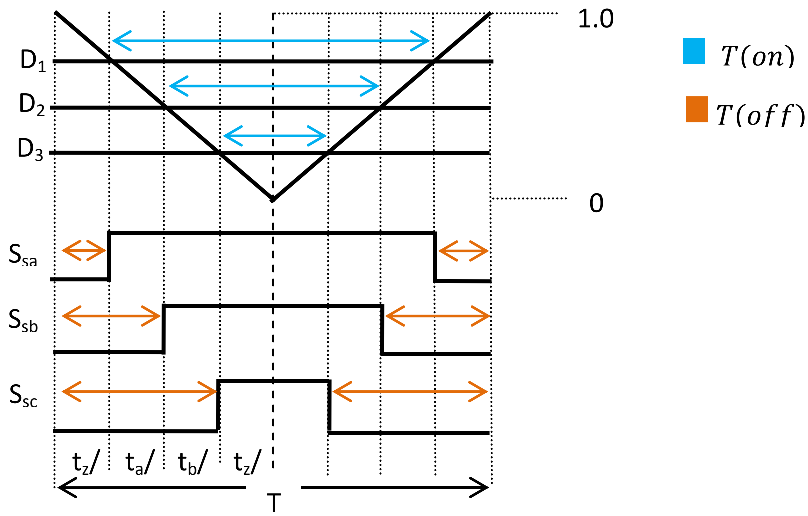


Figure 3.4: Duty Ratio and Reference Switching Time for SVPWM

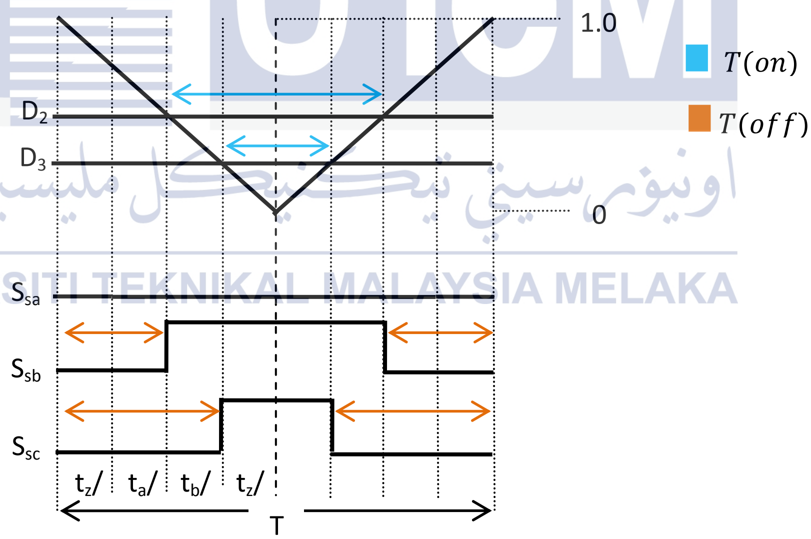


Figure 3.5: Duty Ratio and Reference Switching Time for DSVPWM

Step 7: PWM Generation

The function of PWM generation block is to compare signal of duty ratio with the triangular signal. The block diagram is constructed based on principle if duty ratio signal is greater triangular signal, the output is high (1) and if duty ratio signal is less than triangular signal, the output is low (0).

Step 8: Mapping of Vectors

The block of mapping vector is used to map the switching state for each sector based on the location reference voltage vector. If the reference voltage vector located at sector 1, the mapping of switching state is from V_0 (000) to $V_1$100 to V_2 (110) to V_7 (111), and from V_7 (111) to V_2 (110) to V_1 (100) to V_0 (000). For the DSVPWM technique, the mapping switching state when the reference voltage vector located at sector 1 is $V_1$100 to V_2 (110) to V_7 (111), and from V_7 (111) to V_2 (110) to V_1 (100). All the mapping switching state of each sector for SVPWM and DSVPWM is tabulated in Table 3.1 and Table 3.2.

Table 3.1SVPWMMapping Vector

Sector	Mapping Vectors for SVPWM							
	1	2	3	4	5	6	7	8
1	V_0 (000)	V_1(100)	V_2 (110)	V_7 (111)	V_7 (111)	V_2 (110)	V_1 (100)	V_0 (000)
2	V_0 (000)	V_3(010)	V_2 (110)	V_7 (111)	V_7 (111)	V_2 (110)	V_3(010)	V_0 (000)
3	V_0 (000)	V_3(010)	V_4 (011)	V_7 (111)	V_7 (111)	V_4 (011)	V_3(010)	V_0 (000)
4	V_0 (000)	V_5 (001)	V_4 (011)	V_7 (111)	V_7 (111)	V_4 (011)	V_5 (001)	V_0 (000)
5	V_0 (000)	V_5 (001)	V_6 (101)	V_7 (111)	V_7 (111)	V_6 (101)	V_5 (001)	V_0 (000)
6	V_0 (000)	V_1 (100)	V_6 (101)	V_7 (111)	V_7 (111)	V_6 (101)	V_1 (100)	V_0 (000)

Table 3.2DSVPWM Mapping Vector

Sector	Mapping Switching State for DSVPWM					
	1	2	3	4	5	6
1	V_1(100)	V_2 (110)	V_7 (111)	V_7 (111)	V_2 (110)	V_1 (100)
2	V_3(010)	V_2 (110)	V_7 (111)	V_7 (111)	V_2 (110)	V_3(010)
3	V_3(010)	V_4 (011)	V_7 (111)	V_7 (111)	V_4 (011)	V_3(010)
4	V_5 (001)	V_4 (011)	V_7 (111)	V_7 (111)	V_4 (011)	V_5 (001)
5	V_5 (001)	V_6 (101)	V_7 (111)	V_7 (111)	V_6 (101)	V_5 (001)
6	V_1 (100)	V_6 (101)	V_7 (111)	V_7 (111)	V_6 (101)	V_1 (100)

3.4 Simulation Approach

3.3.1 MATLAB/Simulink Model for SVPWM and DSVPWM

This section shows a model developed using the MATLAB function block and Simulink blocks for SVPWM and DSVPWM technique. DSVPWM model can be develop by changing the formula model in Simulink block and by changing MATLAB functions command. The MATLAB/Simulink model is shown in Figure 3.6 (a) and Figure 3.6(b). By referring to the MATLAB/Simulink model, the development of DSVPWM is using the exact procedure as SVPWM starting from Subsystem 1 until MATLAB Function 2. The contras in the develop procedure is at Subsystem3, Subsystem4 and MATLAB Function3. The method to construct each block is further elaborated step by step.

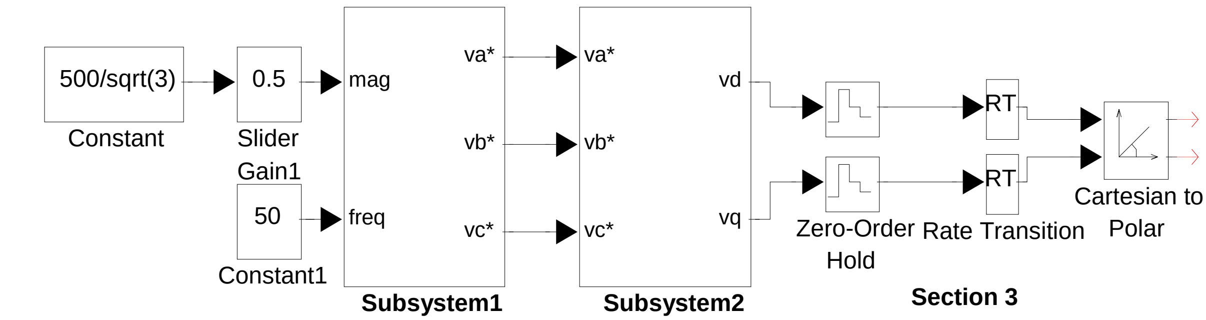


Figure 3.6: (a) MATLAB/Simulink model of SVPWM and DSVPWM

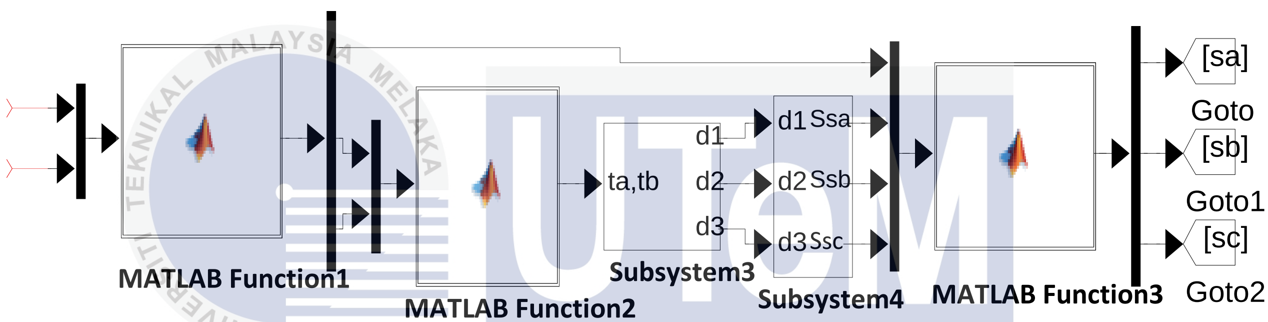


Figure 3.6: (b) MATLAB/Simulink model of SVPWM and DSVPWM

Subsystem 1: Three-phase Generation

This block is used to simulate the balanced three-phase sinusoidal input reference. 'Math Operations' in the 'Simulink Library Browser' are used in order to construct this block based on three-phase voltage equation. The detail for this block is described in Figure 3.7.

