Faculty of Electrical Engineering

SIMULATION OF SHE-PWM FOR MULTILEVEL INVERTER

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SIMULATION OF SHE-PWM FOR MULTILEVEL INVERTER

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

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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MAY 2014

DECLARATION

I declare that this thesis entitled "Simulation of SHEPWM for Multilevel Inverter" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have read this report and in my opinion this report is sufficient in terms of scope and quality as a partial fulfilment of Bachelor Degree of Electrical Engineering (Power Electronics and Drives).

Signature : ……………….……………….

Supervisor Name : ……………….……………….

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ABSTRACT

Multilevel inverters have been receiving increasing attention in power system nowadays. The major problem for inverter is the harmonic distortion that will affect the performance and contribute in power losses. Thus, there are a variety of control techniques for inverters are introduced but less of the techniques can used to reduce the harmonic at low frequency. The harmonic at low frequency must be reduced due to some equipments are sensitive to the low frequency harmonic. Selective harmonic elimination pulse-width modulation (SHE-PWM) is a technique that can be used to eliminate the harmonic at low frequency which difficult to reduce by using passive filter. SHE-PWM is a low switching frequency strategy that uses Fourier Series and Newton-Raphson analysis to calculate the switching angles for elimination of harmonic. In this research, the main objective is to study the control technique for multilevel inverter and simulate the SHE-PWM for multilevel inverter. The performance of output waveform and total harmonic distortion (THD) for multilevel inverter are analysed and discussed. MATLAB program is important in this research. It is use to calculate the angle of PWM and simulate the SHE-PWM for multilevel inverter. The result shows that the percentage of harmonic at low harmonic order for SHE-PWM had been eliminated compare with other methods. In conclusion, the SHE-PWM technique can eliminate the selected harmonic at lower harmonic order.

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ABSTRAK

Penyongsang berperingkat semakin mendapat perhatian dalam bidang sistem kuasa pada masa kini. Masalah utama bagi penyongsang adalah herotan harmonik yang memberi kesan kepada prestasi peralatan dan menyumbang kepada kehilangan kuasa. Oleh itu, pelbagai teknik kawalan penyonsang wujud akan tetapi teknik-teknik yang boleh digunakan untuk mengurangkan harmonik pada frekuensi yang rendah amat kurang. Harmonik pada frekuensi rendah perlu di kurangkan kerana beberapa peralatan akan sensitive terhadap harmonic di peringkat rendah. Penghapusan Harmonik Terpilih Pemodulatan Denyut Lebar (HT-PDL) merupakan satu teknik yang boleh dgunakan untuk menghapuskan harmonic pada frekuensi rendah yang mana sukar untuk dikurangkan dengan menggunakan penapis pasif. HT-PDL adalah satu strategi penukaran frekuensi rendah yang menggunakan analisis Siri Fourier dan Newton-Rapson untuk mengira sudut beralih untuk penghapusan harmonik. Dalam kajian ini, objektif utama adalah untuk mengkaji teknik kawalan penyongsang berperingkat dan simulasi untuk HT-PDL untuk penyongsang berperingkat. Prestasi gelombang keluaran dan jumlah herotan harmonik (JHH) untuk penyongsang berperingkat dianalisa dan dibincangkan. MATLAB amat penting dalam kajian ini. MATLAB digunakan untuk mengira sudut PDL dan mensimulasi penyongsang berperingkat menggunakan HT-PDL. Hasilan kajian ini menunjukkan bahawa peratusan harmonic pada susunan harmonic yang rendah. Kesimpulanya, SHE-PWM boleh menghapuskan harmonik yang terpilih pada peringkat harmonik yang rendah.

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NOMECLATURE

AC	-	Alternating Current
AM	-	Amplitude Modulation
APOD	-	Alternative Position Opposition Disposition
DC	-	Direct Current
FFT	-	Fast Fourier Transform
IEEE	-	Institute of Electrical and Electronic Engineers
MATLAB	-	Matrix Laboratory
MOSFET	-	Metal-Oxide Semiconductor Field Effect Transistor
POD	-	Phase Opposition Disposition
PWM	-	Pulse-Width Modulation
R	-	Resistance
RC	-	Resistance-Capacitor
RL	-	Resistance-Inductance
SHE	-	Selective Harmonic Elimination
SPWM	-	Sinusoidal Pulse-Width Modulation
SVC	-	Space Vector Control

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SVM	-	Space Vector Modulation
THD	-	Total Harmonic Distortion
THDi	-	Total Harmonic Distortion of Current
THDv	-	Total Harmonic Distortion of Voltage

CHAPTER 1

INTRODUCTION

1.1 Background

Multilevel inverters are mostly used nowadays to generate an Alternating Current (AC) voltage from Direct Current (DC) voltage. The concept of a multilevel inverter is several voltage levels are added to each other to create a smoother stepped waveform with lower harmonic distortion. Moreover, multilevel inverters synthesize an AC voltage into a staircase which approximately to a desired sinusoidal waveform by divided the main DC voltage supply into several small DC sources. The multilevel inverters can yield operating characteristics likes high voltages, high power levels and high efficiency using multiple levels. They can operate without the use of transformer. Hence, multilevel inverters are mostly used in high power system. There are three main types of multilevel inverters such as diode-clamped, capacitor-clamped and cascade H-bridges. Cascade H-bridges is chosen due to its features such as its battery management capability, redundant inverter operation and scalability. Furthermore, it has the least components for given number of levels. Harmonic minimization is important to get the smoother waveform for multilevel inverter. There are several techniques have been introduced but the most popular technique is selective harmonic elimination pulse width modulation (SHE-PWM). It is one of the effective techniques to reduce the harmonic in lower switching frequency. In theoretical, SHE-PWM technique can provide the highest quality among the PWM techniques. Typically, this method is selected due to a system may be developed which can be solved for the switching angle that eliminate selected harmonic. The advantages of SHE-PWM technique include that it produced the desired fundamental sinusoidal voltage while at the same time certain order harmonics are eliminated.

1.2 Research Motivation

In high power applications, multilevel voltage source inverters (VSI) have been receiving increasing attention in the recent years. These inverters are suitable in high voltage and high power applications due to their ability to synthesize waveforms with better harmonic spectrum and attain higher voltages without increasing the switching frequency and decreasing the inverter output power. There are three types of multilevel inverter topologies which are cascade inverter, flying capacitor and diode clamped. The cascade multilevel inverter is chosen in this study because it requires less circuit elements from the others. The number of output voltage levels can be easily adjusted by adding or removing the full bridge cells. However, the performances of multilevel inverter in some applications will be affected by the lower harmonic frequency. A key issue in designing the effective multilevel inverter is to ensure total harmonic distortion (THD) in the voltage output is low enough. Moreover, the harmonic at lower frequency are difficult to reduce or eliminate which not same as the harmonic at higher frequency that can be easily reduced by passive filter. Several techniques are introduced to reduce the harmonic at low frequency such as active power filter. The disadvantages of active power filter are it has complex circuit, costly and difficult to control compared to SHE-PWM technique. Thus, SHE-PWM technique had been introduced for elimination of harmonic at low frequency. One of the advantages of the SHE-PWM technique is its ability to operate in low switching frequency that makes it suitable for high power applications. This SHE-PWM technique can be used to synthesize output waveform of both half-bridge and full-bridge inverter.

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1.3 Objective

The objectives of this research are

1. To study the control technique for multilevel inverter.
2. To simulate the selective harmonic elimination (SHE-PWM) for multilevel inverter.
3. To analyse and investigate the performance of multilevel inverter using SHE-PWM using Newton-Raphson technique.

1.4 Scope

The scope of project in this research is to analyse and investigate the performance of three phase multilevel inverter using SHE-PWM. It will also focus on the three phase seven-level inverter for several loads which are resistance (R), resistance-inductance (RL) and resistance-capacitance (RC) and the simulation of SHE-PWM. Besides that, the calculation of switching angles in SHE-PWM technique is discussed and shown in this research. The switching angle will determined using Newton-Raphson method in m-file or MATLAB and the value of angle is use to turn ON or OFF switching drive in simulink or MATLAB. Lastly, it covers also the THD of current and voltage for single phase of different type techniques for R, RL and RC load. A comparison is made to show the different between these topologies such as SHE-PWM, unipolar, bipolar and square wave.

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1.5 Project Outline

A brief outline of the contents of the project report is organised as following:

Chapter 1 introduces the project background and the problem statement of thus project. It also covers the objective and scope for this project.

Chapter 2 briefly review the multilevel inverter with its topologies and applications. The modulation and PWM techniques are also discussed in this chapter. Lastly, it also discuss about the definition and effects of harmonic in power system.

Chapter 3 develops the flowchart of this project will be carried out and the simulation of SHE-PWM for multilevel inverter. In this chapter, the milestone and Gantt chart are also covered and the methodology of three phase SHE-PWM for multilevel inverter is discussed. Besides that, the simulink block for each single phase inverter using several techniques for different loads is shown. Lastly, the calculation for switching angles of SHE-PWM techniques is shown.

Chapter 4 briefly discuss the results that obtained from simulation using MATLAB 2010a. The current and voltage waveform of different types of inverter control scheme for R, RL and RC load are shown in this chapter. In addition, the percentage of harmonic for low harmonic order and high harmonic order is collected in a table. The THD for current and voltage are taken down from simulation result and recorded in a table form. In this chapter, the results are being compared and discussed.

Chapter 5 discusses and explains the fundamental of the multilevel inverter using SHE-PWM and others techniques. A short summary of the whole project is made and some recommendation will be added.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Inverter is a device that used to convert DC to AC for operating tools, appliances and other electrical equipment. A multilevel inverter is introduced which it have emerged as a very important alternative that can provides energy in higher power situations. In this recent year, multilevel inverter has gained much intention in the high power systems due to its characteristics, advantages and increasing of research in renewable energy.

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2.2 Multilevel Inverter

The multilevel inverter had been introduced since 1975 which began with the three-level inverter [1]. Moreover, it is to synthesize a near sinusoidal voltage from several levels of DC voltages [2]. The synthesized output waveform has more steps as the number of levels increases which provides a staircase wave that approaches a desired waveform. Besides that, the harmonic distortion of the output decreases as the steps are added to waveform. It is approaching zero as the number of voltage levels increase [2]. Multilevel inverter uses a series power semiconductor switches with several lower voltage DC sources to perform the power conversion with a staircase voltage waveform. This concept can help the multilevel inverter to achieve higher power. Subsequently, a few multilevel inverter topologies have been introduced [1]. The advantages of multilevel inverter are it has lower common mode voltage and lower voltage stress on power switches. Moreover, multilevel inverter also has a lower dv/dt ratio to supply lower harmonic contents in output voltage and current [3].

2.2.1 Multilevel Inverter Topologies

Multilevel inverter has three main types of topologies which are diode clamped inverter, flying capacitor inverter and cascade H-bridge inverter. The details of these three types of topologies will be discussed in this session.

2.2.1.1 Diode Clamped

A three-level diode clamped inverter also known as neutral point clamped inverter essentially was the neutral point converter first proposed by Nabae, Takahashi and Akagi in 1981 [4]. The others level of diode clamped inverter such as four-level, five-level and six-level diode clamped inverter are used as variable speed motor drives and high voltage system interconnections. A single phase three-level diode clamped inverter is shown in Figure 2.1 while a three phase three-level diode clamped is shown in Figure 2.2.

For both single and three phase configuration of diode clamped inverter, the type of semiconductors that used are capacitors and diodes. Capacitors are used to realise voltage divider circuits while diodes are used to ensure that the series connected switches are subjected to predetermined voltages [4].

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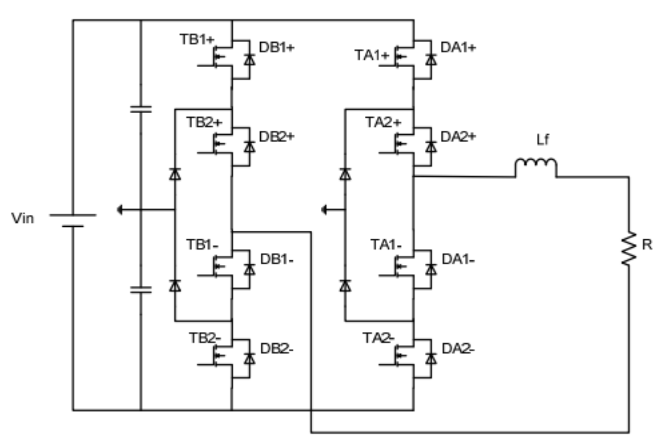

Figure 2.1: Single phase three-level diode clamped inverter [4]

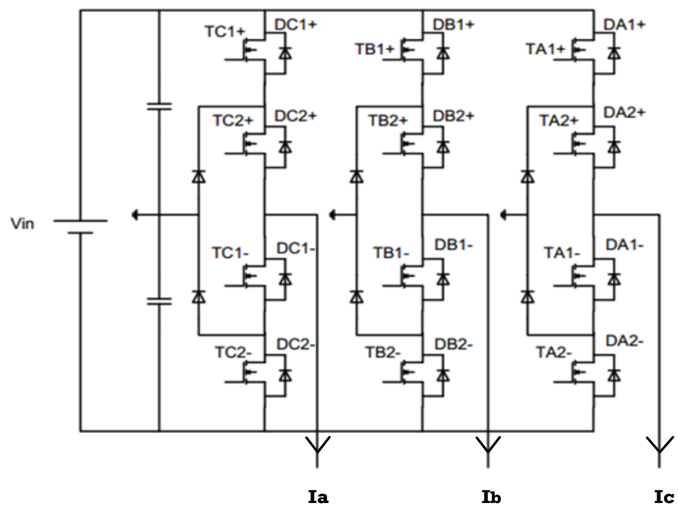

Figure 2.2 : Three phase three-level diode clamped inverter [4]

The advantages for diode clamped inverter are it has less number of capacitors leading to lower cost, weight and volume and can be connected to a single DC-link voltage. It also has high efficiency for fundamental frequency switching [4]. It consists of some disadvantages such as clamping diodes are subject to high voltage stress when more than three levels are employed. Moreover, it is difficult to balance the charge of capacitors with more than three levels topology. The three-level topology suffers from low frequency ripple in neutral point when operating at large modulation indices and low power factor [4].

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2.2.1.2 Flying Capacitor

In 1992, a flying capacitor based inverter was introduced by Meynard and Foch. Its structure is similar to diode clamped inverter except the inverter uses capacitor instead of using clamping diode. Flying capacitor inverter has a ladder structure of DC side capacitors which the voltage on each capacitor is different with the next capacitor. Moreover, the size of voltage steps in the output waveform is given by the voltage increment between two adjacent capacitor legs [1]. Figure 2.3 shows the single phase three-level flying capacitor inverter and the three phase three-level flying capacitor inverter is shown in Figure 2.4. In this topology, different combinations of the switches define the same output voltage which is enough to guarantee balanced voltages in the floating capacitors for any operating condition by using proper modulation scheme. This is different from diode clamped inverter because each leg of capacitor can be analysed independently from others [4].

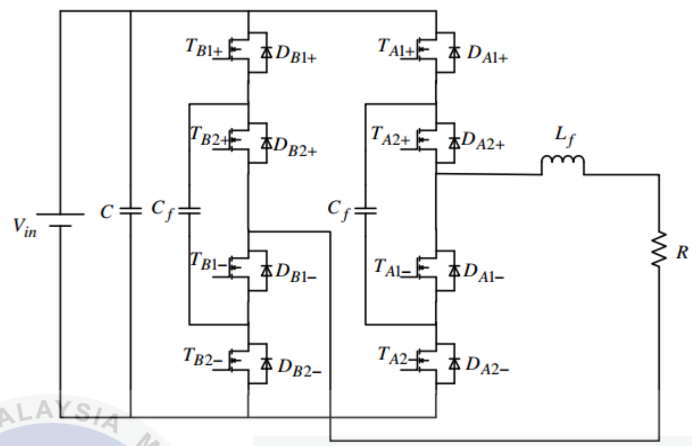

Figure 2.3 : Single phase three-level flying capacitor inverter [4]

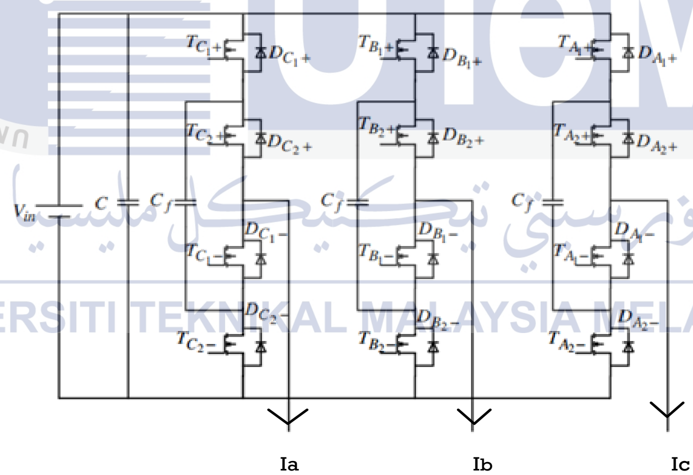

Figure 2.4 : Three phase three-level flying capacitor inverter [4]

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Flying capacitor inverter has some advantages which are its phase redundancies are available for voltage balancing of capacitors. Next, the real and reactive power flow can be controlled. It also has a large number of capacitors enables the inverter to ride through short duration outages and deep voltage sags [4]. On the other hand, the disadvantages of flying capacitor inverter are it has complicated control to track the voltage levels for all capacitor and a poor switching utilization and efficiency for real power transmission. It requires a large number of capacitor which are more costly and bulky, packaging more difficult in inverter with increase number of levels [4].

2.2.1.3 Cascade H-Bridges Inverter

In cascade H-bridges inverter, each separate DC source is connected to single phase H-bridge inverter [1]. The voltage and power level may be easily scaled since it consists of series power conversion cells. Each inverter level can provide three voltage outputs which are positive DC voltage, zero and negative DC voltage. The voltage outputs are produced by connecting the DC source to the AC output with different combinations of four switches [5]. The DC sources must be isolated from each other due to the series connection for output terminals of H-bridges [3]. The three phase of cascade H-bridges multilevel inverter is shown in Figure 2.5.

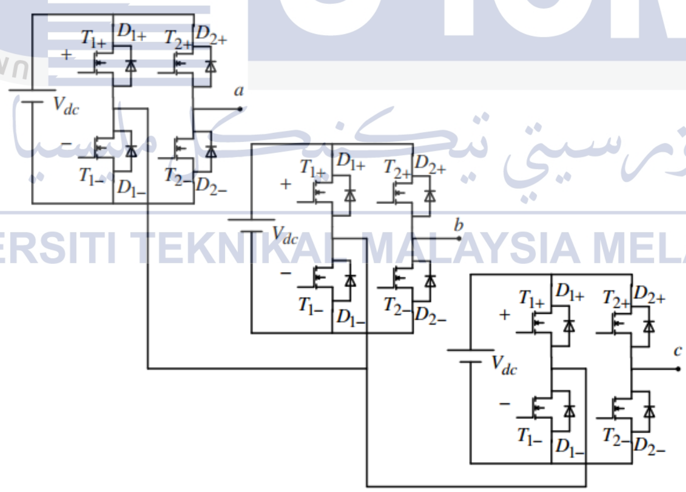

Figure 2.5: Three phase of cascade H-bridges multilevel inverter [4]

In cascade H-bridges inverter, it has some advantages likes it has less power devices requirement and simple design. Besides that, the number of possible output voltage levels is more than twice the number of DC sources. The series H-bridges design can be used for

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modularized layout and packaging. In addition, it enables manufacturing process to be more quickly and less cost [1]. Although it has some advantages but it also consists of some disadvantages. One of the disadvantages of cascade H-bridges inverter is each H-bridge need separate DC sources which limit its application to products that already have multiple separate DC sources [1]. A large number of isolated voltages required to supply each H-bridge.