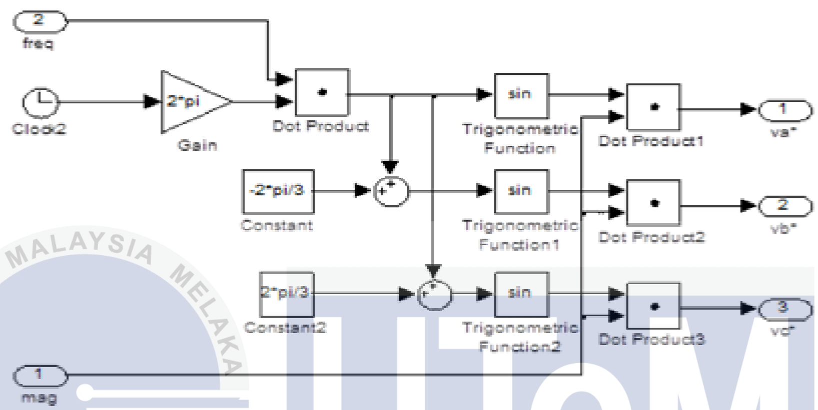


Figure 3.7: Three-phase sinusoidal input reference is detail for Subsystem1

Subsystem 2: Three to Two Transformations

Clark transformation equations is used to convert three-phase sinusoidal input voltage into two-phase. This is once again implemented using 'Math Operations' in the 'Simulink Library Browser'. Figure 3.8 shows the details of the block.

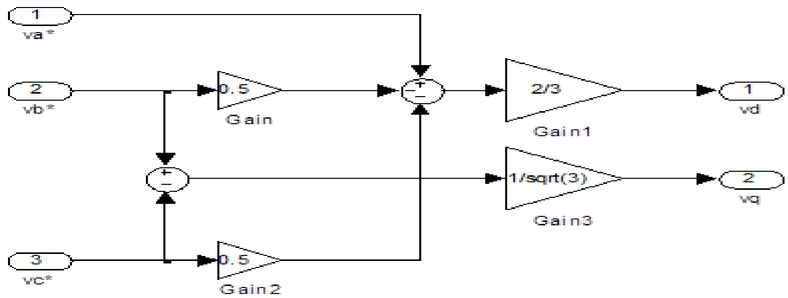


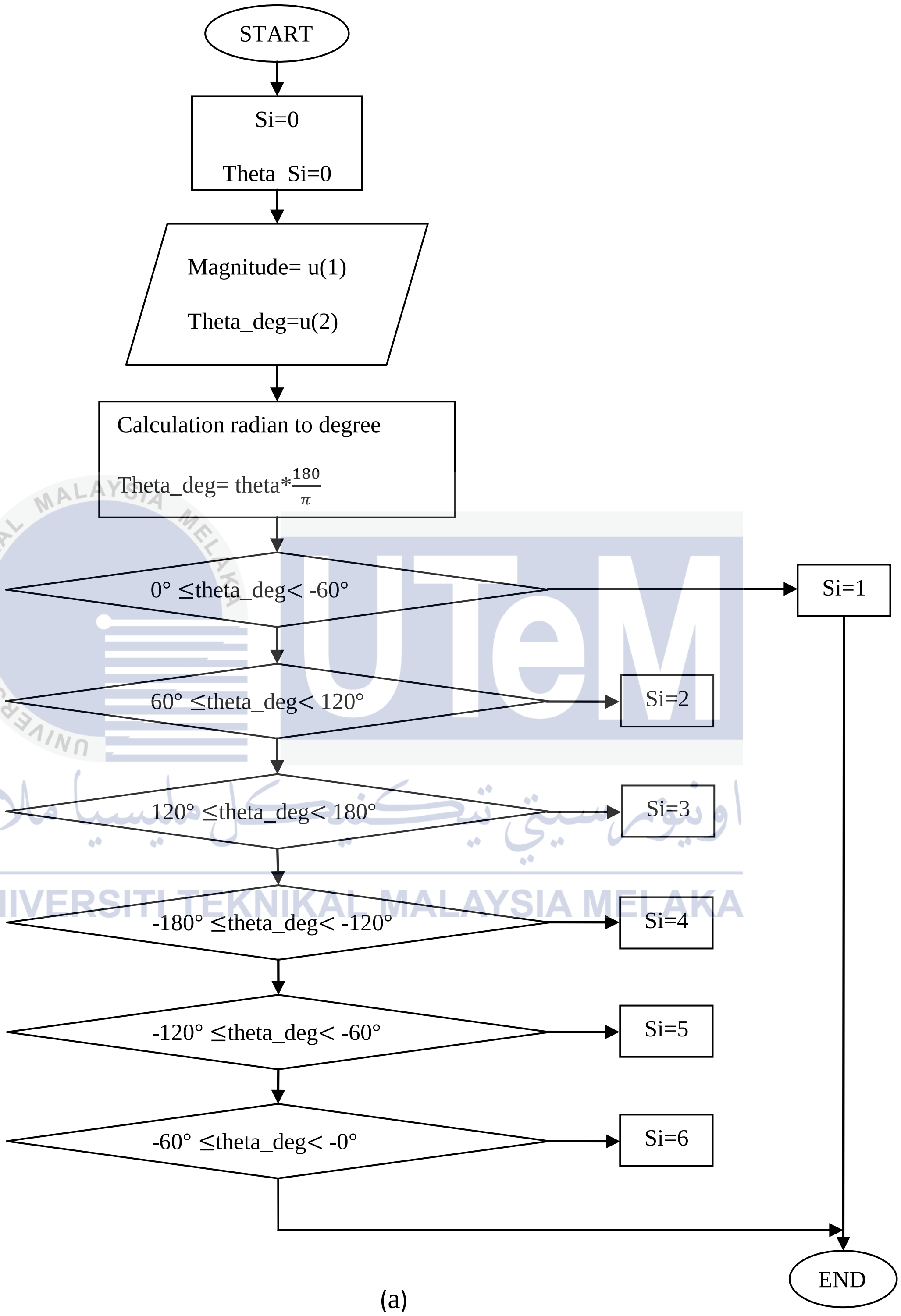
Figure 3.8: Three to Two Transformations is detail for Subsytem2

Section 3: Cartesian to Polar Conversion

Aim of this section is to transformed two-phase equivalent into polar form. This section consists of three MATLAB tools which is 'Zero Order Hold', 'Rate Transition' and 'Cartesian to Polar'. 'Simulink' sub library provided 'Zero Order Hold' and 'Rate Transition' while 'Simulink Extras' sub library provided 'Cartesian to Polar'. 'Zero Order Hold' sample and hold its input from block 2(V_d and V_q) for specified time which is (1/5e3). 'Rate Transition' used to transfer data (V_d and V_q) at one rate to the input of 'Cartesian to Polar' at different rate. V_d and V_q which in cartesian coordinate [x,y] transform into polar coordinate $[r, \theta]$ using 'Cartesian to Polar' block.

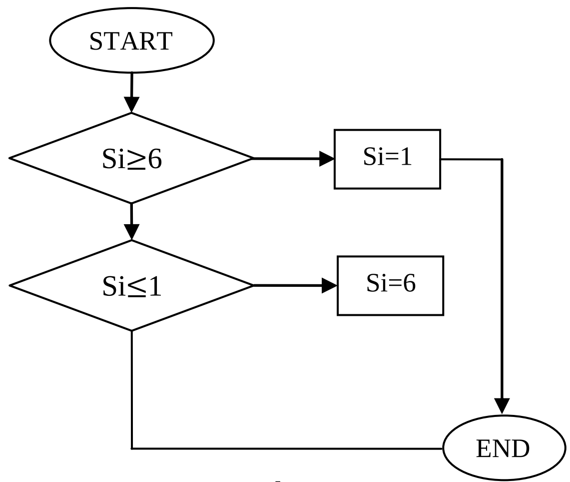
MATLAB Function1: Sector Identification and Alpha and Beta Voltage Vectors

Figure 3.9(a),(b) and (c) shows the flow chart to construct MATLAB code to generate sector identification as well as Alpha and beta voltages vectors. The complete MATLAB Code is attached in the appendix.