2.2.2 Trinary Multilevel Inverter Topology

The structure of trinary multilevel inverter is same as the H-bridge cascaded multilevel inverter. The only different for trinary multilevel inverter is the value of DC sources input. Two sets of H-bridges connected with different value of DC sources will produce different level of output voltage. Hence, the advantages of trinary multilevel inverter are reliability and modularity compare to cascade H-bridge multilevel inverter. Furthermore, the trinary multilevel inverter use less components compare to the multilevel topologies for higher level of output. Table 2.1 shows the switching sequences of 7-level trinary DC source multilevel inverter.

Table 2.1: Switching sequences of 7-level trinary DC source multilevel inverter

V_{out}	**HB 1**				**HB 2**			
	S_{11}	**S_{12}**	**S_{13}**	**S_{14}**	**S_{21}**	**S_{22}**	**S_{23}**	**S_{24}**
$3V_{dc}$	0	1	0	1	1	0	0	1
$2V_{dc}$	0	1	1	0	1	0	0	1
V_{dc}	1	0	0	1	0	1	0	1
0	0	1	0	1	0	1	0	1
$-V_{dc}$	0	1	1	0	0	1	0	1
$-2V_{dc}$	1	0	0	1	0	1	1	0
$-3V_{dc}$	0	1	0	1	0	1	1	0

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2.2.3 Application of multilevel inverter

Multilevel inverters are used in the medium-voltage and high-power applications. However, it is also a good solution that can apply in low-power range compared to two-level inverters if metal-oxide semiconductor field effect transistors (MOSFET) are used as switching devices. In this application, the effect of clamping diode in diode-clamped multilevel inverters is important for determining its efficiency. The use of multilevel inverters topology enables efficiency operation at high switching frequency. This will reduces the output filter requirement lead to size of inverter reduced [6].

For electric utility applications, cascade multilevel inverters have been developed. With the invention of new inverter, it can generate almost sinusoidal waveform voltage while switching one time per fundamental cycle. In short, the cascade multilevel inverter is more efficiency and suitable for utility applications compared to traditional multi-pulse and PWM inverters. Next, it can uses for power supply, hybrid electric vehicle motor drive, harmonic compensation and so on [7].

In addition, one of the major advantages of multilevel inverter is increasing the power rating. Multilevel inverter allows voltage or current to share among a number of switches so it does not need to be limited in size by the prevailing semiconductor technology. This advantage has justified the multilevel inverter suitable for large motor drives and utility applications at very high power levels. The stringent harmonic standards also the advantage of multilevel inverter which by a given switching frequency limit, it will produce lower switching harmonic spectrum components [8].

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2.3 Modulation

A process of some characteristic of one wave is varied in accordance with some characteristic of another wave is called modulation. There are two basic types of modulation which are angular modulation including phase or frequency modulation and amplitude modulation. Pulse modulation is a special case of amplitude modulation (AM). The carrier frequency of pulse modulation is gated at a pulse rate. Harmonics corresponding to multiples of that whole number will be missing when the reciprocal of the duty cycle of the AM is a whole number [9].

In multilevel inverter, it is operated in the switched mode which means the switches in the inverter are always either one of two states either turned off or turned on completely. An undesirable loss of efficiency and unbearable rise in switch power dissipation will occur during any operation in the linear region. Next, the switches alternate between these two states either ON or OFF is to control the flow of power in the inverter. The inductors and capacitors at the input and output nodes of the inverter filter the switched signal. The desired average value is controlled by modulating the width of the pulses and this process is called PWM [8]. PWM is the process of modifying the width of pulses directly proportional to a small control signal. When the control voltage increases, the width of resulting pulse become wider. Moreover, PWM can be defined as a modulation technique that conform the width of pulse [10].

2.3.1 Pulse-Width Modulation for Two-Level Inverters

PWM modulation for two-level inverter is comparing between a reference wave and a triangular carrier wave. In reference wave, it has the frequency and amplitude wanted for the output signal. On the other hand, the triangular carrier wave had the amplitude of half DC input voltage and its frequency is dependent on application but higher than the reference wave frequency. The switches in the inverter change their state is depended on the reference wave frequency. The switches will turn ON or OFF every time the triangular carrier wave crosses the reference wave. When the carrier wave crosses the reference wave which it become higher than the reference, the top switches will turns off while the bottom switches will turn on so its output is Vdc/2. Next, the carrier wave is lower than the reference wave, the switches change states and the outputs become –Vdc/2. The two level PWM reference wave, triangular carrier wave and PWM signal are shown in Figure 2.6 and Figure 2.7 [11].

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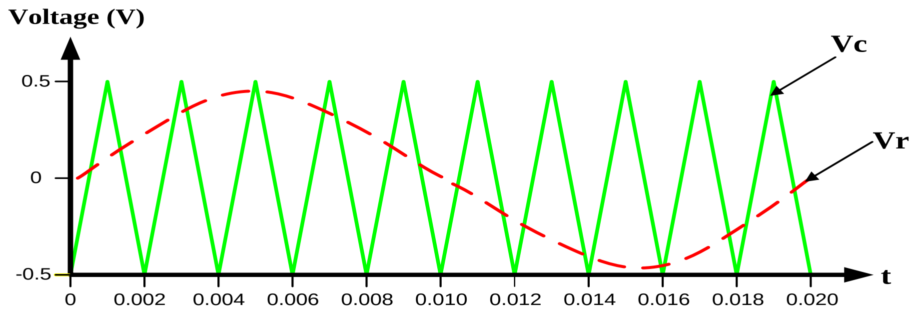

Figure 2.6 : PWM reference (red) and triangular carrier (green)

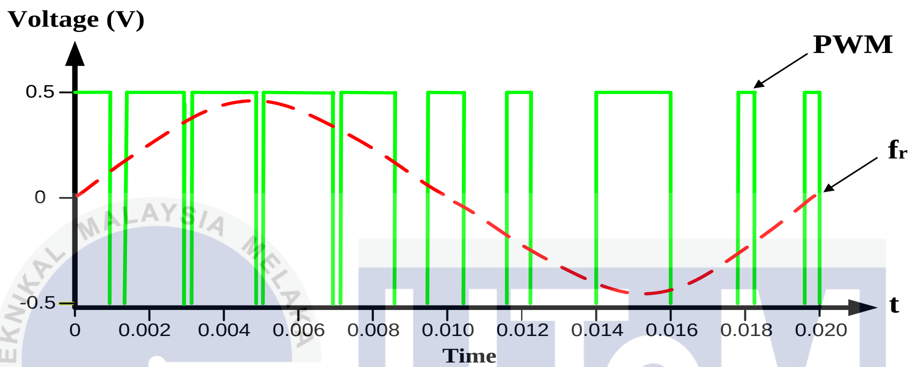

Figure 2.7 : PWM signal (green)

2.3.2 Pulse-Width Modulation for Multilevel Inverters

Multilevel inverter uses high switching frequency carrier wave in comparison to reference waves to generate a sinusoidal output wave. Phase-shifting techniques are used to reduce harmonic distortions in the output signal. The number of carrier waves used is dependent to the number of switches to be controlled in inverter. In addition, two sinusoidal carrier wave modulation methods are alternative position opposition disposition (APOD) and phase opposition disposition (POD) [11].

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2.3.2.1 Phase Shifted Carrier Pulse-Width Modulation

Phase shifted carrier PWM is a multicarrier modulation strategy which all carrier waves phase shifted from each other. It is used in cascaded multilevel inverter. For a cascaded multilevel inverter with *n* number of full bridge modules in each phase-leg are also *n* number of triangular carrier waves. There is phase shifted with 180°/*n* in between the triangular wave for each full bridge module with amplitudes the magnitude of the total DC voltage. Moreover, the magnitudes for the carrier waves are modulated by the actual voltage level in the appropriate module. In five-level cascaded multilevel inverter, there are two triangular carrier waves for two modules shown in Figure 2.8. The modules create the two voltages with phase shifted carrier PWM modulation. Two reference waveforms for two legs in each inverter modules are phase shifted 180° from each other. Both carrier wave compared to the reference waves which one reference wave is for modulation to the left full-bridge module switches and the other one is for modulation of the right full-bridge module switches [11].

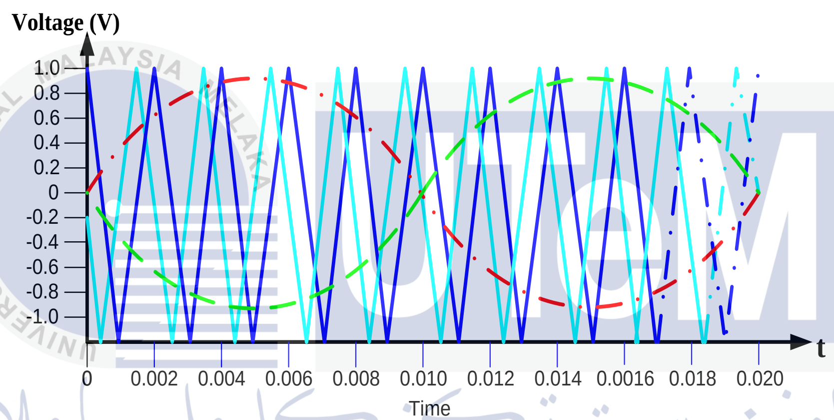

Figure 2.8 : The carrier and reference waves for five-level cascaded multilevel inverter

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2.3.2.2 Phase Disposition Pulse-Width Modulation

All the carrier waves for phase disposition PWM are in phase. This method is generally accepted as the technique that creates the lowest harmonic distortion in line-to-line voltage. This technique is used in neutral point clamped inverter with *n* number of voltage levels and *n-1* number of triangular carrier wave used. The carrier waves have same frequency and arranged on top of each other with no phase shift. Thus, they span from maximum output voltage to minimum output voltage. The correct output voltage will not be generated during the correct time spans if the sources voltage amplitude changes without the carrier waves are modulated. When one carrier wave is crossed by the reference, it will level up or down the output wave steps with a switch transaction. Hence, one carrier wave modulates the use of one voltage state. Since the reference only crosses one carrier at anytime, there is only one level modulated at that time which is shown in Figure 2.9. Besides that, Figure 2.10 shows the output voltage for five-level neutral-point clamped multilevel inverter with phase disposition PWM [11].

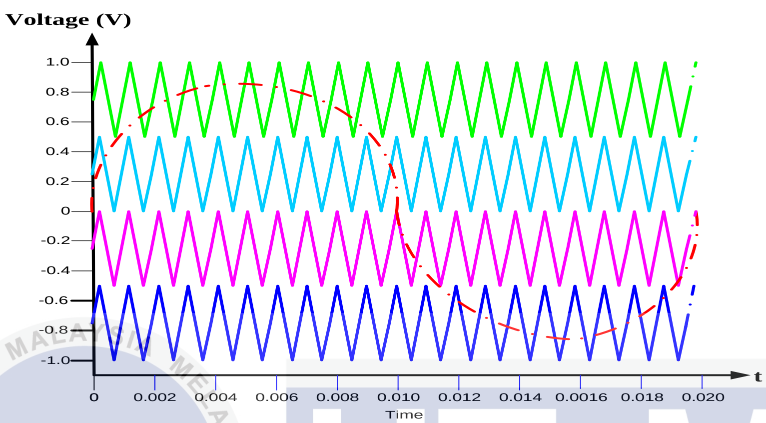

Figure 2.9 : The reference (red) and carrier waves for five-level inverter

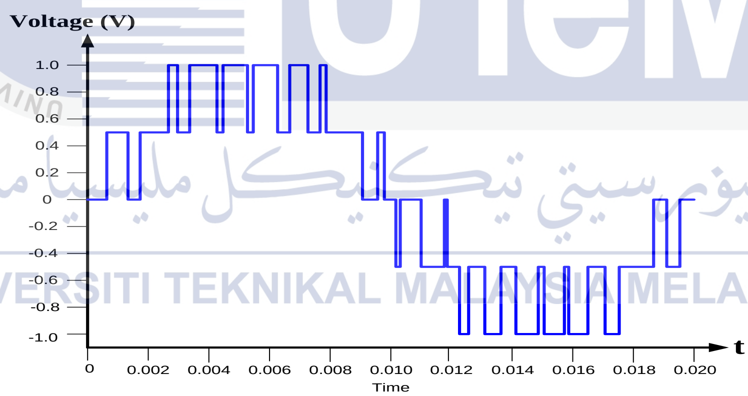

Figure 2.10 : Output voltage for five-level neutral-point clamped multilevel inverter with phase disposition PWM

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2.4 Multilevel Inverter Control Schemes

Multilevel inverter modulation basically has two groups of methods that are modulation with fundamental switching frequency and high switching frequency. A stepped output waveform is achieved for both cases. However, the steps are modulated with PWM in high switching frequency methods. Figure 2.11 shows the classification of multilevel inverter control schemes [11].

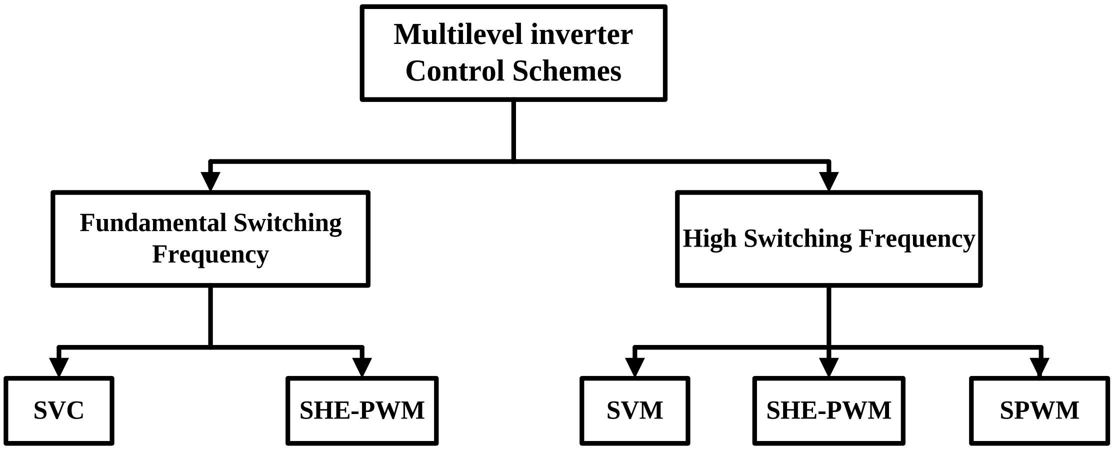

Figure 2.11 : Classification of multilevel inverter control schemes

2.4.1 Space Vector Modulation

Space vector modulation (SVM) is an alternative control method for multilevel inverter which control variable by control system and identifies each switching vector as a point in complex space of (α,β). SVM technique uses a number of level-shifted carrier wave to compare with the reference phase voltage signals [3]. It can only applied in three phase system that the three reference phases are transformed into one reference vector. The reference vector is placed inside a space vector diagram of five-level inverter that is shown in Figure 2.12. SVM is a high frequency modulation alternative to PWM [11]. The space vector diagram consists of six sectors and every corner represents a switching state for inverter. Each phase leg of inverter includes four switching devices and has two different switching states [3]. In subhexagon 1, each of the sectors is a triangle shape and starting from the middle is 000 or 111. The corner of triangle has different switching states which are from 001 to 110. For subhexagon 3, the middle is 330 while the edges values are 440 and 430.

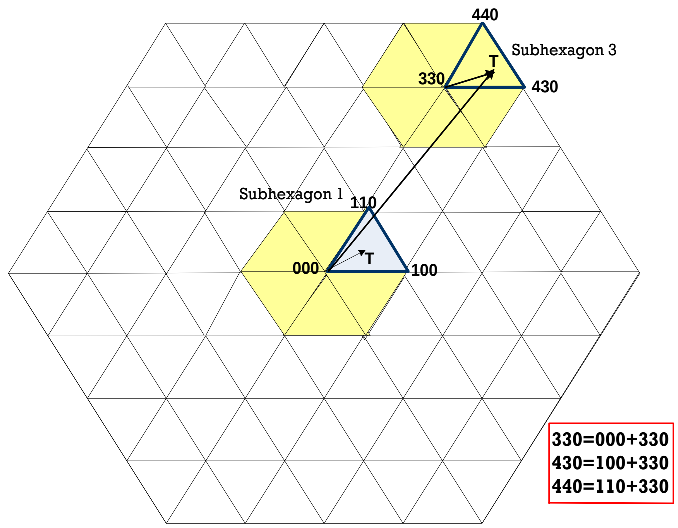

Figure 2.12 : Space vector diagram for five-level inverter

Space vector control (SVC) is a low or fundamental frequency space vector modulation method which opposite to SVM. It generates the desired mean load voltage value in every switching interval. However, the errors will be small in comparison to the reference vector for inverters with a higher number voltage level [11].

The first principle of this method is identification of the center of sub-hexagon that contains the tip of the reference space vector. Second, the reference space vector is mapping to a sector of the inner sub hexagon. Next, the duration of switching vectors and optimum switching sequence are determined by using two level algorithms. The generation of the actual switching vectors for the multilevel inverter by adding the vector at the center of the sub-hexagon to the vector obtained in two-level algorithm [12].

2.4.2 Sinusoidal Pulse Width Modulation

Sinusoidal Pulse Width Modulation (SPWM) is a common technique used for inverter. A sinusoidal control signal at the specific frequency is compared with a triangular waveform to output a sinusoidal waveform. The triangle waveform, V_{tri} is at switching frequency, *fs* which this frequency controls the inverter switches are turned off and on. Moreover, The control signal, $V_{control}$ has a frequency f_1 and is used to modulate the switch duty ratio. It will contains harmonics at switching frequency since the output of the inverter is affected by switching frequency. Amplitude modulation, m_a is the duty cycle of one of the inverter switches [10].

The comparison of $V_{control}$ and V_{tri} is shown as below.

For $V_{control} > V_{tri}$,

$$V_A = \frac{V_{dc}}{2} \tag{2.1}$$

For $V_{control} < V_{tri}$,

$$V_A = -\frac{V_{dc}}{2} \tag{2.2}$$

The amplitude modulation ratio, m_a and the frequency modulation ratio, m_f is calculated using the equations below.

$$m_a = \frac{peak\ amplitude\ of\ V_{control}}{amplitude\ of\ V_{tri}} \tag{2.3}$$

$$m_f = \frac{PWM\ frequency, f_s}{fundamental\ frequency, f_1} \tag{2.4}$$

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The frequency modulation, m_f should be an odd integer. If the m_f is not an integer, there may exist subharmonics at output voltage. If the m_f is not an odd number, DC component may exist and even harmonics are present at output voltage [13]. There are two types of SPWM techniques which are SPWM with bipolar switching and SPWM with unipolar switching [13].

2.4.2.1 Sinusoidal Pulse Width Modulation with Bipolar Switching

The PWM bipolar switching compares between the reference voltage waveform, V_r with the triangular carrier signal, V_c by comprise of a comparator and it will produce the bipolar switching signal. The bipolar generator is shown in Figure 2.13 [13].

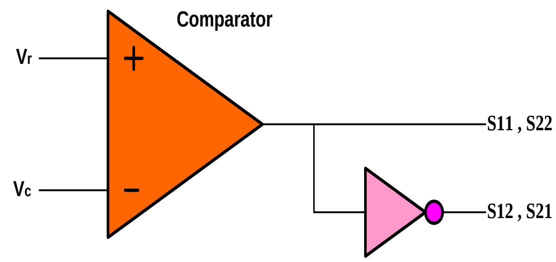

Figure 2.13 : SPWM bipolar generator

Figure 2.14 (a) shows the waveform of bipolar switching SPWM for reference and triangular waveform. Figure 2.14 (b) is the output waveform of 5-level inverter.

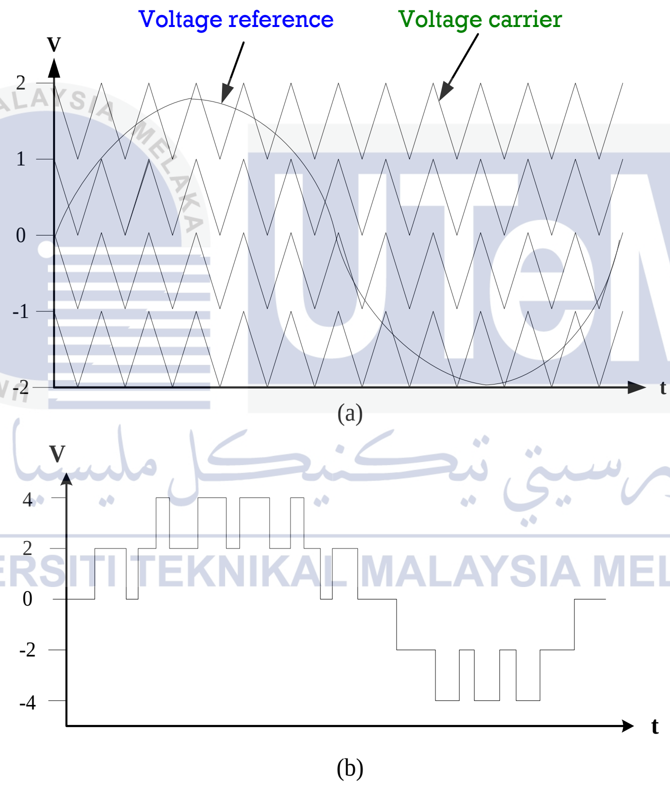

Figure 2.14 : Waveform of bipolar switching SPWM for (a) reference and triangular waveform (b) output waveform

The output of leg A is same and opposite to the output of leg B. The output voltage is determined to get the switching pulses for the devices, switching pattern and output waveforms by comparing the control signal and triangular signal [13].

For $V_r > V_c$,

$$S_{11}\ on\ ;\ V_A = \frac{V_d}{2} \tag{2.5}$$

$$S_{22}\ on\ ;\ V_B = -\frac{V_d}{2} \tag{2.6}$$

For $V_r < V_c$,

$$S_{12}\ on\ ;\ V_A = -\frac{V_d}{2} \tag{2.7}$$

$$S_{21}\ on\ ;\ V_B = \frac{V_d}{2} \tag{2.8}$$

Hence,

$$V_b(t) = V_a(t) \tag{2.9}$$

2.4.2.2 Sinusoidal Pulse Width Modulation with Unipolar Switching

The triangular carrier waveform is compared with two reference signals which are positive and negative signal in this SPWM unipolar switching. The generator of unipolar SPWM uses another comparator to compare between inverse reference waveform, $-V_r$ with the triangular waveform, *Vc*. The unipolar voltage switching signal is produced by comparing these two signals. In addition, the output voltage is switching by unipolar voltage between 0 and V_{dc} or is halved in unipolar cases from 2 V_{dc} to V_{dc}. The load is doubled and the voltage pulse is halved result in the effective switching frequency. The harmonic content of the output voltage waveform is reduced compare to bipolar SPWM. Besides that, the amplitude of the significant harmonics and its sidebands is much lower for all modulation indexes. Hence, it makes the harmonic easy to be filtered with its size being significantly smaller [13]. The SPWM unipolar generator is shown in Figure 2.15.

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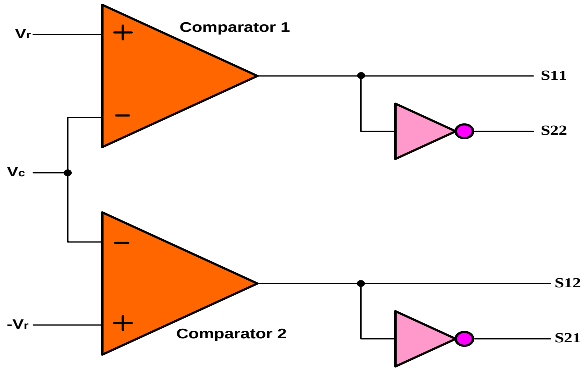
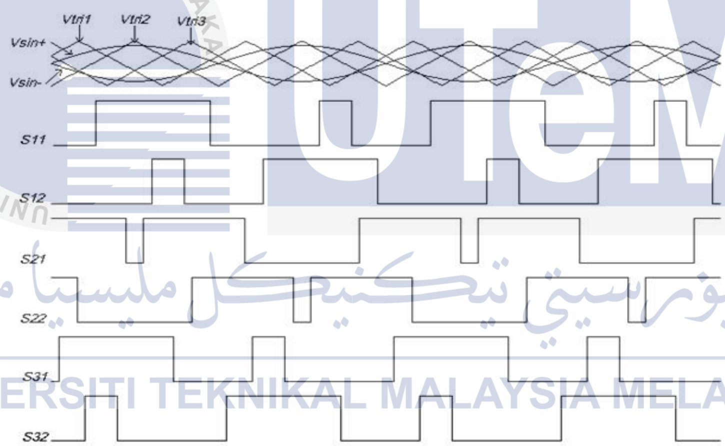
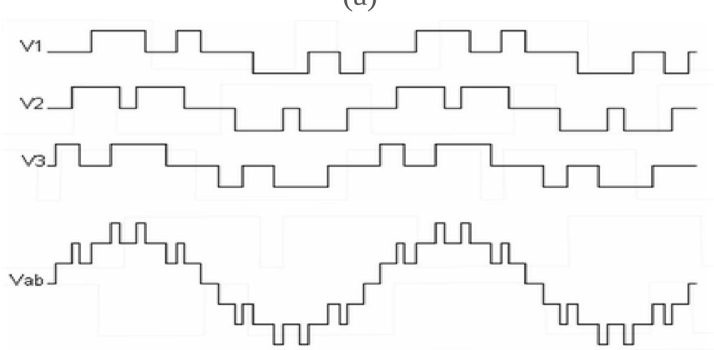


Figure 2.15 : SPWM unipolar generator

Figure 2.16 shows the waveform of unipolar switching SPWM. In Figure 2.16 (a), it shows the reference and triangular waveform for unipolar switching SPWM and the gating pulse of S11, S12, S21, S22, S31 and S32. The Figure 2.16 (b) shows the output waveform using unipolar switching.



(a)



(b)

Figure 2.16 : Unipolar switching SPWM (a) reference and triangular waveform and gating pulse of S1 to S3 (b) output waveform

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2.4.3 Selective Harmonic Elimination Pulse Width Modulation

Among all the PWM techniques, SHE-PWM can theoretically provide the highest quality output. This technique has been a research topic since the early 1960's [14]. In 1973, SHE-PWM technique is introduced by Patel and Hoft [15]. The idea of this technique is that the square-wave output is "chopped" a number of times which are obtained by proper off-line calculation. A look-up table is used to store the result or the result can be interpolated by simple function for real time operation [16]. SHE-PWM technique is a low switching frequency strategy. It uses calculated switching angles to eliminate certain harmonics in the output voltage. The amplitude of any odd harmonic in the output signal can be calculated with the Fourier Series analysis [11]. The switching angles are chosen to set the fundamental to the wanted output amplitude while the other harmonic is set to zero which is shown in Figure 2.17. The switching angles must be lower than $\pi/2$ degrees and m harmonic components can be affected for m number of switching angles, where $m-1$ number harmonic can be eliminated. On the other hand, a correct output would not be achievable if the angles are larger than π. For an n levels inverter,

$$m = \frac{n-1}{2} \tag{2.10}$$

Additional filters added between the inverter and the load if needed can filter out the higher harmonics. For an example, a five-level inverter has $m=2$ and this means it has two switching angles available. $m-1=1$ angle can be used for harmonic component elimination [11]. In Figure 2.18, the first angle, α_1 is set to modulate the fundamental signal amplitude. The second angle, α_2 is set to eliminate a chosen harmonic distortion.

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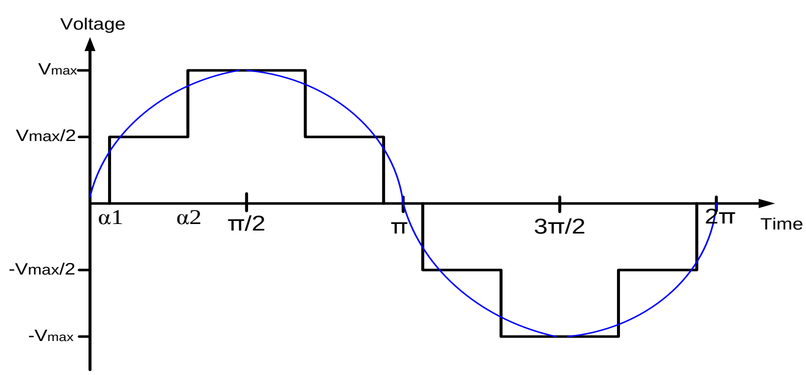

Figure 2.17: Switching with angle determined for five-level inverter by SHE

2.4.3.1 Fourier Series of Selective Harmonic Elimination Pulse-Width Modulation Waveform

The DC component and the even harmonics are equal to zero due to the odd quarter-wave symmetry. The Fourier Series is presented for three-level SHE-PWM as follows:

$$V_{out}(\omega t) = \sum_{n=1}^{\infty} a_n \sin(n\omega t) \tag{2.11}$$

where

$$a_n = \frac{4E}{n\pi}\sum_{k=1}^{N}(-1)^{k+1}\cos(n\alpha_k)\text{ , for odd n} \tag{2.12}$$

N is the number of switching angles per quarter and α_k is the switching angles which must satisfy the following conditions:

$$\alpha_1 < \alpha_2 < \cdots < \alpha_N < \frac{\pi}{2}$$

E is the amplitude of DC source while n is the harmonic order.

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2.4.3.2 Newton's Method for Selective Harmonic Elimination Pulse-Width Modulation Switching Angles

From $a_n = \frac{4E}{n\pi}\sum_{k=1}^{N}(-1)^{k+1}\cos(n\alpha_k)$, the nonlinear equation system of SHE-PWM can be written as below:

$$\cos(\alpha_1) - \cos(\alpha_2) + \cdots \pm \cos(\alpha_N) = \frac{\pi}{4}M \tag{2.13}$$

$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cdots \pm \cos(3\alpha_N) = \frac{3\pi}{4E}h_3 \tag{2.14}$$

$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cdots \pm \cos(5\alpha_N) = \frac{5\pi}{4E}h_5 \tag{2.15}$$

$$\vdots$$

$$\cos(N\alpha_1) - \cos(N\alpha_2) + \cdots \pm \cos(N\alpha_N) = \frac{N\pi}{4E}h_n \tag{2.16}$$

where *M* is the modulation index and $M = h_1/E$.

The cosine terms of α_N are negative for even N while α_N are positive for odd N. According to the above nonlinear system, *N-1* surplus harmonic can be eliminated from the output waveform by setting the equations to zero.

$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cdots \pm \cos(3\alpha_N) = 0 \tag{2.17}$$

$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cdots \pm \cos(5\alpha_N) = 0 \tag{2.18}$$

$$\vdots$$

$$\cos(N\alpha_1) - \cos(N\alpha_2) + \cdots \pm \cos(N\alpha_N) = 0 \tag{2.19}$$

The lowest odd harmonic components need to be eliminated from a single phase system whereas the lowest non-triplen harmonic components are eliminated in three phase system. Generally, all triplen-harmonics in line-to-line voltage will be eliminated by 120 electrical degree phase shift characteristic [16].

There are several steps to calculate the angle α using Newton-Raphson. Step 1 is to find the switching angle matrix.

$$\alpha^j = [\alpha_1{}^j, \alpha_2{}^j, \alpha_3{}^j, \ldots, \alpha_N{}^j] \tag{2.20}$$

Step 2 is to determine the nonlinear system matrix.

$$F^j = \begin{bmatrix} \cos(\alpha_1{}^j) - \cos(\alpha_2{}^j) + \cdots \pm \cos(\alpha_N{}^j) \\ \cos(3\alpha_1{}^j) - \cos(3\alpha_2{}^j) + \cdots \pm \cos(3\alpha_N{}^j) \\ \vdots \\ \cos(N\alpha_1{}^j) - \cos(N\alpha_2{}^j) + \cdots \pm \cos(N\alpha_N{}^j) \end{bmatrix} \tag{2.21}$$

$$\left[\frac{\partial f}{\partial \alpha}\right]^j = \begin{bmatrix} -\sin(\alpha_1{}^j) & +\sin(\alpha_2{}^j) & -\ldots & \pm\sin(\alpha_N{}^j) \\ -3\sin(3\alpha_1{}^j) & +3\sin(3\alpha_2{}^j) & -\ldots & \pm 3\sin(3\alpha_N{}^j) \\ & \vdots & & \\ -N\sin(N\alpha_1{}^j) & +\mathrm{N}\sin(N\alpha_2{}^j) & -\ldots & \pm N\sin(N\alpha_N{}^j) \end{bmatrix} \tag{2.22}$$

Next, step 3 is to get the corresponding harmonic amplitude matrix.

$$T = \begin{bmatrix} \frac{M\pi}{4} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.23}$$

Thus, the equation can be written as

$$F(\alpha) = T \tag{2.24}$$

From equation 2.22 and 2.24, calculates the $\Delta\alpha$ that shown as following

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$$\left[\frac{\partial f}{\partial \alpha}\right]^j [\Delta\alpha]^j = -F^j \tag{2.25}$$

After solved the equation 2.25, the new approximate solution is obtained from

$$\begin{aligned} \alpha_{1,j+1} &= \alpha_{1,j} + \Delta\alpha_1 \\ \alpha_{2,j+1} &= \alpha_{2,j} + \Delta\alpha_2 \\ &\vdots \\ \alpha_{n,j+1} &= \alpha_{n,j} + \Delta\alpha_n \end{aligned} \tag{2.26}$$

The iteration will stop when exact solution is obtained which means that the value of α is such that F(α)=0. Next, the iteration will also be stopped when the value get is smaller than a specific value, $\boldsymbol{\varepsilon}$ as given by

$$\left|\frac{\alpha_{j+1} - \alpha_j}{\alpha_j}\right| \leq \varepsilon \tag{2.27}$$

2.4.3.3 Advantages and Disadvantages of Selective Harmonic Elimination-Pulse Width Modulation

SHE-PWM has several advantages compared to traditional modulation techniques. It has acceptable performance with low switching frequency to fundamental frequency ratios [11]. The lower harmonics can be eliminated in reducing harmonic interference to system. Next, SHE-PWM can direct control over output waveform harmonics. It also has the ability to leave triplen harmonics uncontrolled to take the advantage of circuit topology in three phase systems [11]. Due to these advantages, the SHE-PWM technique provides high quality output for multilevel inverter.

Although SHE-PWM is a good and efficient technique to be chosen but it also has the drawbacks. The drawback of SHE-PWM technique is a heavy computational burden and a complicated hardware [11]. Besides that, the look-up table requires large memory space if the number of switching angle is increased [16]. The use of SHE-PWM is somewhat hindered due to the difficulty to calculate the switching angle. This is because the equations are nonlinear and restricting it to numerical methods such as Newton-Raphson algorithm [17].

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2.4.4 Quasi Square Wave

Quasi square wave is a modified square wave that has a dead space or step between square waves. It can used to reduce the harmonic or distortion that bring problem to electrical devices. Each quasi-square wave provides two degree of delay angle and phase. Figure 2.18 shows the quasi-square wave waveform [18]. The α is the dead space between square waves and there has two delay angle in a half cycle waveform.

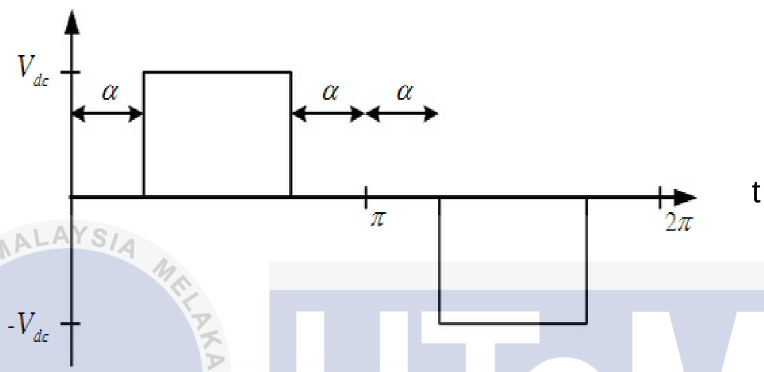

Figure 2.18 : Quasi-square wave waveform [17]

The calculation of quasi-square wave is as follows.

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$$a_n = 0 \tag{2.28}$$

$$b_n = 2\left[\frac{1}{\pi}\int_{\alpha}^{\pi-\alpha} V_{dc}\sin(n\theta)\,d\theta\right] \tag{2.29}$$

$$= \frac{2V_{dc}}{n\pi}\left[-cosn\theta\Big|_{\alpha}^{\pi-\alpha}\right] \tag{2.30}$$

$$= \frac{2V_{dc}}{n\pi}[\cos(n\alpha) - cosn(\pi-\alpha)] \tag{2.31}$$

The $a_n = 0$ is because the half wave is symmetry.

If n is even, $b_n = 0$;

If n is odd, $b_n = \frac{4V_{dc}}{n\pi}\cos(n\alpha)$;

Therefore, the amplitude of the fundamental is $b_1 = \frac{4V_{dc}}{n\pi}\cos(\alpha)$.