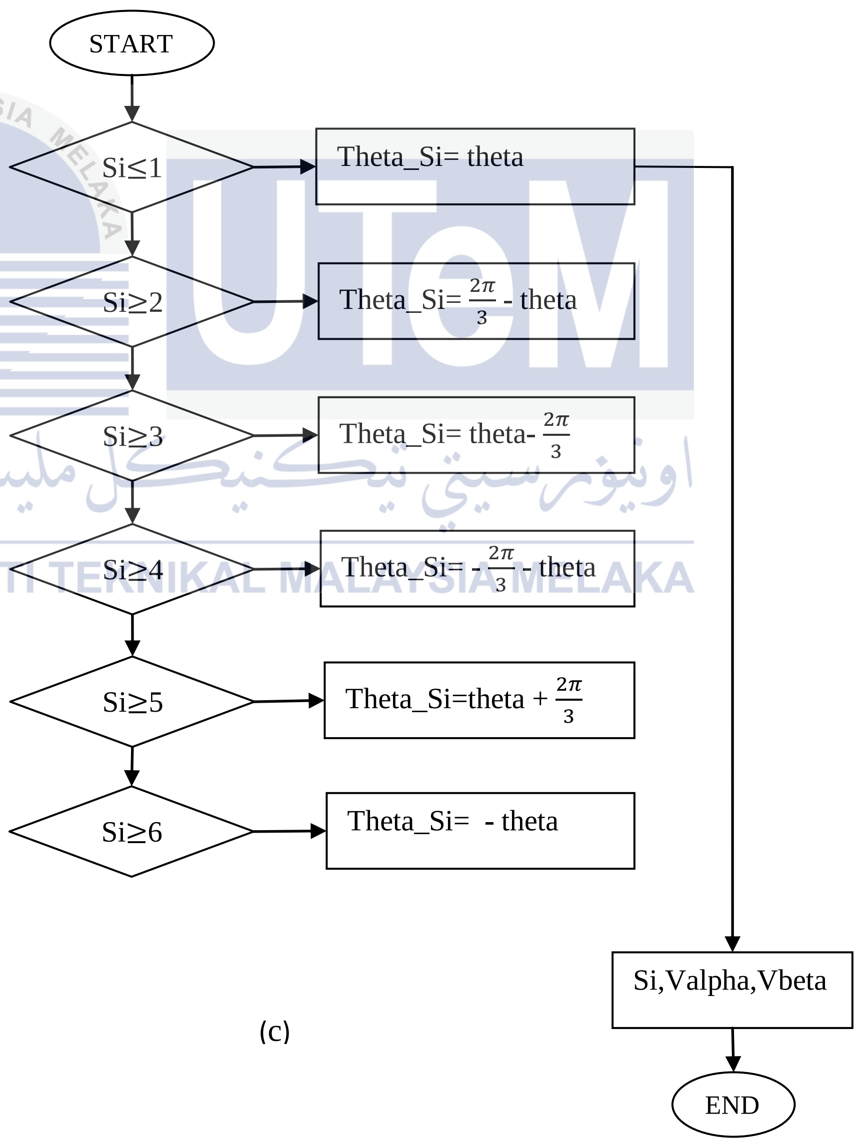


(a)

Figure 3.9: (a) Flow Chart of Sector Identification and Alpha Beta Voltage Vectors



(b)

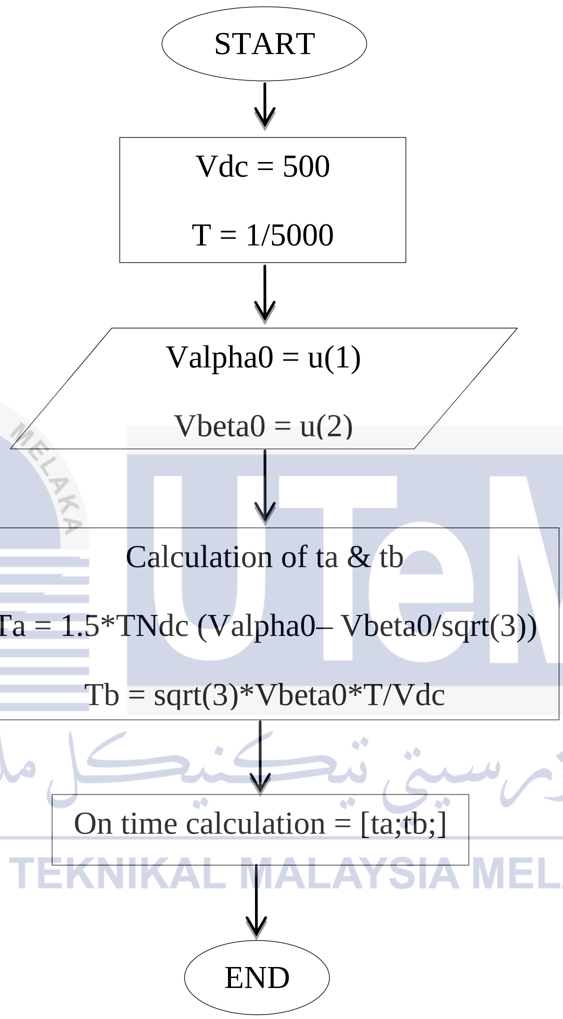


(c)

Figure 3.9: (b) and (c) Flow Chart of Sector Identification and Alpha Beta Voltage Vectors

MATLAB Function2: On Time Calculation

MATLAB code to calculate switching time (t_a, tb) is described in from of flow chart shown in Figure 3.8.The complete MATLAB Code is enclosed in the appendix.



Subsystem 3: Duty Ratios Calculation

As the duty ratio for SVPWM and DSVPWM is difference, the constructed subsystem is depending on their respective equation mention earlier in step 6. Once again 'Math Operation' tools are used to build up Subsystem3. Detail of the Subsystem3 for SVPWM is presented in Figure 3.10(a) as well as the detail of Subsystem3 for DSVPWM is presented in Figure 3.10(b).

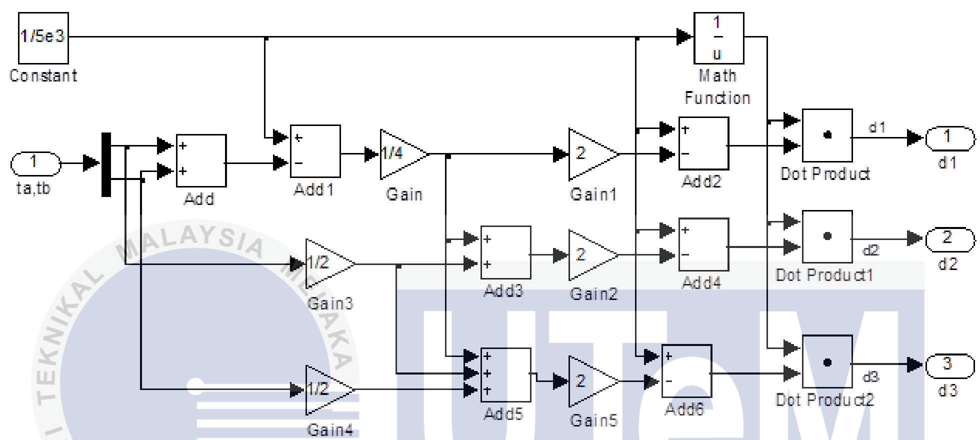


Figure 3.10: (a) Duty Ratios Calculation is detail of Subsystem3 for SVPWM

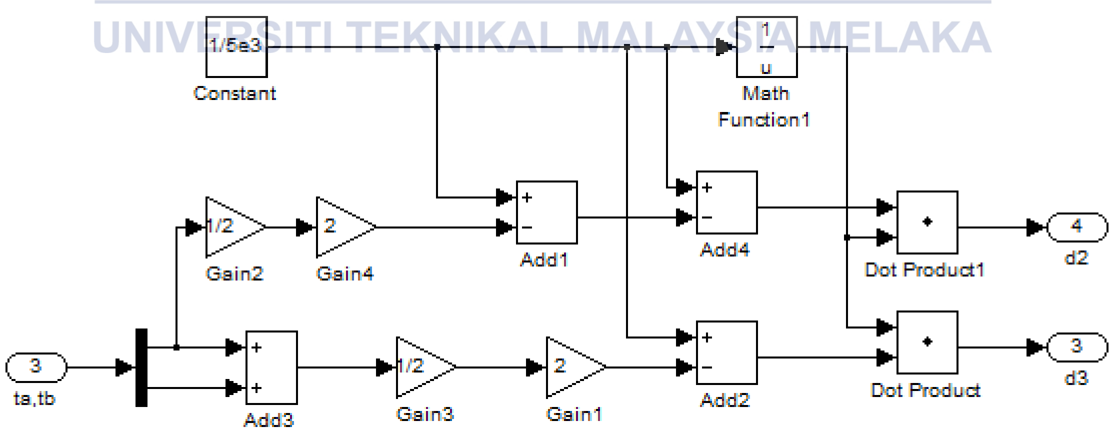


Figure 3.10: (b) Duty Ratios Calculation is detail of Subsystem3 for DSVPWM

Subsystem 4: PWM Generation

This Simulink block is composed of Repeating Sequence, Relational Operator and Data Type Conversion. Both of Repeating Sequence and Relational Operator found at the ‘commonly used block’ in the ‘Simulink Library Browser’. The goals of Data Type Conversion are to have Real World Values of the input and the output as well as to have the Stored Integer Values of the input and the output be equal. Illustration in Figure 3.11(a) describes the detail of Subsytem4 for SVPWM and Figure 3.12 (b) describe DSVPWM.