For the harmonic elimination, the *n* harmonic will be eliminated if

$$\alpha = \frac{90°}{n} \tag{2.32}$$

Although quasi-square wave can eliminate selected harmonic at low frequency by using the calculation but it only can eliminate one harmonic in one time. Hence, this is the disadvantage of the quasi-square wave method compare to SHE-PWM.

2.5 Harmonic Distortion

Harmonic distortion is the deviation of the voltage and current waveforms from sinusoidal. Harmonic is caused by nonlinear loads. When nonlinear loads draw nonsinusoidal current from a sinusoidal voltage source, harmonic is created. It is generated with purpose by active components. Harmonic distortion is caused by nonlinear devices where driven frequency is the power system fundamental component, f_0 [19]. The supply of power to non-linear loads causes the flow of harmonic currents while the voltage harmonics are caused by the flow of harmonic currents through the impedance of the supply circuits [20]. There is a limit for THD which is 5% for voltage THD and 3% for any single harmonic according to IEEE Std 519.

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2.5.1 Calculation of Total Harmonic Distortion

Total Harmonic Distortion (THD) can be defined as the level of harmonic distortion or the degree of harmonic content in an alternating signal. It is used to measure the quality of waveform [20]. This term has come into a common usage to define either voltage or current distortion factor [21]. It is defined by

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} {y_h}^2}}{y_1} \tag{2.33}$$

Generally, harmonic distortion is expressed as a percentage. THD can divides into two types which are THD of current, THDi and THD of voltage, THDv [17]. When dealing with current harmonics, the equation is

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} {I_h}^2}}{I_1} \tag{2.34}$$

When the total *rms* value is known, the above equation can be written as

$$THD_i = \sqrt{\left(\frac{I_{rms}}{I_1}\right)^2 - 1} \tag{2.35}$$

When dealing with voltage harmonics, the equation is

$$THD_u = \frac{\sqrt{\sum_{h=2}^{\infty} {U_h}^2}}{U_1} \tag{2.36}$$

2.5.2 Types of Harmonic

The harmonic emission of power electronic components can be categorized into characteristic and non-characteristic harmonics. The converter topology and switching pattern applied can used to determine the characteristic harmonic emissions. The switching frequency, f_c divided by the power system fundamental frequency f_o is defined as the modulation frequency, m_f [19]. In a six-pulse converter, the characteristic harmonics are non-triple odd harmonics such as 5th, 7th, 11th and 13th [21]. On the contrary, non-characteristic harmonics do not related to the converter topology. It is determined by the operating point and control scenario of the individual converter [19]. This results in beat frequencies and a demodulation of characteristic harmonics and the fundamental. In addition, it will cause an imbalance in AC power system, asymmetrical delay angle or cycloconverter operation [21].

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2.5.3 Effects of Harmonic

In power electronics system, harmonics will reduce power quality and increase power losses. Besides that, harmonics can affect the ageing of equipment which causes the equipment breakdown easily. It disturbs the operation of sensitive loads such as regulation systems, computer equipment, control and monitoring systems. Furthermore, harmonics cause overloads on installation equipment which will lead to nuisance tripping and installation

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breakdown [20]. Hence, harmonics should be reduced to improve the efficiency and quality of power system.

Harmonics also bring to economic impact in which overloads on the distribution system mean the level of subscribed power must be added. Thus, additional losses are produced unless the installation can be upgraded. The current distortion can cause tripping and breakdown of production equipment. All these causes may lead to extra costs in equipment maintenance or replacement drops in productivity and higher energy bills. This has contributed to reducing the competitiveness of companies and indirectly affects the economic [20].

In motor application, the harmonics will create a negative torque on motors running which it will consumes more electrical energy to overcome the counter torque. Triple harmonics that are present in the motor will cause a current to flow in neutral wire. This means the neutral wire has to be oversized. Besides that, the presence of harmonic has increased the operating temperature of the motor [7]. This heating effect most often reduce the equipment's lifespan and disturb the smoothly operation of the equipment.

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2.5.4 Indicators for Measurement Principles

The power factor is the ration of active power, P and apparent power, S which. It can also use cos α to find the power factor which is defined by the following equation.

$$PF = \frac{P}{S} \tag{2.37}$$

$$\cos\alpha = \frac{P_1}{S_1} \tag{2.38}$$

where P_1 is the fundamental active power and S_1 is the fundamental apparent power.

When harmonic exists, the measured power factor is not equal to *cos α*. For an example, the power factor is less than *cos α*. This is an initial indication that significant the presence of harmonic.

The active power, P of a signal that contains harmonic distortion is the sum of active powers corresponding to the voltages and currents in the same frequency order. If there is no harmonic distortion in that signal, the $cos\varphi_1$ will equal to $cos\ \varphi$. The equation can be written as

$$P = \sum_{h=1}^{\infty} V_h I_h cos\varphi_h \tag{2.39}$$

where φ_h is the displacement between voltage and current of h order harmonic.

In apparent power, S is given by

$$S = V_{rms} I_{rms} \tag{2.40}$$

With the presence of harmonics, the equation will changes to

$$S^2 = \left(\sum_{n=4}^{\infty} {V_h}^2\right)\left(\sum_{n=1}^{\infty} {I_h}^2\right) \tag{2.41}$$

Consequently, the equation of $S^2 = P^2 + Q^2$ is no longer valid in the presence of harmonics. The distortion power, D is defined as

$$S^2 = P^2 + Q^2 + D^2 \tag{2.42}$$

$$D = \sqrt{S^2 - P^2 - Q^2} \tag{2.43}$$

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CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the flowchart, milestone and Gantt chart will be developed. Next, the SHE-PWM technique for three phase multilevel inverter is discussed and explained in this chapter. Besides that, simulation of single phase square wave, SHE-PWM, unipolar and bipolar will be discussed and the simulink block diagram of each technique is shown. Moreover, the simulation of three phase multilevel inverter for SHE-PWM and trinary are discussed with the simulink block. All the techniques will be tested for different loads which are R, RL and RC.

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3.2 Research Methodology

In this research, the methodology will be explained by using flowchart, milestone and Gantt chart. The flowchart will shows the flow of progress that carried out for this project. Next, the activities of this research are shown by using milestone while the timeline for the activities is shown in Gantt chart.

3.2.1 Flowchart

The flowchart shown in Figure 3.1 is described about the flow of methodology that carried out through this research. It is divided into a few phases to be more systematically and detail which discussed as following.

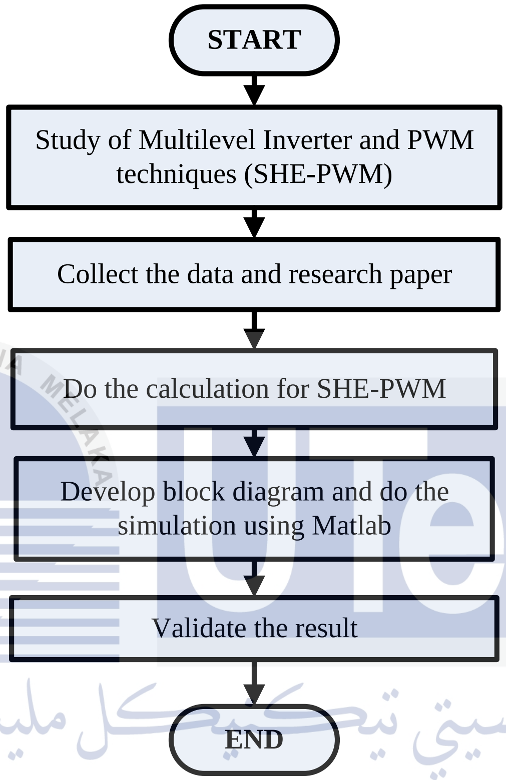

Figure 3.1 : Flowchart of the SHE-PWM

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Phase 1: Study about the multilevel inverter and PWM techniques

In this phase, it is the beginning of the project which study about the concept and theory of multilevel inverter and the PWM switching method such as SHE-PWM. The SHE-PWM will be discussed in detail and the calculation for this method is shown. Besides that, the harmonic and its effect also will be studied in this research.

Phase 2: Collect data and research paper

The data and research paper that related to SHE-PWM for multilevel inverter are collected and studied.

Phase 3: Do the calculation for SHE-PWM

After the study of multilevel inverter and its control scheme of SHE-PWM, the switching angles for this technique is needed to calculate for elimination of selected harmonic. The calculations used in this method are Fourier Series and Newton-Raphson analysis.

Phase 4: Develop block and simulate the SHE-PWM for multilevel inverter

In Phase 4, the SHE-PWM for multilevel inverter is developed and designed using simulink of MATLAB program. Then, it will be simulated to get the current and voltage waveform for different loads such as R, RL and RC.

Phase 5: Validate the results

When the simulation is done, the results is collected and analysed. The current and voltage waveform that produced in the output of multilevel inverter is shown and the total harmonic distortion (THD) will also be discussed and analysed. The result is compared and satisfied whether the objective of this research has achieved.

3.2.2 Milestone Research

Milestone 1: Research and study on multilevel inverter.

Milestone 2: Collect data and research paper.

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Milestone 3: Calculate the switching angles for SHE-PWM

Milestone 4: Develop simulink block of SHE-PWM for multilevel inverter

Milestone 5: Simulate the SHE-PWM for multilevel inverter

Milestone 6: Collect and analyse the result

Milestone 7: Validate the result

Milestone 8: Report Writing

3.2.3: Gantt Chart

Table 3.1 : Timeline for milestone

Milestone	Year/Semester																											
	2013														2014													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Research and study on multilevel inverter																												
Collect data and research paper																												
Calculate the switching angles for SHE-PWM																												
Develop simulink block of SHE-PWM for multilevel inverter																												
Simulate the SHE-PWM for multilevel inverter																												
Collect and anlyse the result																												
Validate result																												
Report Writing																												
Submit Report																												

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From Table 3.1, the research and study on multilevel inverter will be carried out from week 1 until week 7 in 2013. From week 3 to week 7 of year 2013, the first activity will be done is to collect the data and research paper for multilevel inverter and its control schemes. Next, the switching angles for SHE-PWM will be calculate at the period of week 5 to week 10 in the same year. After that, the simulink block of SHE-PWM for multilevel inverter will be developed in week 7 to week 14 of year 2013 and week 1 to week 4 of year 2014. At the same time, the simulink block will be simulated. The results from simulation is collected and analysed at week 3 to week 7 in year 2014. Lastly, for week 5 until week 9 in year 2014, the result is validated and record in report. The time for report writing is long which is from week 7 year 2013 until week 13 year 2014. The report will be submitted on week 14.

3.3 Selective Harmonic Elimination Pulse-Width Modulation for Three Phase Multilevel Inverter

SHE-PWM technique is an effective method to eliminate the selected harmonic at lower frequency or harmonic order in inverter which is difficult to eliminate by using passive filter. The technique is further extended to be used in multilevel inverter. In addition, this multilevel SHE-PWM technique provides highest output power quality at low switching frequencies among the other PWM techniques.

In SHE-PWM techniques, Fourier Series and Newton-Raphson analysis is used to calculate the switching angles. The simple algebraic equations that calculated the switching angles are formed according to the given modulation index. These equations use pre-calculated switching angles according to predefined criteria. Since the equations can be solved by using microprocessor or digital signal processors, the look up table no longer needed.

In this study, the solution of multi-variable constrained optimization problems can be solved by using MATLAB or optimization toolbox. It is an very useful software in optimization problem. The algorithm for determination of α and β values is discussed and shown. As there is no triplen harmonics in three phase star connected system, there is no need to extend the algorithm to eliminate the triple harmonics in the solution of nonlinear equation set.

For the determination of switching angles during real time operation is considered to be impractical. The switching angles can easily determined by look up table. The look up table stores switching angles corresponding to the modulation index. However, the memory of look up table occupies large space and makes the algorithm very long. Hence, another technique that used to determine the switching angles is by Fourier Series and Newton-Raphson analysis. Figure 3.2 shows the flowchart for three-phase SHE-PWM multilevel inverter using this algorithm.

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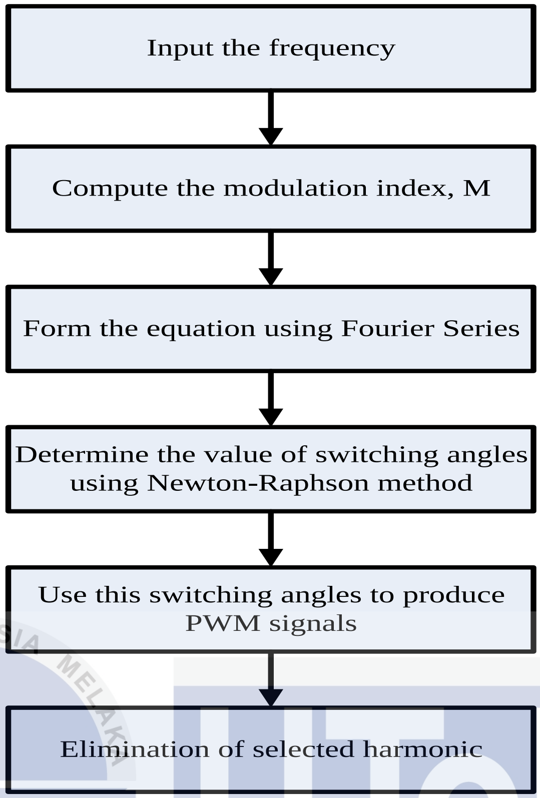

Figure 3.2 : Flowchart of SHE-PWM algorithm

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3.4 Simulation of Single Phase Inverter

A simulation of single phase inverter is produced and shown as below. The single phase inverter will be tested for several loads such as R, RL and RC loads that are connected in series. The parameter of the simulation is shown in Table 3.2.

Table 3.2 : Parameter of the simulation

Parameter	**Value**
Voltage	100V
Frequency	50Hz
Resistance, R	100Ω
Inductance, L	0.2H
Capacitance, C	30μF

3.4.1 Square Wave Inverter

Square wave inverter is the basic type of inverter which has an output is an alternating square wave. It can be simplified or justified with a switching scheme of full bridge inverter. Figure below shows the simulation block of square wave inverter using R load. The value of resistance, R used in square wave inverter is 100 Ω while the value of inductor, L is 0.2 H. The value for capacitance, C is 30 µF used in square wave inverter. Besides that, the supply voltage, V_1 in this simulation is 100 V for every load. The load will be changed for RL and RC load respectively. The simulink block diagram of square wave inverter is shown in Figure 3.3.

In the simulation, a PWM generation is connected to single phase H-bridge inverter subsystem. A supply voltage and load of R or RL or RC are also connected to the subsystem. The output current and voltage waveform will be displayed by using the scope. In addition, the PWM switching signals also shown in the other scope.

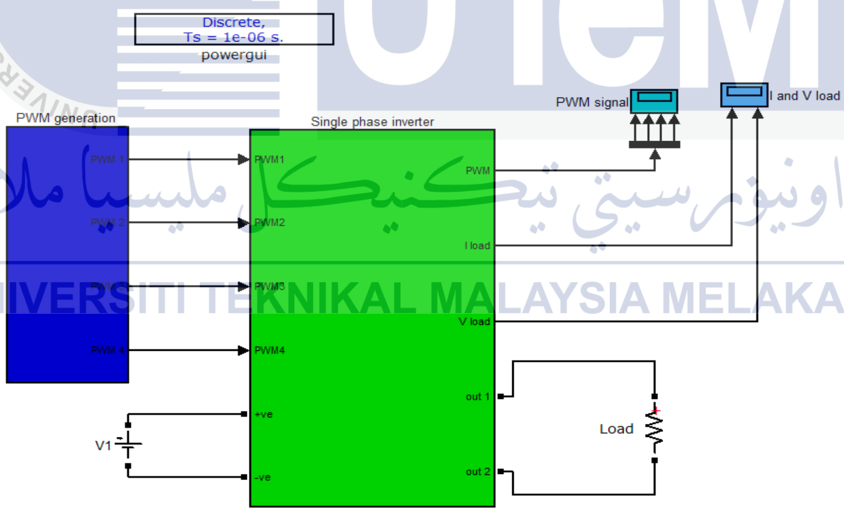

Figure 3.3 : Simulink block for single phase square wave inverter using R load

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3.4.2 Unipolar Inverter

In this unipolar switching scheme, it is based on the comparison of the two modulation signals with a frequency triangular wave. Figure 3.4 shows the simulation block of unipolar inverter while Figure 3.5 shows the simulink block of unipolar inverter for R load. The value of resistance, R used in square wave inverter is 100 Ω while the value of inductor, L is 0.2 H. The value for capacitance, C is 30 μF used in square wave inverter. Besides that, the supply voltage in this simulation is 100 V for every load. The load will be changed for RL and RC load respectively.

In the simulation, a sine wave and a repeating sequence is connected to a PWM generation. The PWM generation is different from the unipolar in the switching scheme. Then, it will connect to a single phase H-bridge inverter subsystem. A supply voltage and load of R or RL or RC are also connected to the subsystem. The output current and voltage waveform will displayed by using the scope. In addition, the PWM switching signal also showed in another scope.

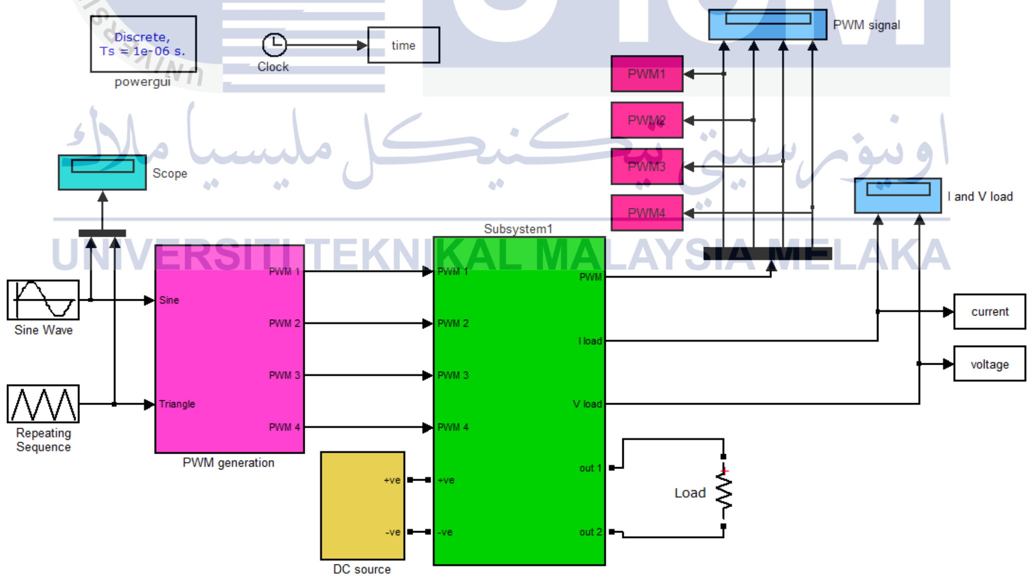

Figure 3.4 : Simulink block for single phase unipolar inverter using R load

In the power generation connection, a sine input and a triangular input is connect to two comparator which the sine wave signal will compare with the triangular wave signal by subtract both value. The triangular input is compared with two sine inputs. There are four outputs produced in this power generation block.

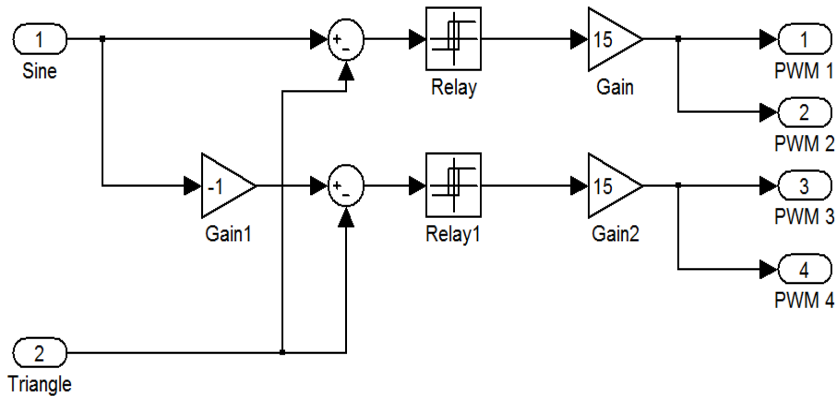

Figure 3.5 : Power generation of single phase unipolar inverter

3.4.3 Bipolar Inverter

Bipolar switching scheme is the diagonally opposite transistors which turned on or turned off at the same time. The output voltage is determined by comparing the control signal and the triangular signal to get a switching pulse. In the simulation, the bipolar inverter block diagram is same as the unipolar inverter. However, the power generation of bipolar is different from unipolar which is shown in Figure 3.6.

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The value of resistance, R used in square wave inverter is 100 Ω while the value of inductor, L is 0.2 H. The value for capacitance, C is 30 μF used in square wave inverter. Besides that, the supply voltage in this simulation is 100 V for every load. The load will be changed for RL and RC load.

In bipolar power generation, there are one sine input and triangular input connected to a comparator which both of the input value will be subtracted to get the output. There are four output produced in this power generation. The bipolar power generation is different with the unipolar is it only compare one sine wave with one triangular wave.

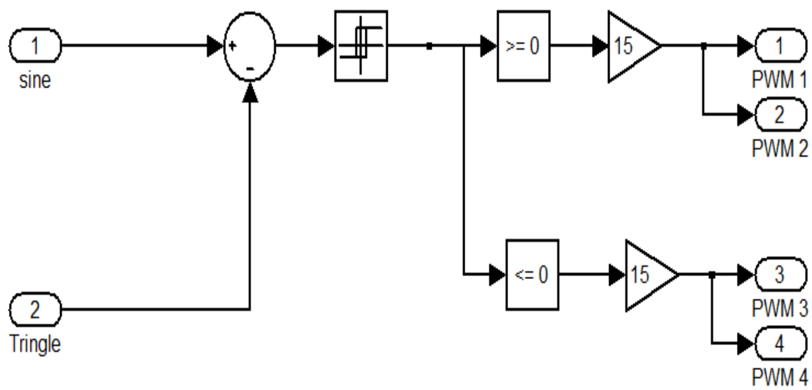

Figure 3.6 : Power generation for single phase bipolar

3.4.4 Selective Harmonic Elimination Pulse-Width Modulation Inverter

SHE-PWM is a technique that can be used to select which of the harmonic need to be eliminated. Figure 3.7 shows the simulation block of SHE-PWM inverter for RC load. The value of resistance, R used in square wave inverter is 100 Ω while the value of inductor, L is 0.2 H. The value for capacitance, C is 30 µF used in square wave inverter. Besides that, the supply voltage in this simulation is 100 V for every load. The load will be changed for R and RL load.

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In the simulation, a subsystem that contains of five pulse generator is connected to a single phase H-bridge inverter subsystem. A supply voltage and load of R or RL or RC are also connected to the subsystem. The output current and voltage waveform will be displayed by using the scope. The switching angle, α is obtained by using Newton-Raphson and Fourier Series. Refer to Appendix A for the calculation of the angles $(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5)$ using m-file.

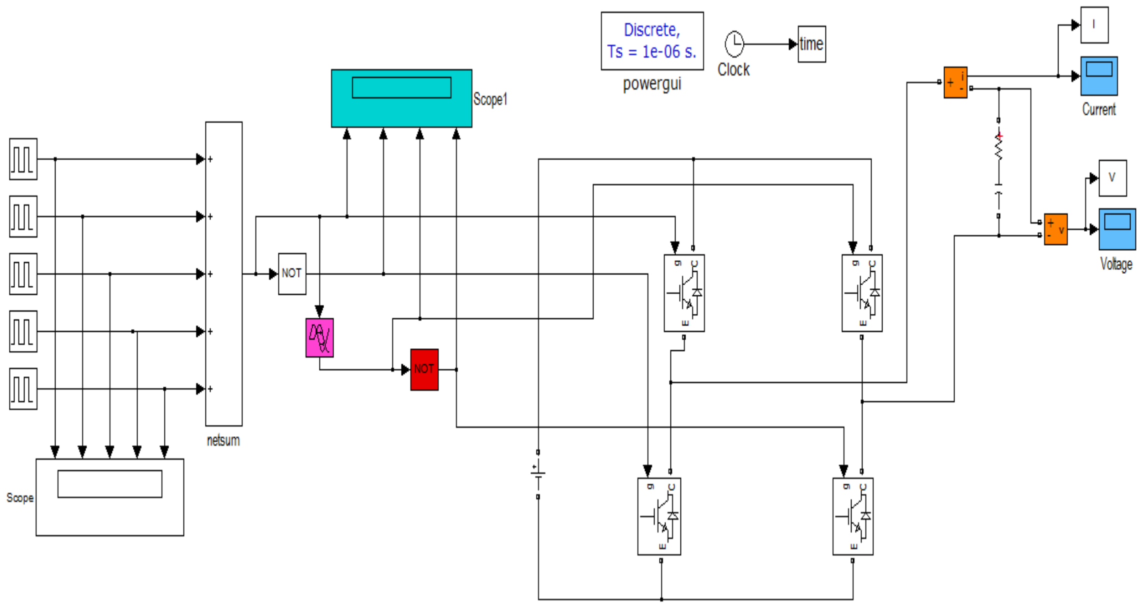

Figure 3.7 : Simulink block for single phase SHE-PWM inverter using RC load

3.5 Three Phase Simulation

The simulation of three phase multilevel inverter using different control schemes are produced which shown as below. Three phase multilevel inverters are tested using different loads which are R, RL and RC loads which are connected in series. The parameter of the simulation shows in Table 3.3.

Table 3.3 : Parameter of the simulation

Parameter	Value
Voltage	100V
Frequency	50Hz
Resistance, R	100Ω
Inductance, L	0.2H
Capacitance, C	30µF

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3.5.1 Three Phase Selective Harmonic Elimination Pulse-Width Modulation of Seven-Level Inverter

The simulation block of three phase SHE-PWM seven-level inverter is shown in Figure 3.8. The value of resistance, R used in SHE-PWM inverter is 100 Ω while the value of inductor, L is 0.2 H. The value for capacitance, C is 30 μF used in square wave inverter. Besides that, the supply voltage in this simulation is 100 V for every load. The load will be changed for RL and RC load.

The simulink consists of three phase block which are phase A, phase B and phase C. Each of these blocks is connected using two H-bridge inverter. The switching angles α and β are the inputs signal for the phase inverter blocks. The block is connected to the R, RL and RC load. The waveforms of line-current and line-voltage are display using the scope. Moreover, there is another scope used to measure phase voltage.

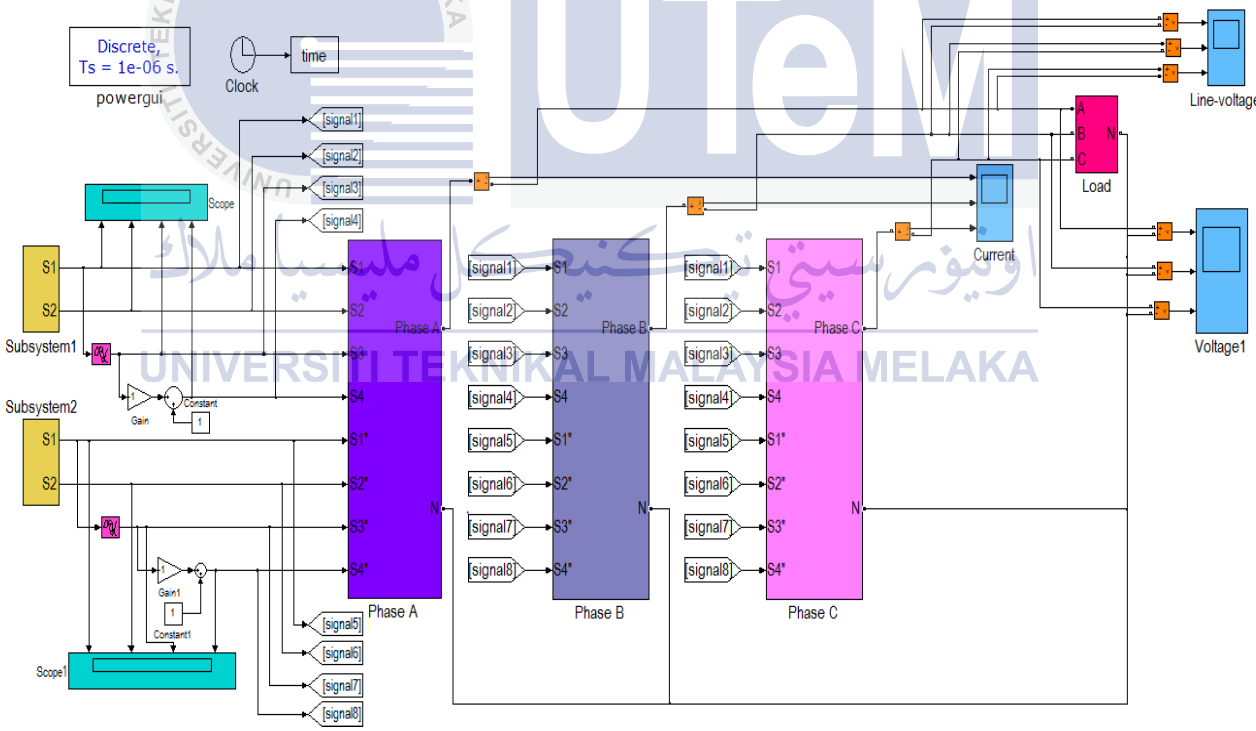

Figure 3.8 : Simulink Block of three phase SHE-PWM inverter

The Figure 3.9 shows the connection circuit of the subsystem block and Figure 3.10 is the connection for block phase A.

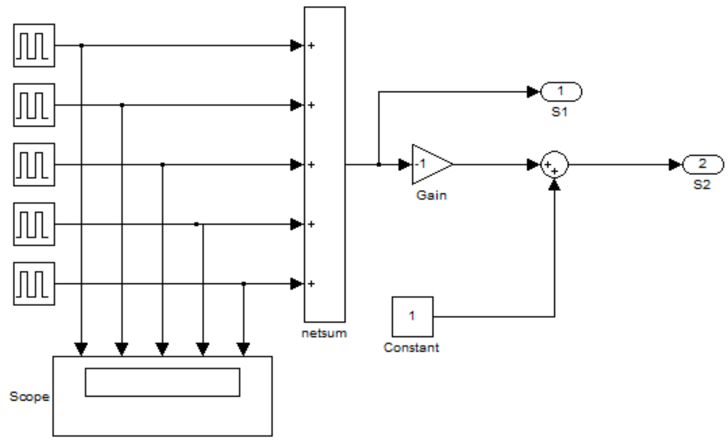

Figure 3.9 : Connection circuit of subsystem block

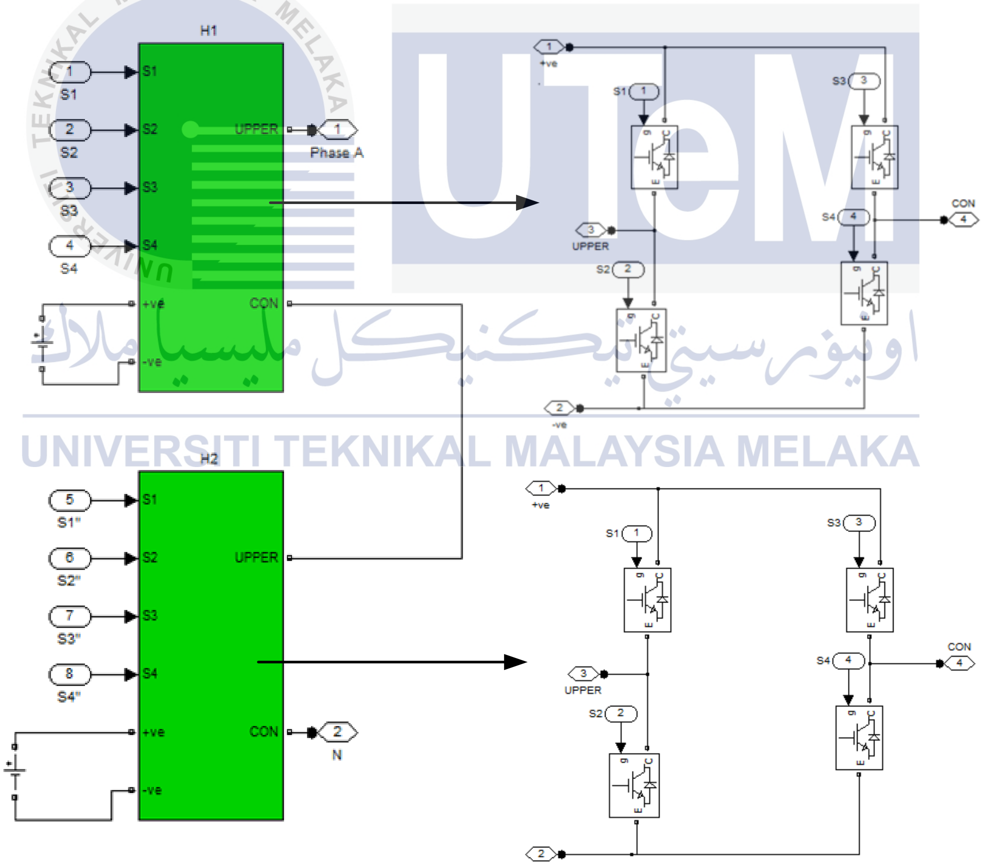

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Figure 3.10 : Connection of H-bridge in block of phase A

3.5.2 Three Phase Trinary Seven-Level Inverter

Three phase trinary seven-level inverter simulink block is shown in Figure 3.11. The value of resistance, R used in trinary multilevel inverter is 100 Ω while the value of inductor, L is 0.2 H. The value for capacitance, C is 30 μF used in square wave inverter. Besides that, the supply voltage in this simulation is 100 V for every load. The load will be changed for RL and RC load.

The three phase trinary multilevel is using three switching signal and three H-bridge connected with a load. There are 8 switching signals as the inputs of the H-bridge which their function are switch on or off the leg of H-bridge. Each of the H-bridge is connected with a voltage source separately.

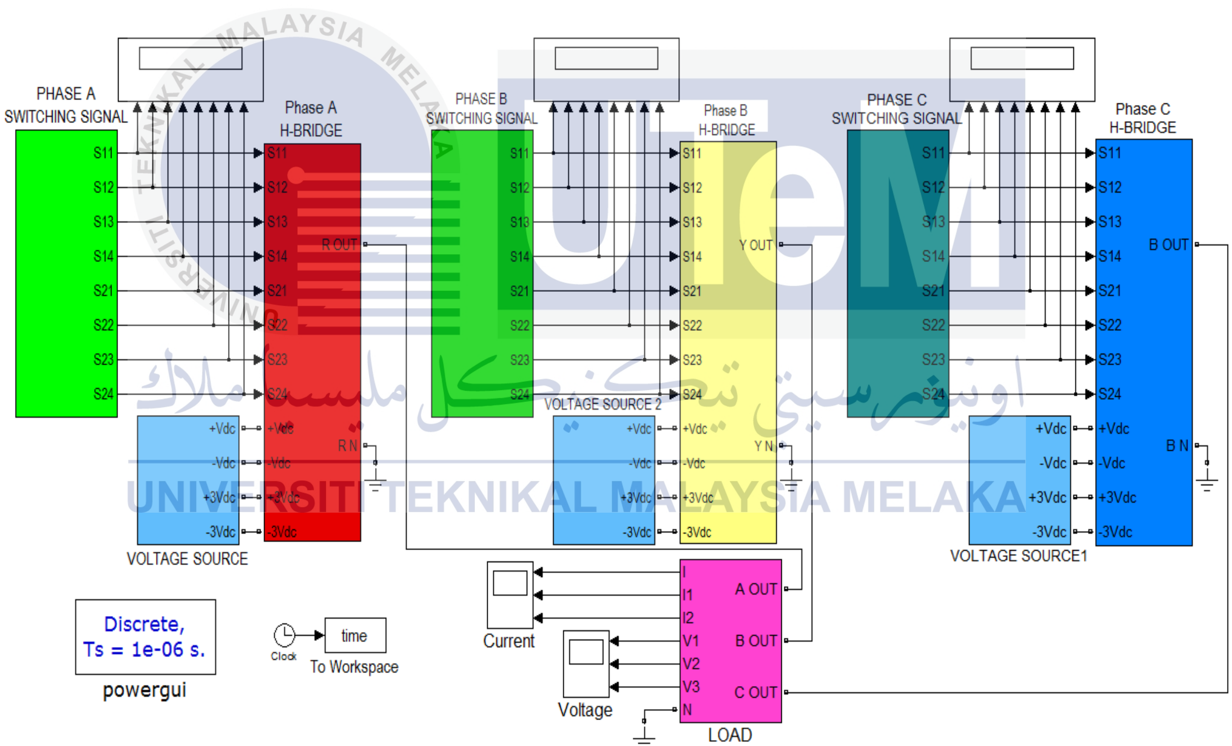

Figure 3.11 : Simulink block of three phase trinary inverter

3.6 Calculation of Selective Harmonic Elimination Pulse-Width Modulation

Let the modulation index, M=0.85. Then use Newton-Raphson shown below.

$$\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - \cos(\alpha_4) + \cos(\alpha_5) = \frac{\pi}{4} 0.85$$

$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) - \cos(3\alpha_4) + \cos(3\alpha_5) = 0$$

$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) - \cos(5\alpha_4) + \cos(5\alpha_5) = 0$$

$$\cos(7\alpha_1) - \cos(7\alpha_2) + \cos(7\alpha_3) - \cos(7\alpha_4) + \cos(7\alpha_5) = 0$$

$$\cos(9\alpha_1) - \cos(9\alpha_2) + \cos(9\alpha_3) - \cos(9\alpha_4) + \cos(9\alpha_5) = 0$$

After that, set an initial value j=0 and assume

$$\alpha^0 = [{\alpha_1}^0, {\alpha_2}^0, {\alpha_3}^0, {\alpha_4}^0, {\alpha_5}^0]^T$$

Then, linearize the equation and solve $d\alpha^0$

$$F^0 + \left[\frac{\partial f}{\partial \alpha}\right]^0 d\alpha^0 = T$$

$$d\alpha^0 = [d{\alpha_1}^0 \;\; d{\alpha_2}^0 \;\; d{\alpha_3}^0 \;\; d{\alpha_4}^0 \;\; d{\alpha_5}^0]^T$$

$$d\alpha^0 = INV\left[\frac{\partial f}{\partial \alpha}\right]^0 (T - F^0)$$

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where INV is inverse matrix.