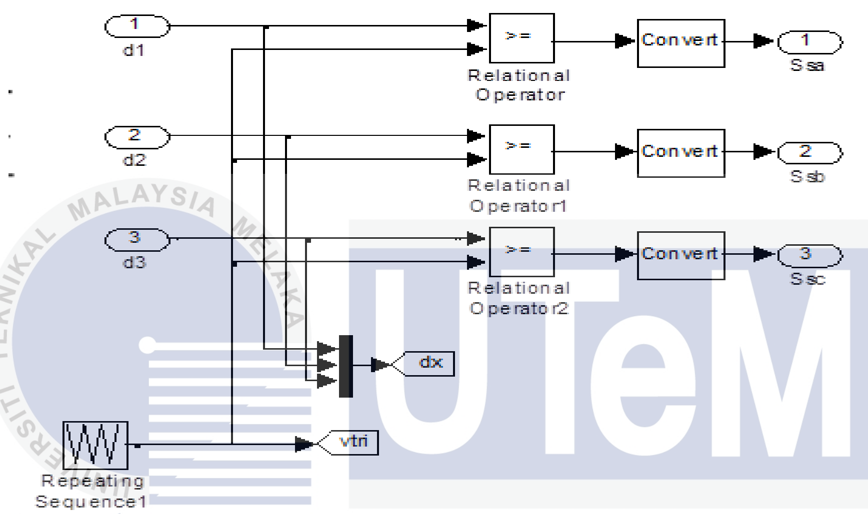


Figure 3.11: (a) PWM Generation is detail of Subsystem4 for SVPWM

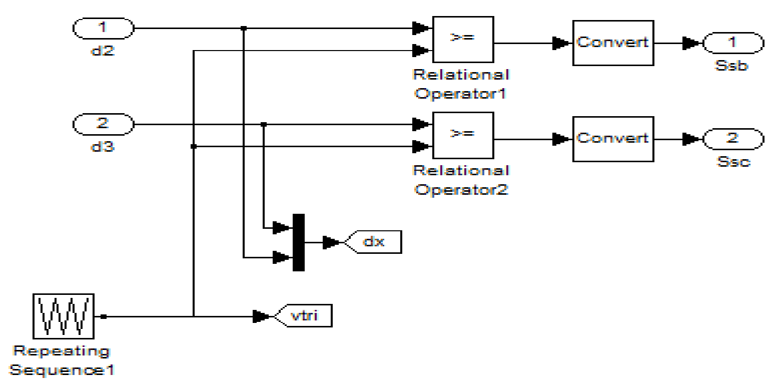


Figure 3.11: (a) PWM Generation is detail of Subsystem4 for DSVPWM

MATLAB Function3: Mapping of Vectors

The mapping of switching pattern for SVPWM and DSVPWM is assembled as MATLAB Code. The whole MATLAB code is hooked up within the appendix.

3.3.2 Simulation model of SVPWM and DSVPWM

Figure 3.12 shows the simulation model of SVPWM and DSVPWM. This simulation models are builded following the procedure described in 3.3.2.

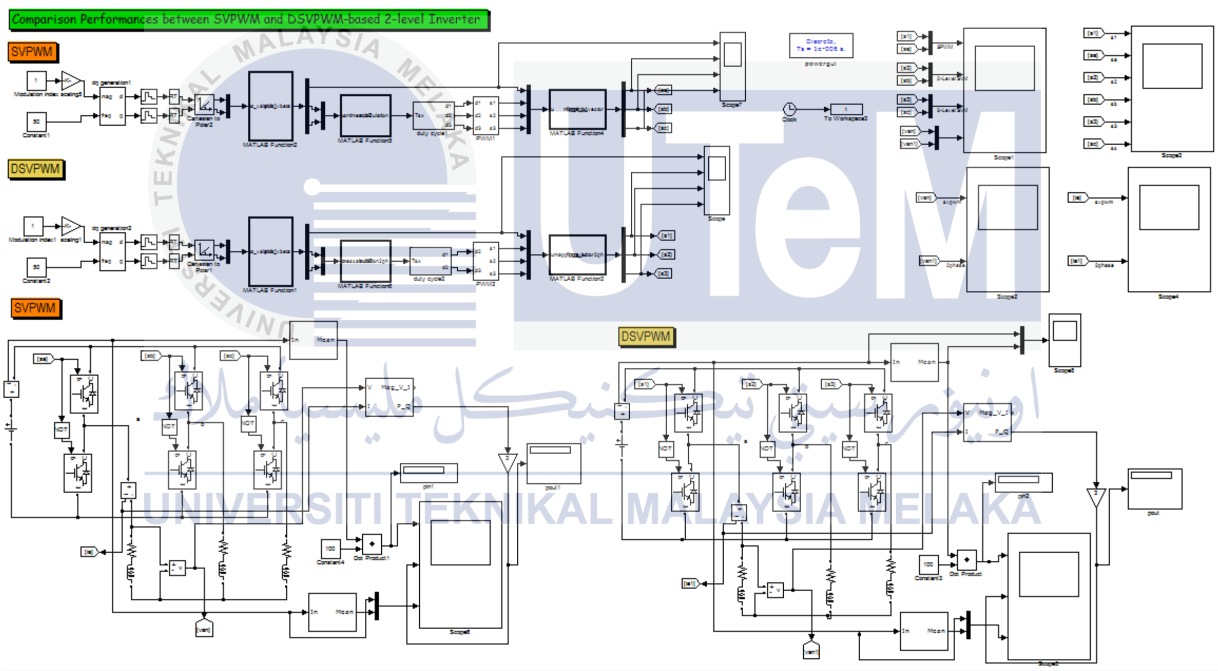


Figure 3.12: Simulation model of comparison performance between SVPWM and DSVPWM based-2-level VSI

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the simulation results from MATLAB/Simulink. Each of the results are analyses based the theoretical information. This chapter also determines whether the objectives are achievable or not. Analysis is perform for both SVPWM and DSVPWM on four categories which are voltage vector plane, phase voltage and phase current, total harmonic distortion as well as efficiency.

4.2 Simulation Results

4.2.1 Voltage Vector Plane

Simulation results performed using MATLAB/Simulink model as shown in Figure 3.12. The DC bus is equal to 100V is connected to the input inverter, 50 Hz fundamental frequency, 5k Hz of carrier frequency, 10 ohms resistance value and 25mH inductance value are set up in the simulation model. Figure 4.1 shows voltage vector plane generated form the simulation of SVPWM and DSVPM. The voltage vector plane is the output of three to two phase transformations block. The hexagon shape represents the voltage vector plane for each sector. Area of the voltage vector plane to be considered as sector 1and other sector is identified by the programmer by limiting the angle.

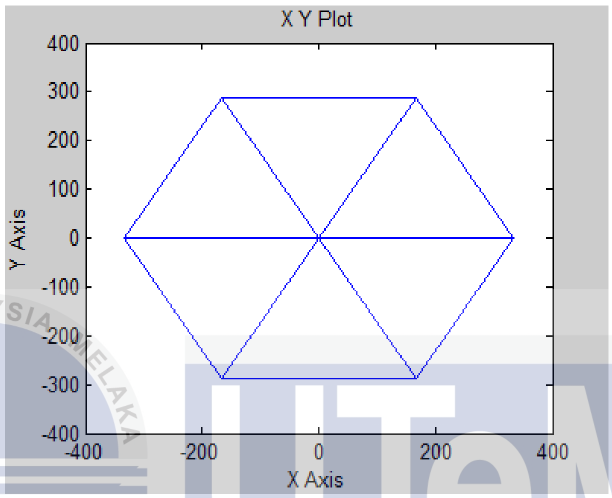


Figure 4.1: Voltage Vector Plane

4.2.2 Switching Pattern

The switching pattern is different for each sector. Switching pattern for sector 1of both SVPWM and DSVPWM is set as the reference switching pattern. Figure 4.2 (a) and Figure 4.2(b) illustrated the reference switching pattern for SVPWM and DSVPWM. Sa,Sb and Sc are the switching for phase a, phase b and phase c. For DSVPWM, only two phases operate while the other one remain constant. Phase a for DSVPWM remain constant as it tied to the upper(positive) DC bus.

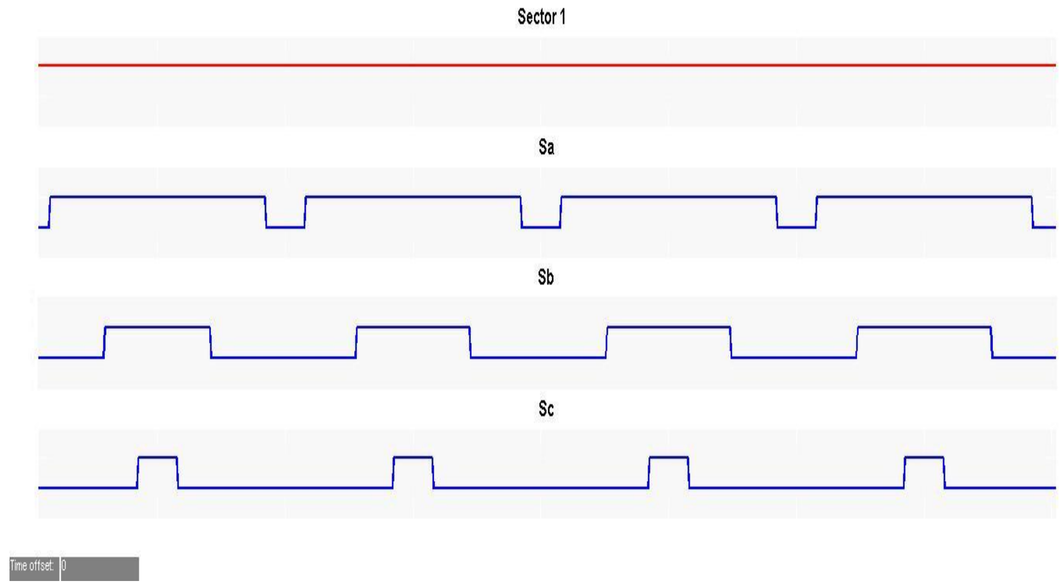


Figure 4.2: (a) Switching Pattern for Sector 1 of SVPWM

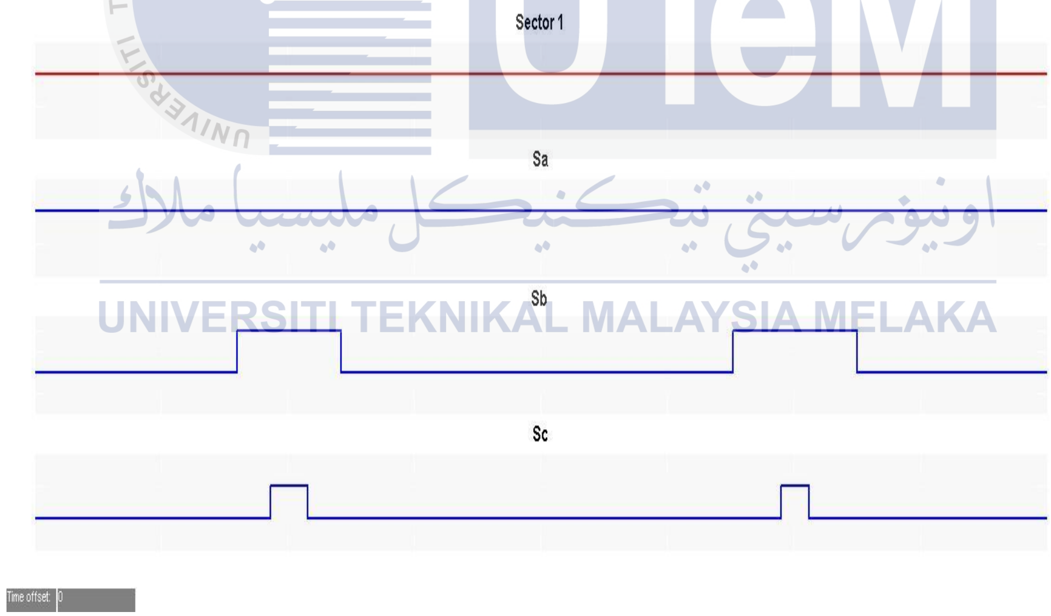


Figure 4.2: (b) Switching Pattern for Sector 1of DSVPWM

4.2.3 Phase Voltage and Phase Current

Phase voltage and phase current for both SVPWM and DSVPWM are measured at modulation index equal to 1. At time 0.002 second, phase voltage for SVPWM and DSVPWM is similar which is 66.67 V. Phase current for DSVPWM is slightly increase by 0.007 A from SVPWM. The value of phase current for SVPWM and DSVPWM is 4.728A as well as 4.735A. Figure 4.3 and Figure 4.4 shows phase voltage and phase current for SVPWM and DSVPWM.