The initial values is updated and statisfy the condition.

$$\alpha^{j+1} = \alpha^j + d\alpha^j$$

$$\alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \alpha_5 < \frac{\pi}{2}$$

By using MATLAB program, the switching angles are obtained as below.

$$\alpha_1 = 22.5833$$

$$\alpha_2 = 33.6015$$

$$\alpha_3 = 46.6430$$

$$\alpha_4 = 68.4979$$

$$\alpha_5 = 75.0974$$

After obtain the alpha, α angles, the beta, β angles will be calculated by using another formula which is shown as below. The detail coding to set α and β using m-file is show in appendix A. β angle is another switching angle that will used to control the switching of second H-bridge in each phase.

$$\beta_1 = \frac{\alpha_2 - \alpha_1}{2} + \alpha_1 = \frac{33.6015 - 22.5833}{2} + 22.5833 = 28.0924$$

$$\beta_2 = \frac{\alpha_3 - \alpha_2}{2} + \alpha_2 = \frac{46.6430 - 33.6015}{2} + 33.6015 = 40.1222$$

$$\beta_3 = \frac{\alpha_4 - \alpha_3}{2} + \alpha_3 = \frac{68.4979 - 46.6430}{2} + 46.6430 = 57.5705$$

$$\beta_4 = \frac{\alpha_5 - \alpha_4}{2} + \alpha_4 = \frac{75.0974 - 68.4979}{2} + 68.4979 = 71.7976$$

$$\beta_5 = \frac{90 - \alpha_5}{2} + \alpha_5 = \frac{90 - 75.0974}{2} + 75.0974 = 82.5487$$

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CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter shows the simulation results of the inverter waveform using different techniques such as square wave, SHE-PWM, unipolar and bipolar. Each of the waveform will be tested using different loads which are R, RL and RC. The THD of the four type techniques with different loads is recorded in a table. Moreover, the harmonic for 3^{rd}, 5^{th}, 7^{th} and 9^{th} order for all inverters are also recorded in a table. This can shows the different between SHE-PWM with other techniques which it can eliminate the harmonic at low frequency compared to others techniques.

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4.2 Single Phase Simulation Results

After the set up the simulink block using MATLAB program, the single phase waveform results is obtained and shown in scope. By using the Fast Fourier Transform (FFT) analysis, the waveforms and harmonics obtained are shown as below for different types of inverter of several loads R, RL and RC.

4.2.1 Single Phase Square Wave Inverter

The current and voltage waveform obtained for square wave inverter of R, RL and RC loads are shown as following. In addition, the THD and percentage of harmonic are also shown in following figures.

4.2.1.1 Single Phase Square Wave Inverter for R Load

By using R load, the current and voltage waveform produced in square wave are shown in Figure 4.1 and Figure 4.2. The shapes of the both waveforms are same.

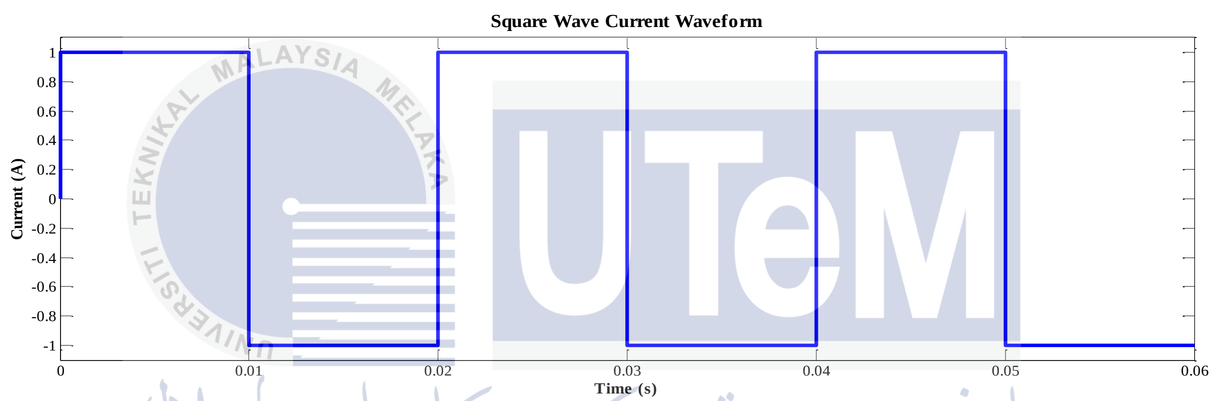

Figure 4.1 : Square wave current waveform for R load

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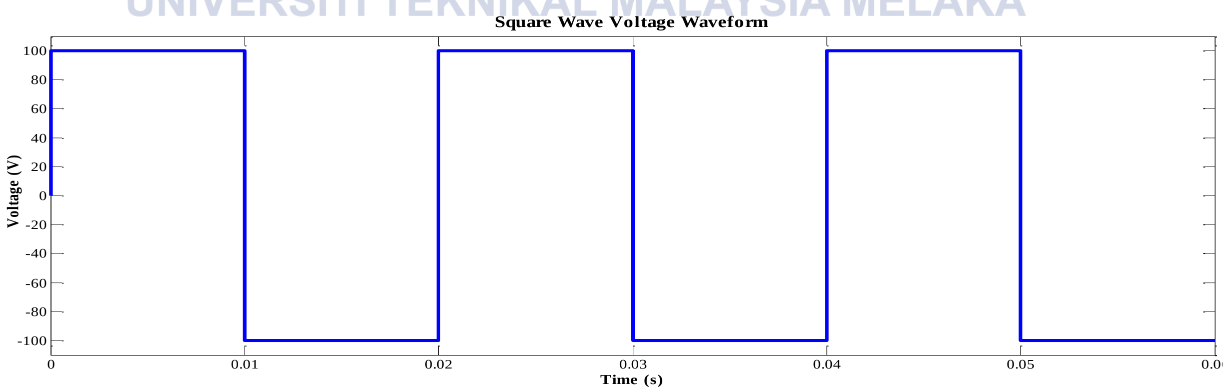

Figure 4.2 : Square wave voltage waveform for R load

Figure 4.3 and Figure 4.4 show the percentage of harmonic versus the harmonic order for current and voltage of R load. The THD of current and voltage can be obtained from the figures below. The THDi is same as the THDv which is 48.34 %.

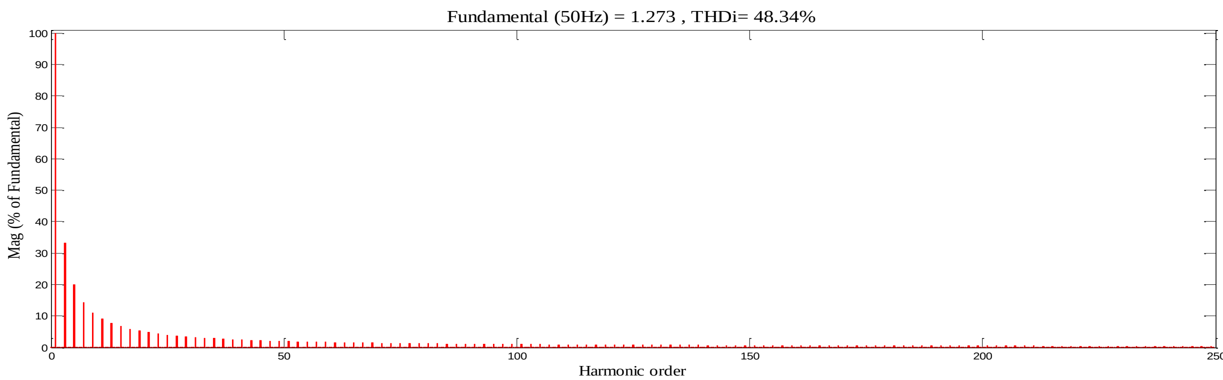

Figure 4.3 : Square wave current harmonic for R load

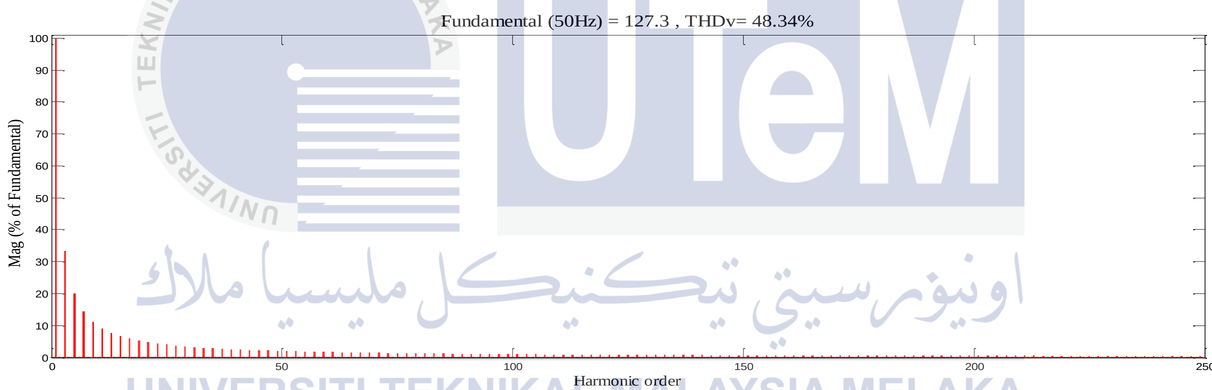

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Figure 4.4 : Square wave voltage harmonic for R load

4.2.1.2 Single Phase Square Wave Inverter for RL Load

In RL load, the shape current waveform is different from R load which it is in curve shape whereas the voltage waveform is still the same as in R load which is shown in Figure 4.5 and Figure 4.6. This is due to an inductive load presents some considerations in designing the switches in full bridge circuit which the switch must be bidirectional. Thus, the current is expressed as sum of forced and natural response that makes it not in smooth square wave form.

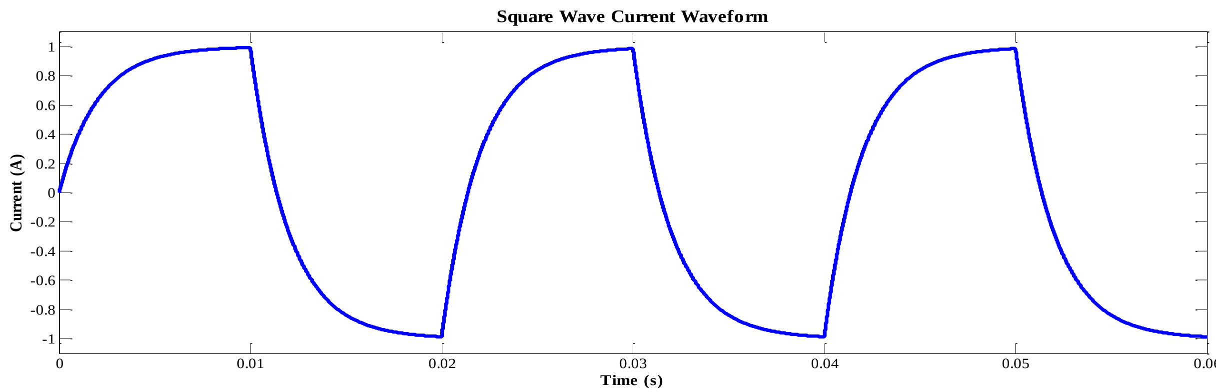

Figure 4.5 : Square wave current waveform for RL load

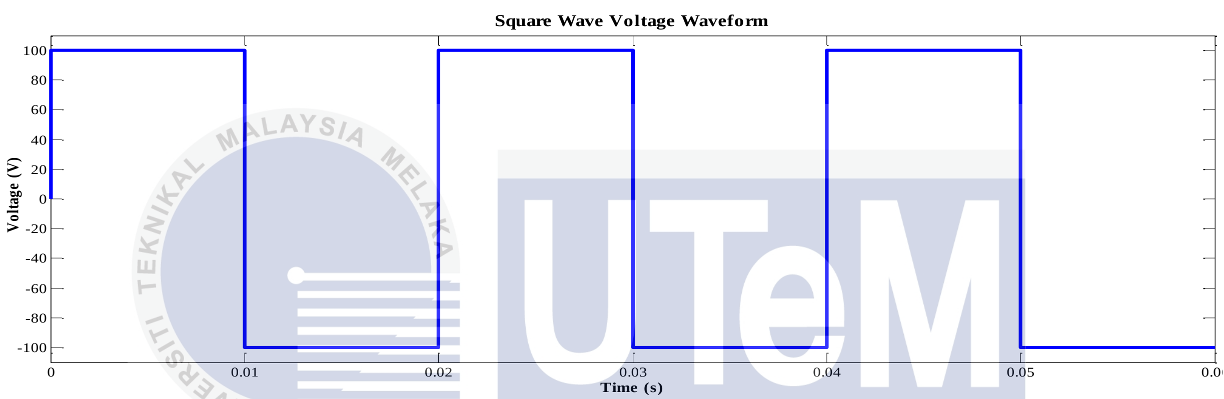

Figure 4.6 : Square wave voltage waveform for RL load

Figure 4.7 and Figure 4.8 show the percentage of harmonic versus the harmonic order for current and voltage of RL load. The THD of current and voltage can be obtained from the figures below which are 21.52 % and 48.34 % respectively. The THDv is same with R load.

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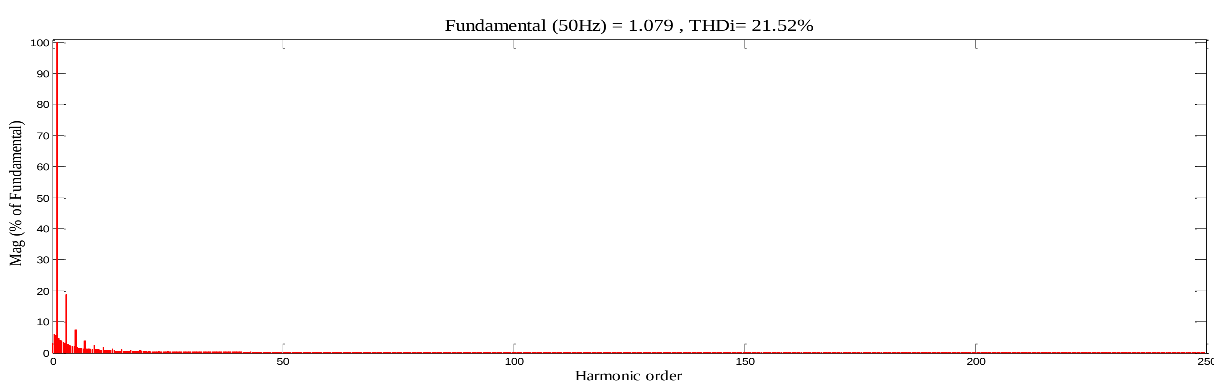

Figure 4.7 : Square wave current harmonic for RL load

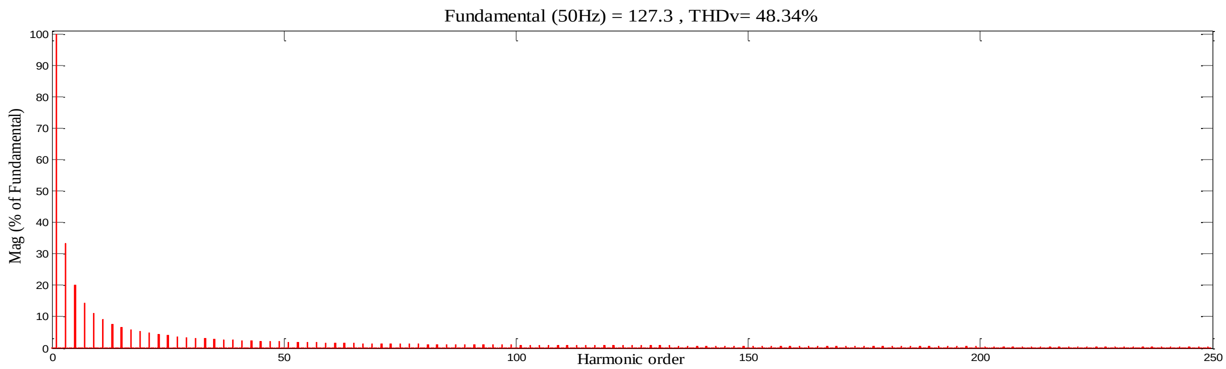

Figure 4.8 : Square wave voltage harmonic for RL load

4.2.1.3 Single Phase Square Wave Inverter for RC Load

In RC load, the square wave current and voltage waveform are shown in Figure 4.9 and Figure 4.10. The current waveform will be discharged and it is curve in the shape because of the present of capacitor in the load. The capacitor is a passive filter which makes change in the waveform current of inverter. On the other hand, the voltage waveform is still same as the R and RL load.