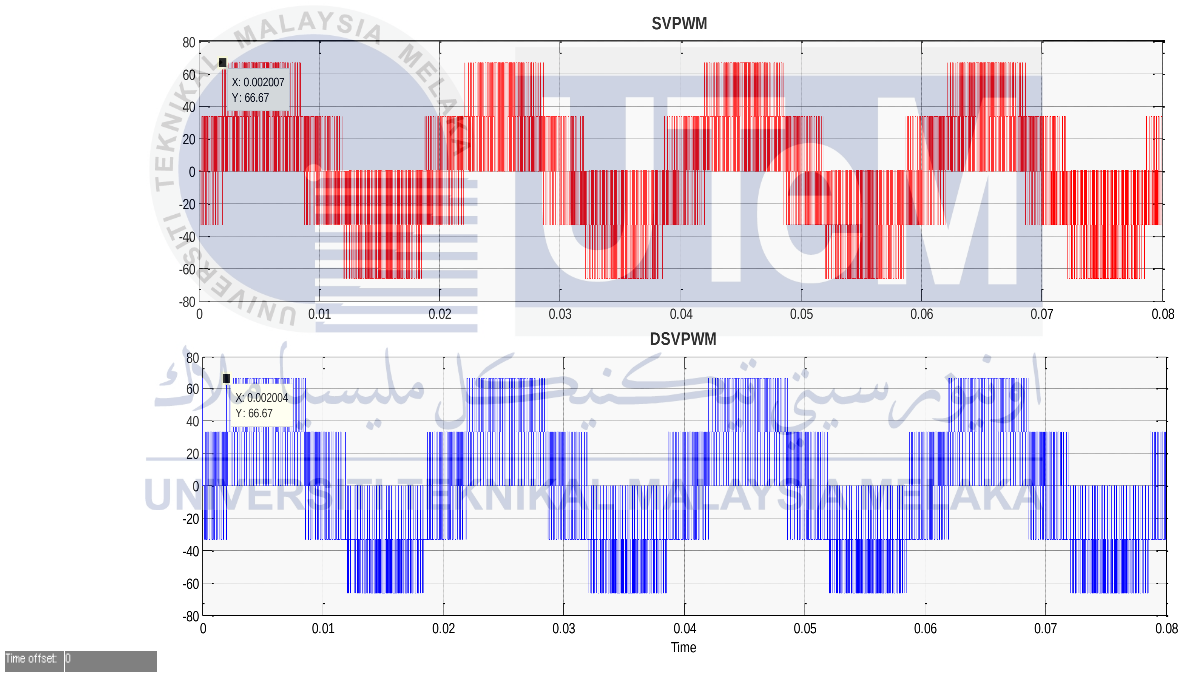


Figure 4.3: Phase voltage for SVPWM and DSVPWM

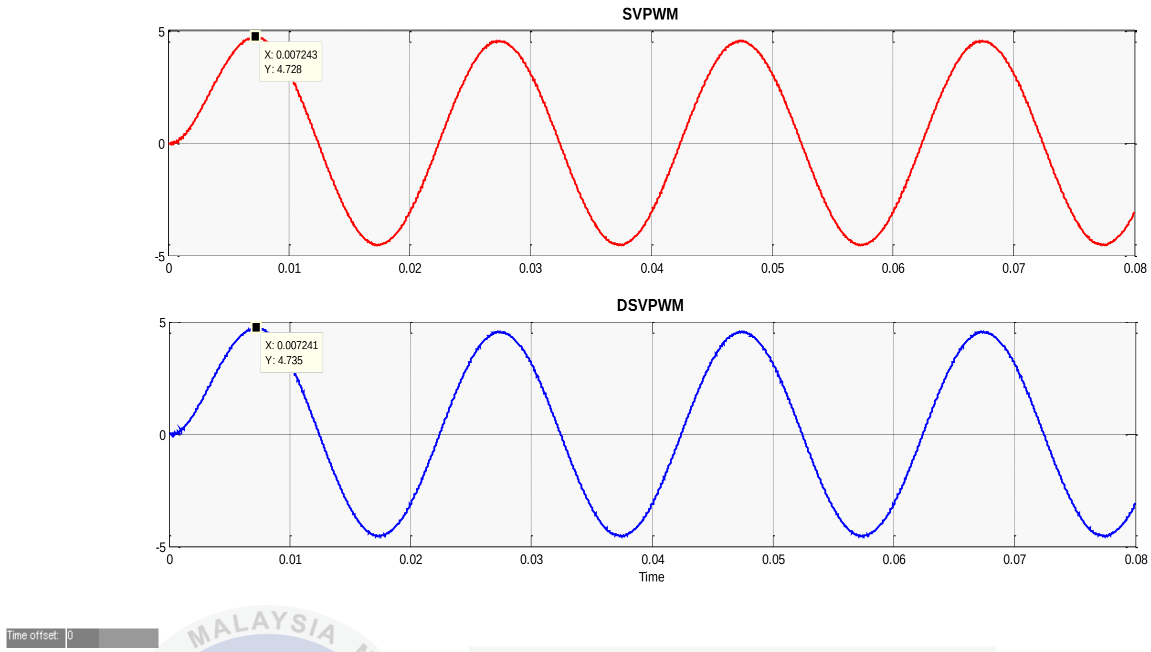


Figure 4.4: Phase current for SVPWM and DSVPWM

4.2.5 Total Harmonic Distortion (THD)

From the simulation results, THD for SVPWM and DSVPWM is slightly similar for both voltage and current at modulation index 1. The THD of phase voltage for DSVPWM is 52.43% reducing about 0.2% from THD value for SVPWM (52.63%).THD values for phase current of SVPWM and DSVPWM at modulation index 1 is similar, 0.65. The entire harmonic spectrums are shown in Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.8.

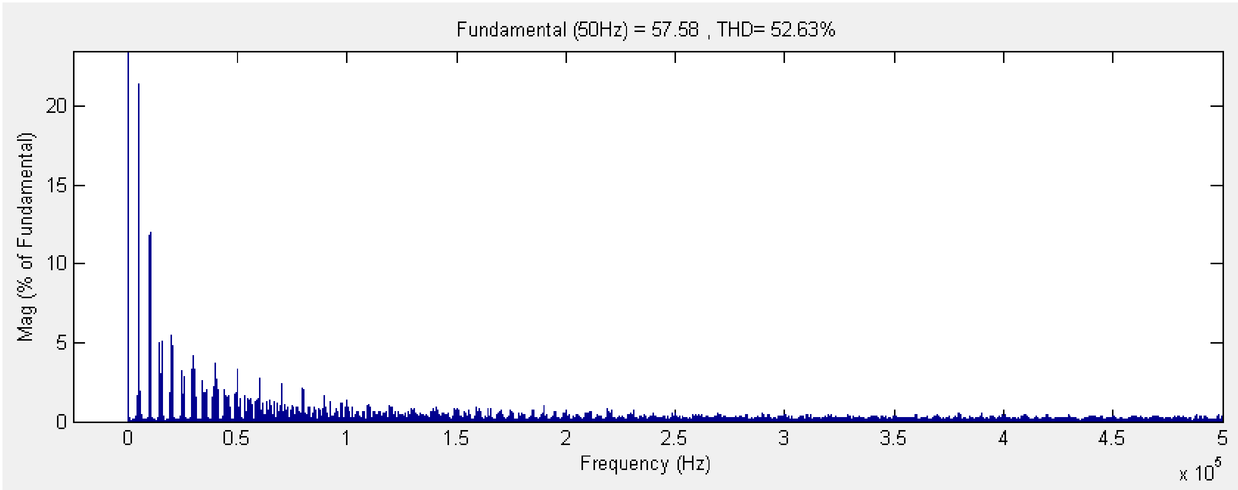


Figure 4.5: Spectrum of Phase Voltage Harmonic for SVPWM at MI=1

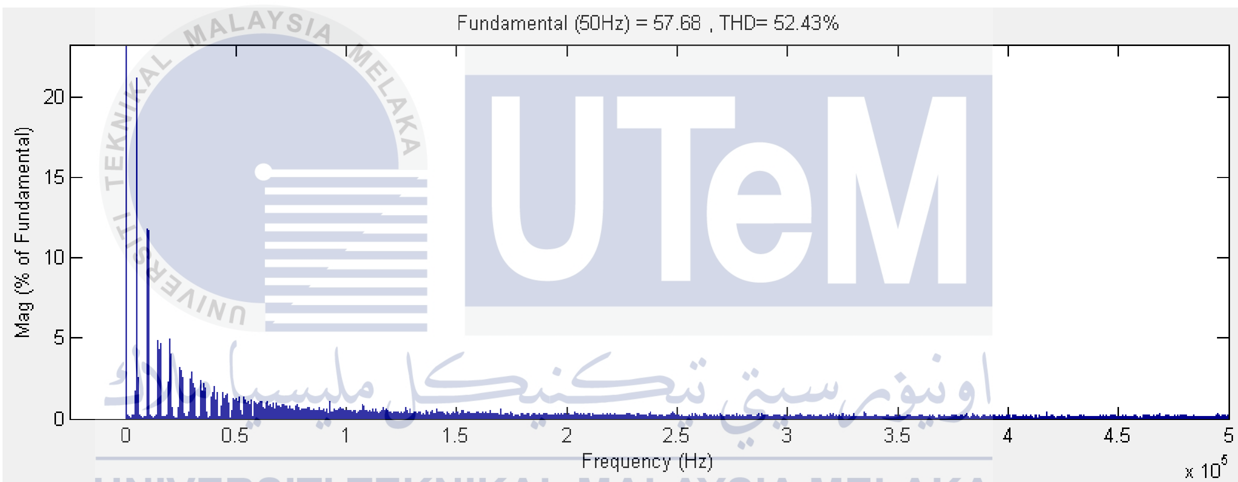


Figure 4.6: Spectrum of Phase Voltage Harmonic for DSVPWM at MI=1

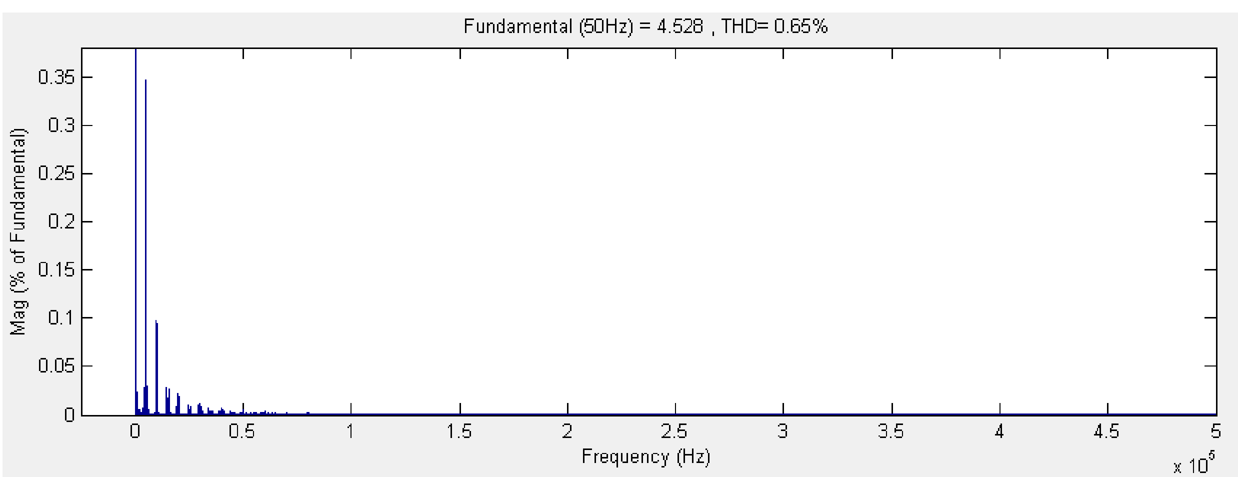


Figure 4.7: Spectrum of Phase Current Harmonic for SVPWM at MI=1

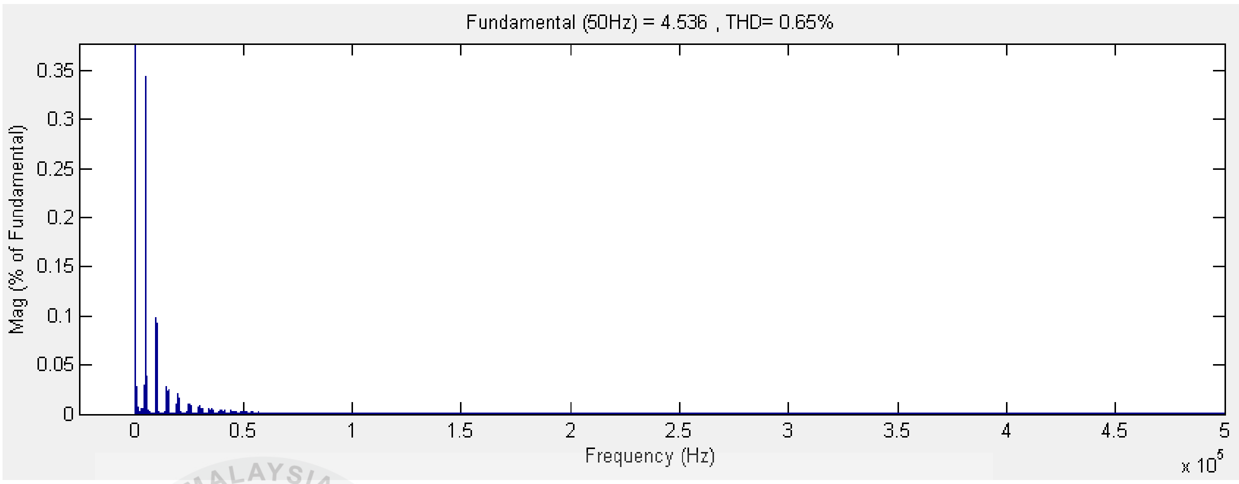


Figure 4.8: Spectrum of Phase Current Harmonic for DSVPWM at MI=1

4.2.6 Comparison of Efficiency and THD between SVPWM and DSVPWM

The following parameters are selected to observe the comparison between SVPWM and DSVPWM technique:

a) V_{DC}=100 V

b) Carrier Frequency= 5k Hz

c) Fundamental Frequency= 50 Hz

d)Modulation Index= 0.5 until 1.0

All the data are summarize in Table 4.1. Based on Figure 4.9, the overall efficiency of DSVPWM for modulation index starting from 0.5 until 1.0 can be concluded as increasing. By referring to Figure 4.10, the THD of voltage for SVPWM and DSVPWM is almost similar. Figure 4.11 described the THD of current have slightly difference in value. THD of current for DSVPWM is slightly greater than SVPWM.

Table 4.1: Comparison of Efficiency and THD for SVPWM and DSVPWM

MI	SVPWM					DSVPWM				
	Pin (W)	Pout (W)	Efficiency (%)	THD (%)		Pin (W)	Pout (W)	Efficiency (%)	THD (%)	
				V	I				V	I
0.5	76.68	73.1	95.33	124.75	0.95	78.04	76.84	98.46	124.76	1.61
0.6	110.9	106.1	95.67	106.41	0.83	112.1	110.8	98.84	106.24	1.36
0.7	150.5	144.8	96.21	90.58	0.74	152.2	151.3	99.41	90.61	1.12
0.8	197.4	190.1	96.30	77.51	0.68	198.6	197.5	99.44	77.13	0.91
0.9	249	240.8	96.70	64.48	0.64	251	249.7	99.48	64.71	0.74
1.0	307.8	298.2	96.88	52.63	0.65	309.7	308.7	99.67	52.43	0.65

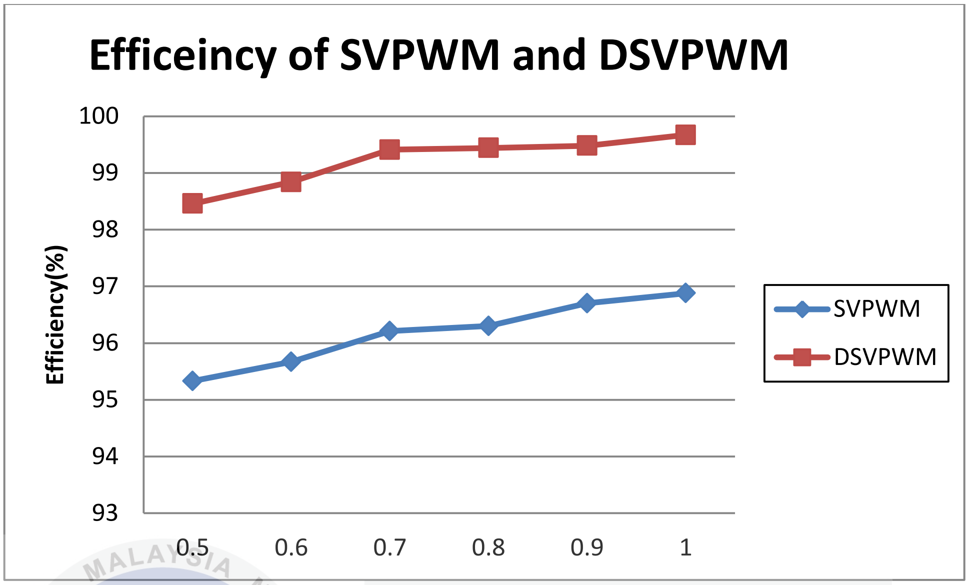


Figure 4.9:Graph of Efficiency Versus Modulation Index for SVPWM and DSVPWM

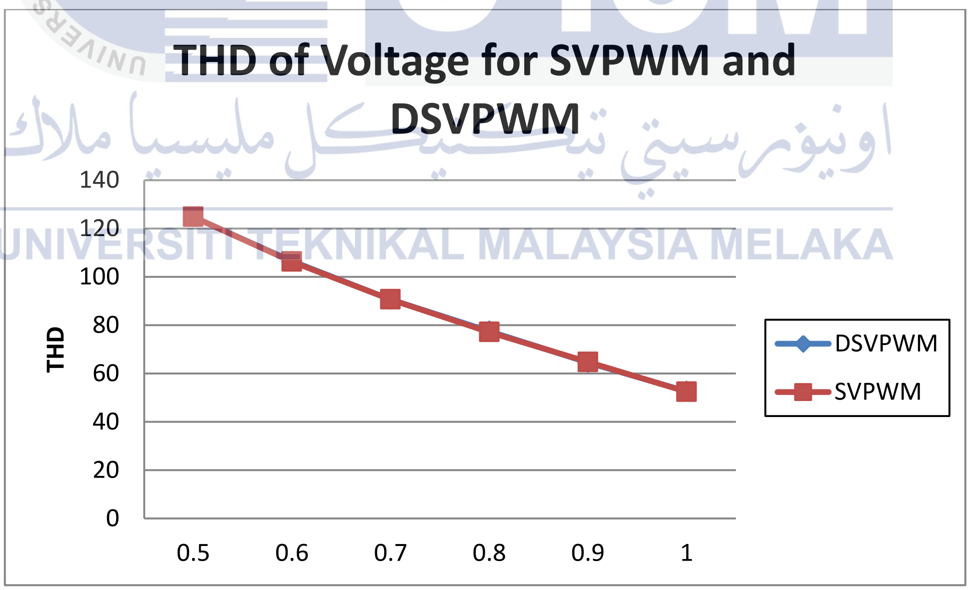


Figure 4.10: Graph of THD of Voltage versus Modulation Index for SVPWM and DSVPWM

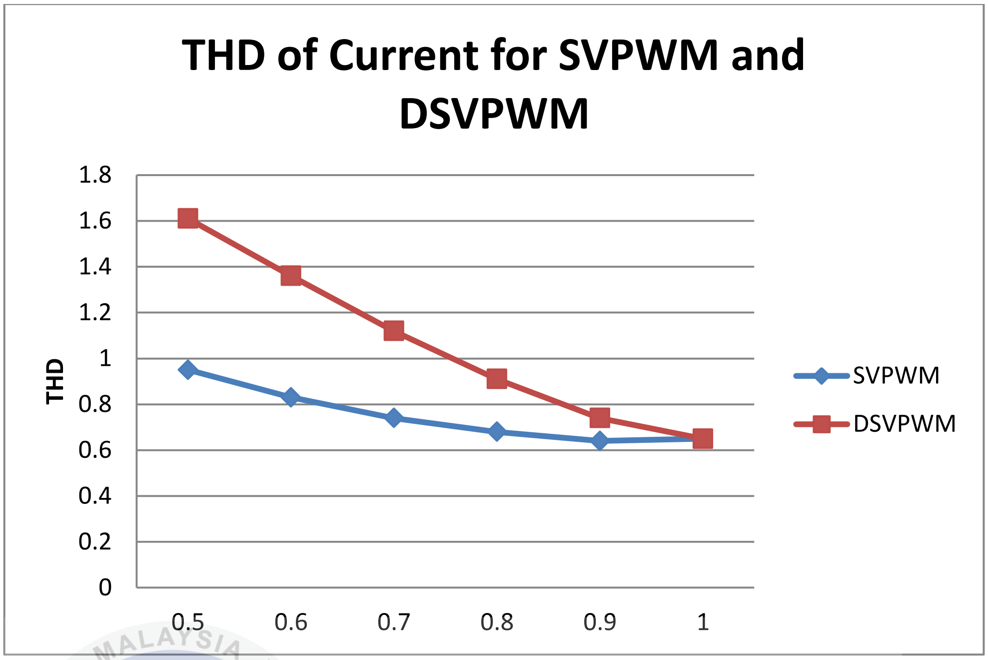


Figure 4.11: Graph of THD of Current versus Modulation Index for SVPWM and DSVPWM

4.2.7 Switching Frequency

Figure 4.12 shows the switching frequency of SVPWM and DSVPWM technique. Waveform of SVPWM shows that all three phases' quantities are active while waveform of DSVPWM shows that one of three phase's quantities is hold. Thus DSVPWM technique offers less switching losses compare to SVPWM technique.