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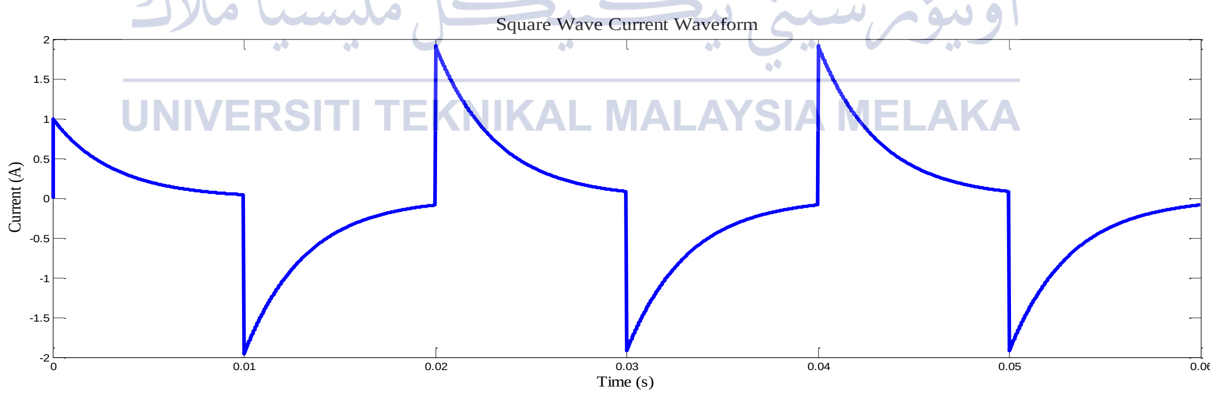

Figure 4.9 : Square wave current waveform for RC load

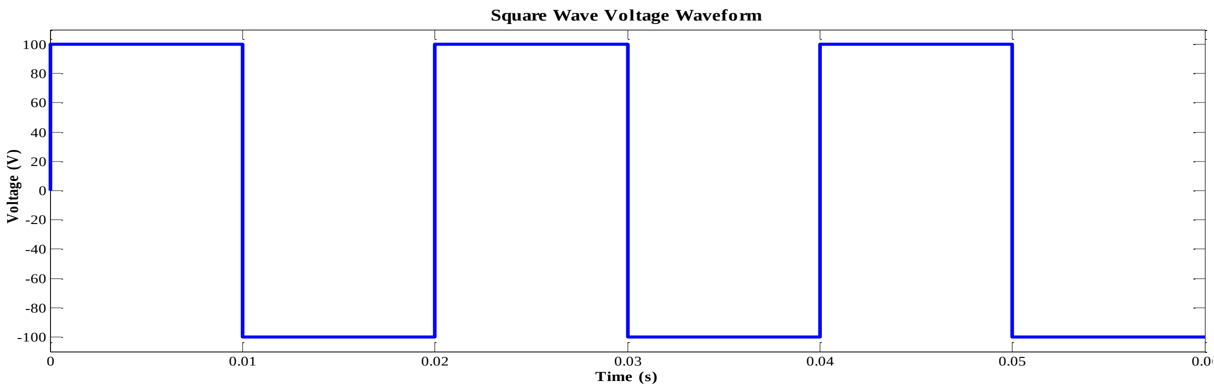

Figure 4.10 : Square wave voltage waveform for RC load

Figure 4.11 and Figure 4.12 show the percentage of harmonic versus the harmonic order for current and voltage of RC load. The THD of current and voltage can be obtained from the figures below which are 66.59 % and 48.34 % respectively. The THDv of RC load is same as R and RL loads.

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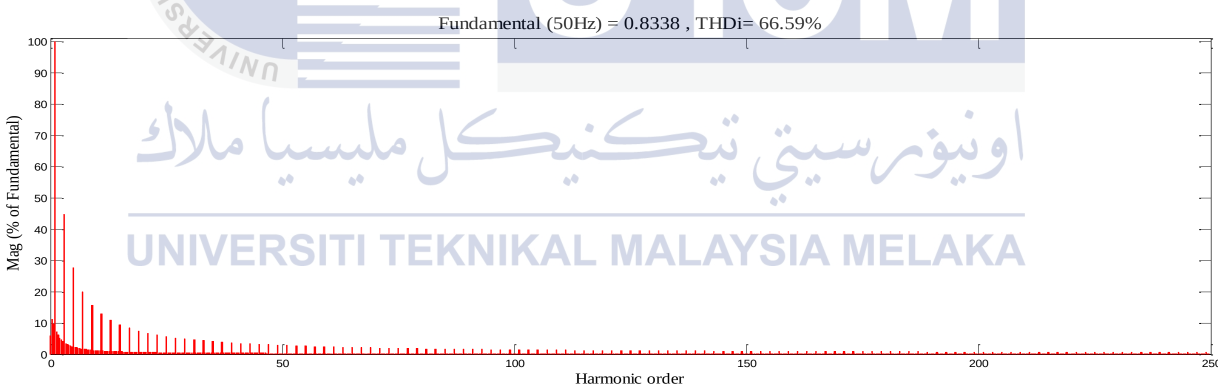

Figure 4.11 : Square wave current harmonic for RC load

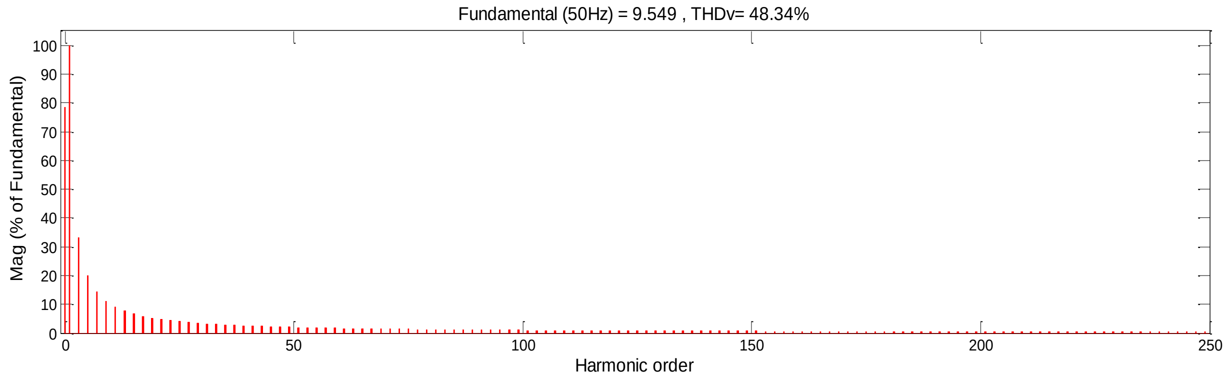

Figure 4.12 : Square wave voltage harmonic for RC load

4.2.2 Single Phase Unipolar Inverter

The current and voltage waveform obtained for unipolar inverter of R, RL and RC loads are shown as following. In addition, the total harmonic distortion (THD) and percentage of harmonic are also shown in following figures.

4.2.2.1 Single Phase Unipolar Inverter for R Load

By using R load, the current and voltage waveform produced in unipolar are shown in Figure 4.13 and Figure 4.14. The shapes of the both waveforms are same. For unipolar waveform, the current or voltage waveform will be positive at the first half cycle whereas it will be negative in another half cycle.

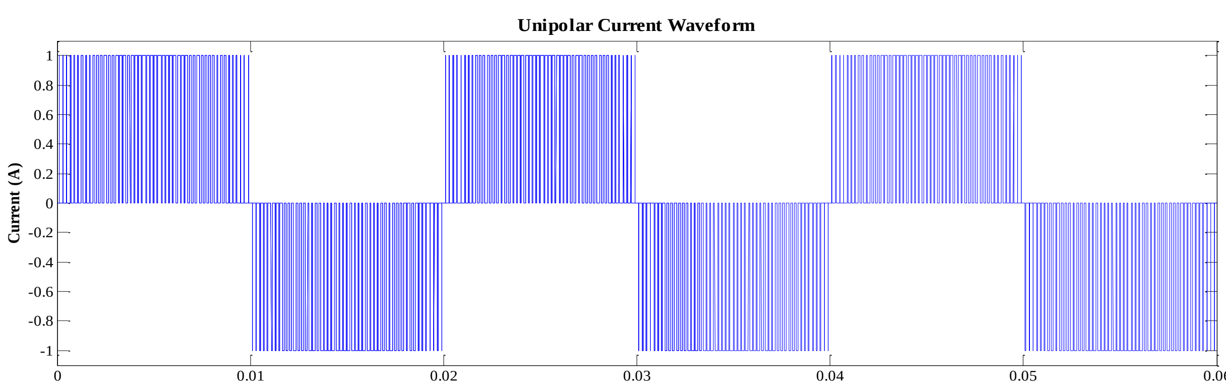

Figure 4.13 : Unipolar current waveform for R load

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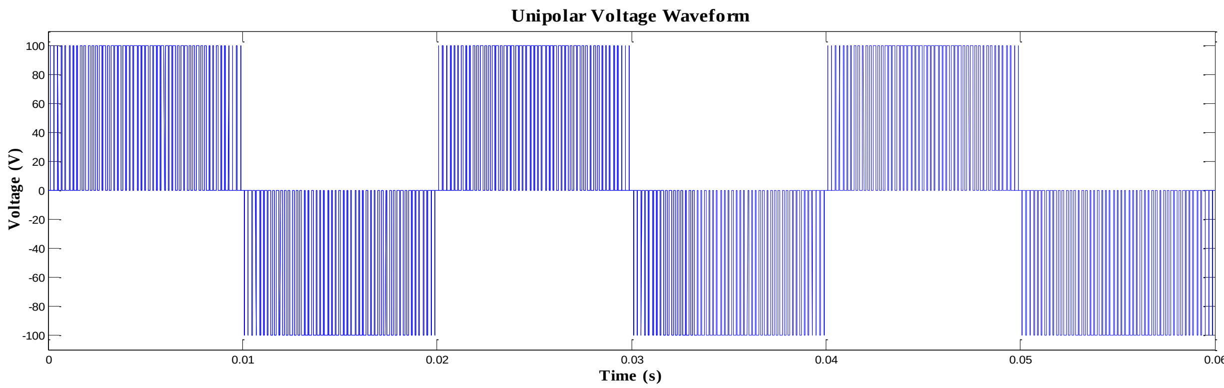

Figure 4.14 : Unipolar voltage waveform for R load

Figure 4.15 and Figure 4.16 show the percentage of harmonic versus the harmonic order for current and voltage of R load. The THDi is same as the THDv which is 83.54 %.

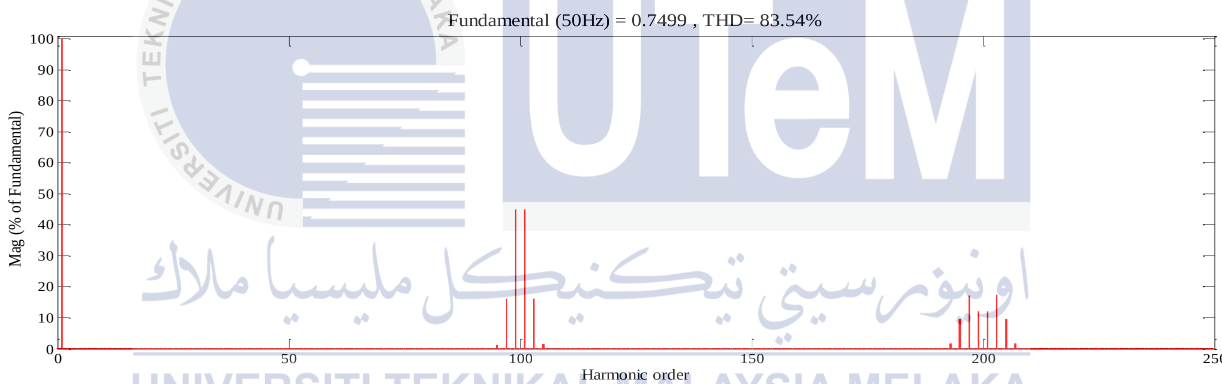

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Figure 4.15 : Unipolar current harmonic for R load

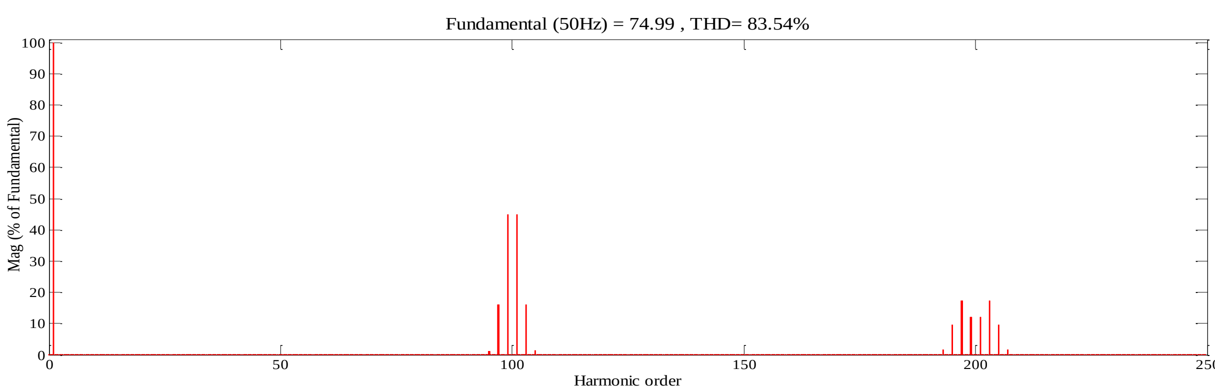

Figure 4.16 : Unipolar voltage harmonic for R load

4.2.2.2 Single Phase Unipolar Inverter for RL Load

In RL load, the shape current waveform is different from R load which it will become likely as sinusoidal shape whereas the voltage waveform will have positive and negative in one cycle which is shown in Figure 4.17 and Figure 4.18. This is because an inductor is added in the load thus make the waveform of current become more likely to sinusoidal shape.

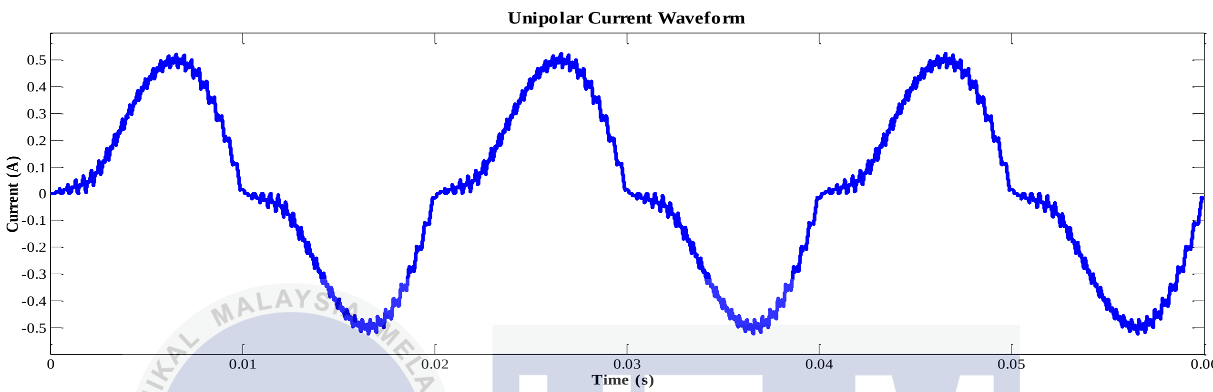

Figure 4.17 : Unipolar current waveform for RL load

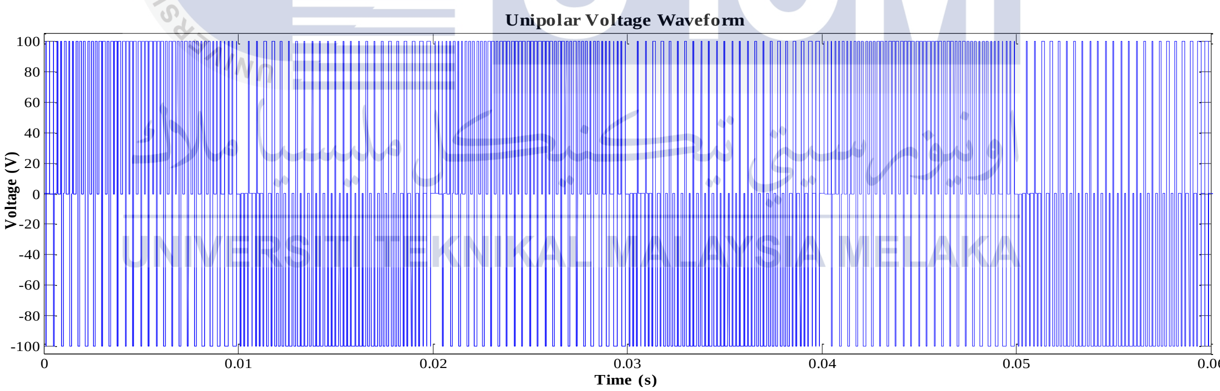

Figure 4.18 : Unipolar voltage waveform for RL load

Figure 4.19 and Figure 4.20 respectively show the percentage of harmonic versus the harmonic order for current and voltage of RL load. The THD of current and voltage can be obtained from the figures below. The THDi and the THDv are 21.67 % and 207.33 %.

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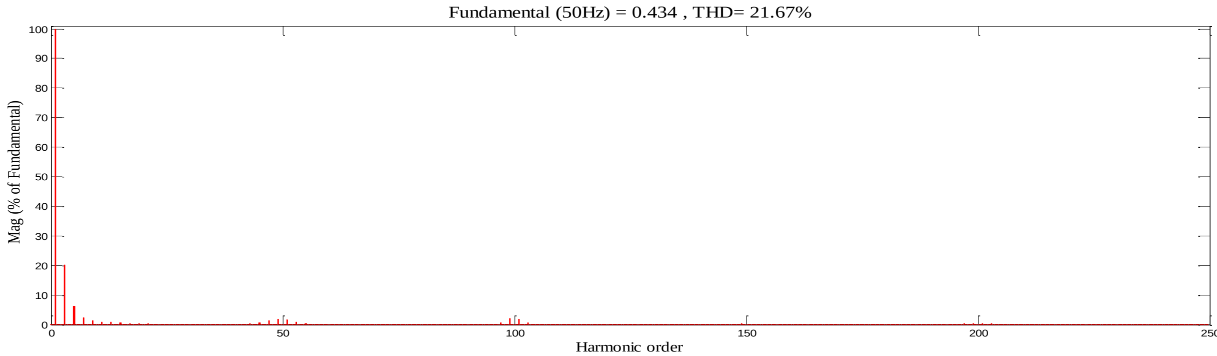

Figure 4.19 : Unipolar current harmonic for RL load

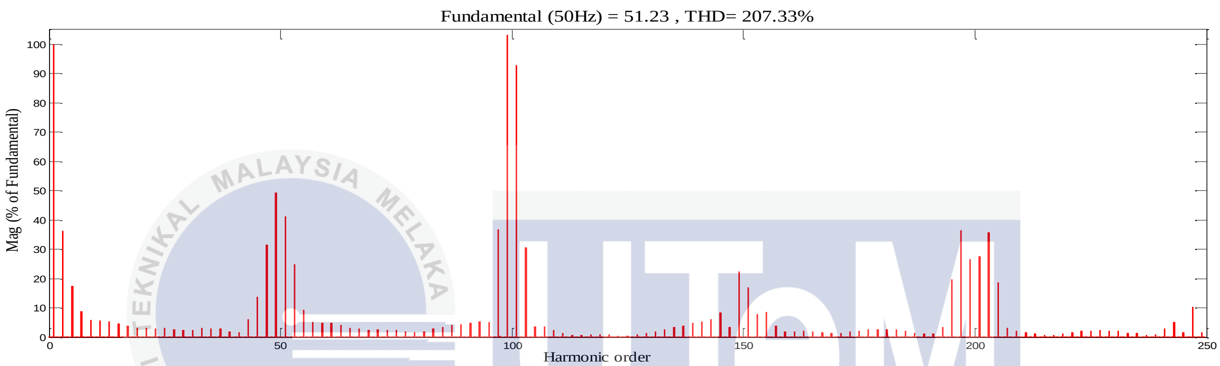

Figure 4.20 : Unipolar voltage harmonic for RL load

4.2.2.3 Single Phase Unipolar Inverter for RC Load

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In RC load, the unipolar current and voltage waveform are shown in Figure 4.21 and Figure 4.22. The current waveform is curve in the shape while voltage waveform will has sinusoidal shape in it due to the presence of capacitor since it is a passive element.