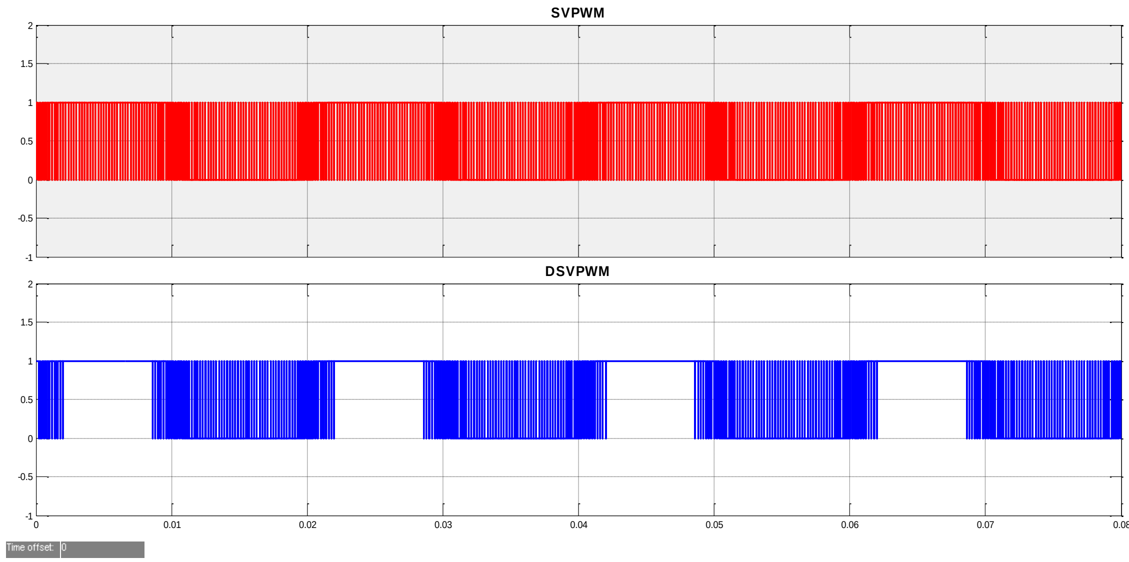


Figure 4.12: Switching frequency of SVPWM and DSVPWM

CHAPTER 5

CONCLUSION

5.1 Conclusions

In this project, Space Vector Pulse Width Modulation (SVPWM) and Discontinuous Space Vector Pulse Width Modulation (DSVPWM) techniques have been investigated and compared. Based on analysis DSVPWM technique only requires two phases to control three-phase voltage source inverter which can improved the efficiency of SVPWM technique due to less switching loses. The investigations provided the implementation of SVPWM and DSVPWM step by step which fulfill objective number one. In term of phase voltage and phase current, both of the technique gives slightly similar value. The phase voltage value is obtained at 0.002 second for both techniques is exactly the same which is 66.67V. The obtained value for phase current of SVPWM and DSVPWM are 4.728A and 4.735A respectively at modulation index 1. From the analysis of the efficiency, it is proven that DSVPWM technique increases the efficiency of SVWPM. However the improvement of efficiency does not increase constantly for every tested modulation index 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0. This technique does not improve Total Harmonic Distortion. The THD for both SVPWM and DSVPWM is slightly similar. Based on analysis and obtained results, all the objectives are achieved. It is recommended that filter block is added in modeling both technique to have better results on THD. This project can be continue by implementing both techniques on multilevel inverters.

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APPENDIX A

MATLAB Code For SVPWM

SECTOR IDENTIFICATION AND ALPHA,BETA VOLTAGE VECTOR

```
function sector_valpha_vbeta =sub1(u)
%initialization
si=0;
theta_si = 0;
%define input
mag=u(1);
theta=u(2);
%Conversion radian-to-degree
theta_deg=theta*180/pi;
%Sector identification
if((theta_deg >=0)&&(theta_deg < 60))
   si = 1;
elseif((theta_deg >=60)&&(theta_deg < 120))
   si = 2;
elseif((theta_deg >=120)&&(theta_deg < 180))
   si = 3;
elseif((theta_deg >= -180)&&(theta_deg < -120))
   si = 4;
elseif((theta_deg >= -120)&&(theta_deg < -60))
   si = 5;
elseif((theta_deg >= -60)&&(theta_deg < 0))
   si = 6;
end
if(si >= 6)
   si = 6;
elseif (si <= 1)
   si = 1;
end

%Calculation of valpha0 and vbeta0
if(si==1)
```

```
   theta_si = theta;
elseif(si == 2)
   theta_si = 2*pi/3-theta;
elseif(si == 3)
   theta_si = theta-2*pi/3;
elseif(si == 4)
   theta_si = -2*pi/3-theta;
elseif(si == 5)
   theta_si = theta+2*pi/3;
elseif(si == 6)
   theta_si = -theta;
end
valpha0 = mag*cos(theta_si);
vbeta0 = mag*sin(theta_si);

% output
sector_valpha_vbeta=[si, valpha0, vbeta0];
```

ON TIMES CALCULATION

```
function ontimescalculation =sub2(u)

%initialization
Vdc = 500;
T = 1/5000;

%define input
valpha0=u(1);
vbeta0=u(2);

%calculation of ta & tb.
ta = 1.5*T/Vdc*(valpha0-vbeta0/sqrt(3));
tb = sqrt(3)*vbeta0*T/Vdc;

% output
ontimescalculation=[ta; tb];
end
```

MAPPING OF VECTOR

```
function mapping_vector = fpga_lut(u)
%initialization
sx=[0; 0; 0];
%define input
si=u(1);
s1=u(2);
```

```
s2=u(3);
s3=u(4);
%generation of gate pulses s1, s2 & s3;
%For sector=1 ************************************************************
if (si == 1)
   if (s1 == 0 && s2 == 0 && s3 == 0)
   sx = [0; 0; 0];
   elseif (s1 == 1 && s2 == 0 && s3 == 0)
   sx = [1; 0; 0];
   elseif (s1 == 1 && s2 == 1 && s3 == 0)
   sx = [1; 1; 0];
   elseif (s1 == 1 && s2 == 1 && s3 == 1)
   sx = [1; 1; 1];
   end
elseif (si == 2)
   if (s1 == 0 && s2 == 0 && s3 == 0)
   sx = [0; 0; 0];
   elseif (s1 == 1 && s2 == 0 && s3 == 0)
   sx = [0; 1; 0];
   elseif (s1 == 1 && s2 == 1 && s3 == 0)
   sx = [1; 1; 0];
   elseif (s1 == 1 && s2 == 1 && s3 == 1)
   sx = [1; 1; 1];
   end
elseif (si == 3)
   if (s1 == 0 && s2 == 0 && s3 == 0)
   sx = [0; 0; 0];
   elseif (s1 == 1 && s2 == 0 && s3 == 0)
   sx = [0; 1; 0];
   elseif (s1 == 1 && s2 == 1 && s3 == 0)
   sx = [0; 1; 1];
   elseif (s1 == 1 && s2 == 1 && s3 == 1)
   sx = [1; 1; 1];
   end
elseif (si == 4)
   if (s1 == 0 && s2 == 0 && s3 == 0)
   sx = [0; 0; 0];
   elseif (s1 == 1 && s2 == 0 && s3 == 0)
   sx = [0; 0; 1];
   elseif (s1 == 1 && s2 == 1 && s3 == 0)
   sx = [0; 1; 1];
   elseif (s1 == 1 && s2 == 1 && s3 == 1)
   sx = [1; 1; 1];
   end
elseif (si == 5)
   if (s1 == 0 && s2 == 0 && s3 == 0)
   sx = [0; 0; 0];
```

```
    elseif (s1 == 1 && s2 == 0 && s3 == 0)
    sx = [0; 0; 1];
    elseif (s1 == 1 && s2 == 1 && s3 == 0)
    sx = [1; 0; 1];
    elseif (s1 == 1 && s2 == 1 && s3 == 1)
    sx = [1; 1; 1];
    end
elseif (si == 6)
    if (s1 == 0 && s2 == 0 && s3 == 0)
    sx = [0; 0; 0];
    elseif (s1 == 1 && s2 == 0 && s3 == 0)
    sx = [1; 0; 0];
    elseif (s1 == 1 && s2 == 1 && s3 == 0)
    sx = [1; 0; 1];
    elseif (s1 == 1 && s2 == 1 && s3 == 1)
    sx = [1; 1; 1];
    end
end
% output
mapping_vector = sx;
end
```