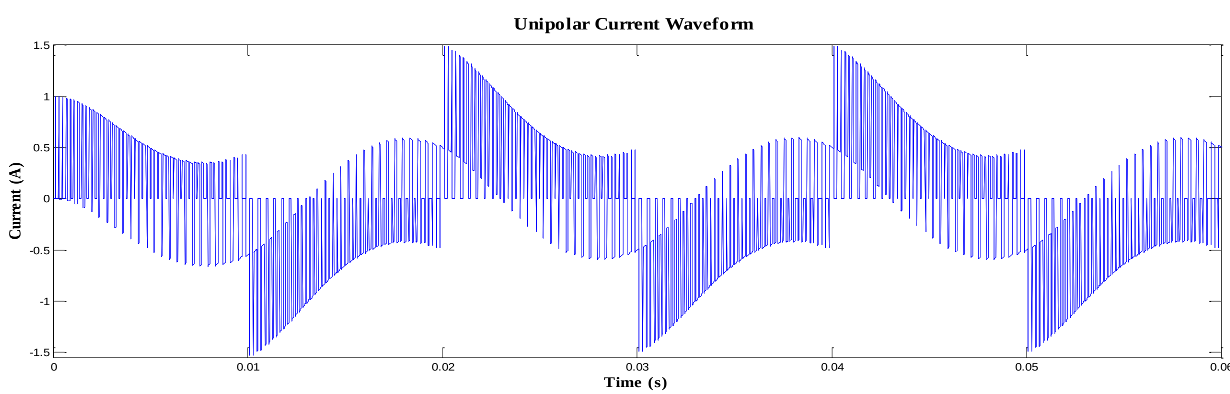

Figure 4.21 : Unipolar current waveform for RC load

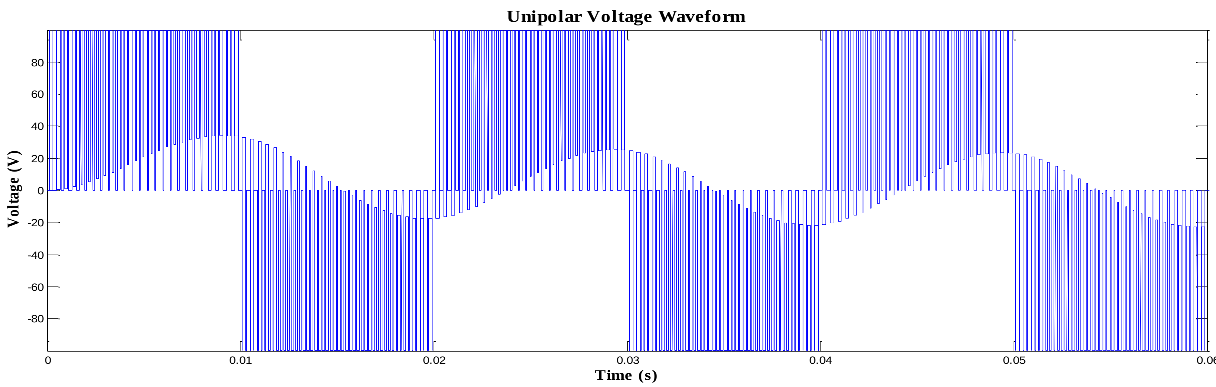

Figure 4.22 : Unipolar voltage waveform for RC load

Figure 4.23 and Figure 4.24 respectively show the percentage of harmonic versus the harmonic order for current and voltage of RC load. The THD of current and voltage can be obtained from the figures below which are 111.85% and 71.95 %.

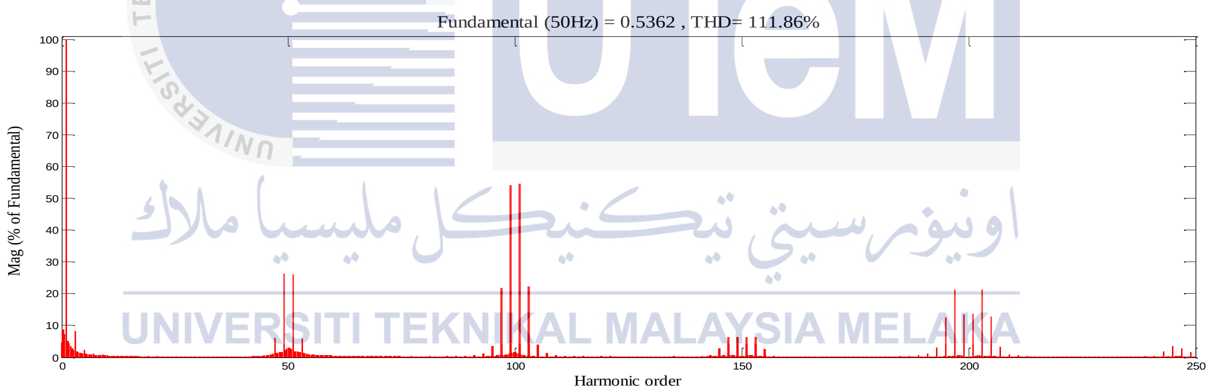

Figure 4.23 : Unipolar current harmonic for RC load

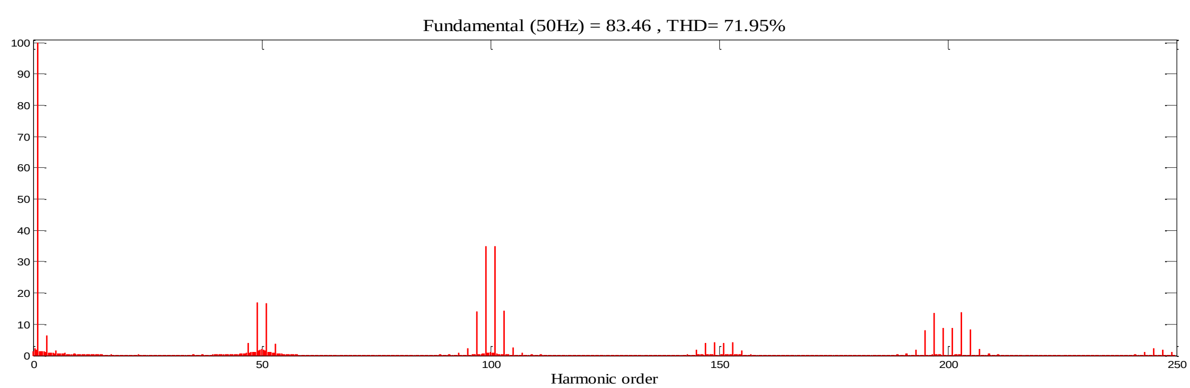

Figure 4.24 : Unipolar voltage harmonic for RC load

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4.2.3 Single Phase Bipolar Inverter

The current and voltage waveform obtained for bipolar inverter of R, RL and RC loads are shown as following. In addition, the total harmonic distortion (THD) and percentage of harmonic are also shown in following figures.

4.2.3.1 Single Phase Bipolar Inverter for R Load

By using R load, the current and voltage waveform produced in bipolar are shown in Figure 4.25 and Figure 4.26 respectively. The shapes of the both waveforms are same. For bipolar waveform, the current or voltage waveform will be positive and negative in one cycle.

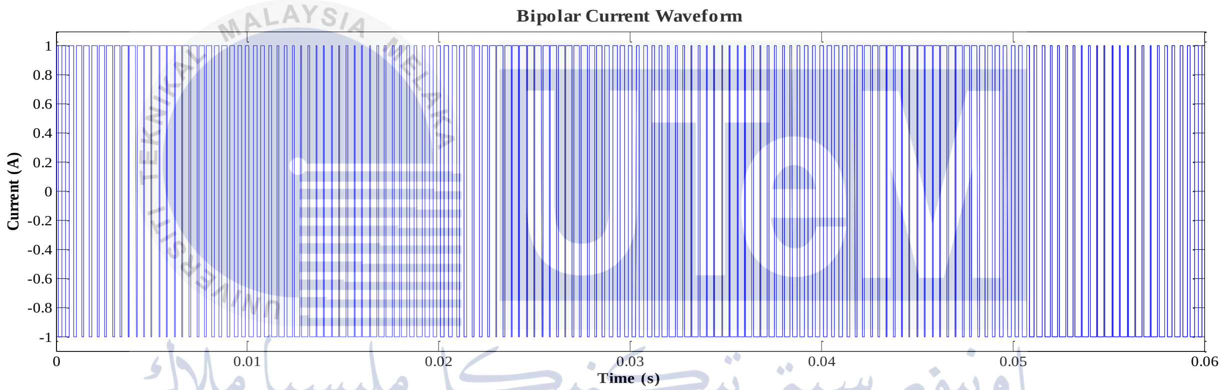

Figure 4.25 : Bipolar current waveform for R load

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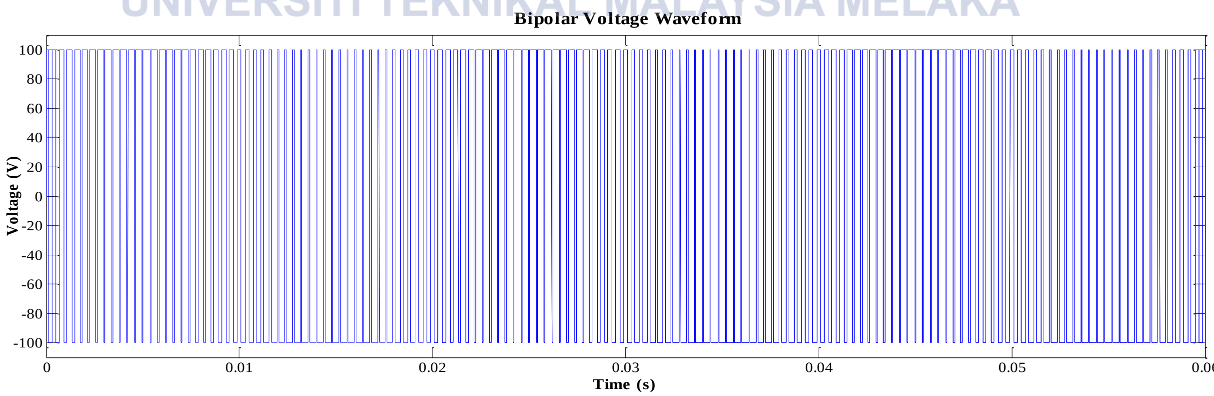

Figure 4.26 : Bipolar voltage waveform for R load

Figure 4.27 and Figure 4.28 show the percentage of harmonic versus the harmonic order for current and voltage of R load. The THD of current and voltage can be obtained from the figures below. The THDi is same as the THDv which is 160.01 %.

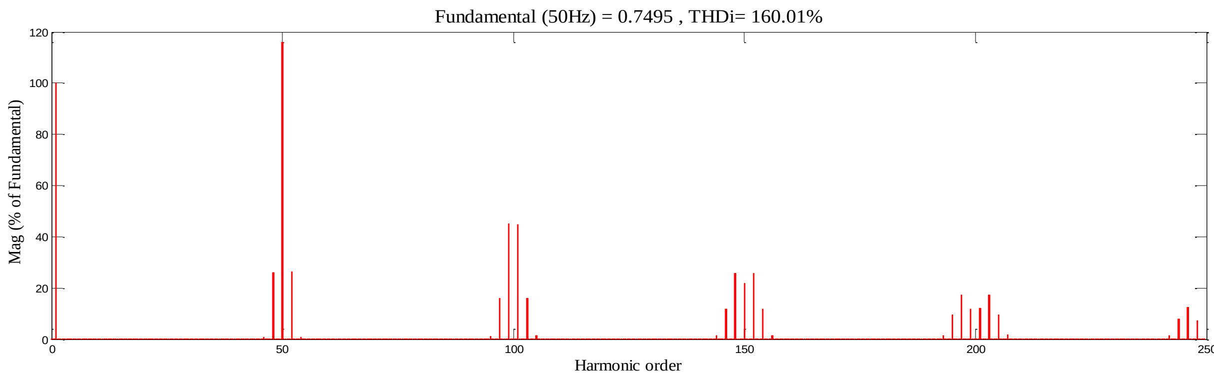

Figure 4.27 : Bipolar current harmonic for R load

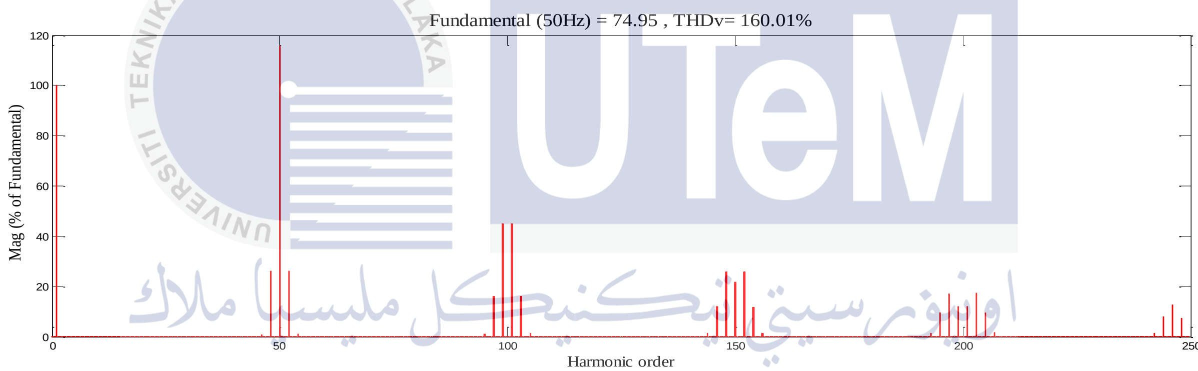

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Figure 4.28 : Bipolar voltage harmonic for R load

4.2.3.2 Single Phase Bipolar Inverter for RL Load

In RL load, the shape current waveform is different from R load which it will become likely as sinusoidal shape whereas the voltage waveform will have positive and negative in one cycle that is same as R load which is shown in Figure 4.29 and Figure 4.30. This is because there is an inductance added into the load. The inductance is a passive element that will eliminate the harmonic in the current.

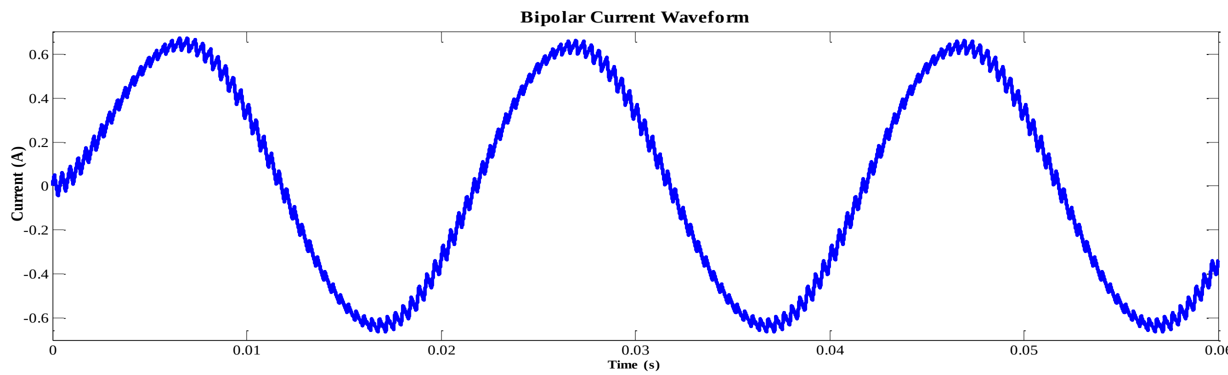

Figure 4.29 : Bipolar current waveform for RL load

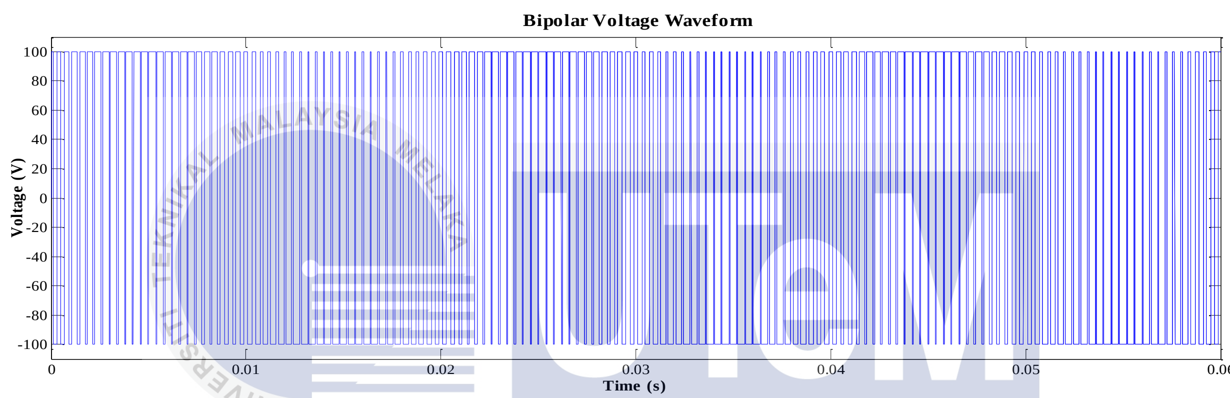

Figure 4.30 : Bipolar voltage waveform for RL load

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Figure 4.31 and Figure 4.32 show the percentage of harmonic versus the harmonic order for current and voltage of RL load. The THD of current and voltage can be obtained from the figures below. The THDi and the THDv are 6.35 % and 160.02 % respectively.

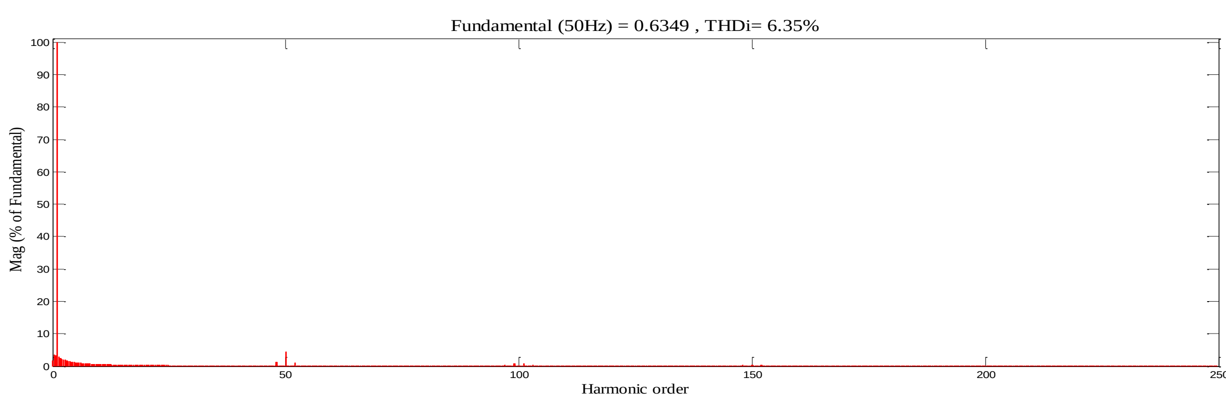

Figure 4.31 : Bipolar current harmonic for RL load

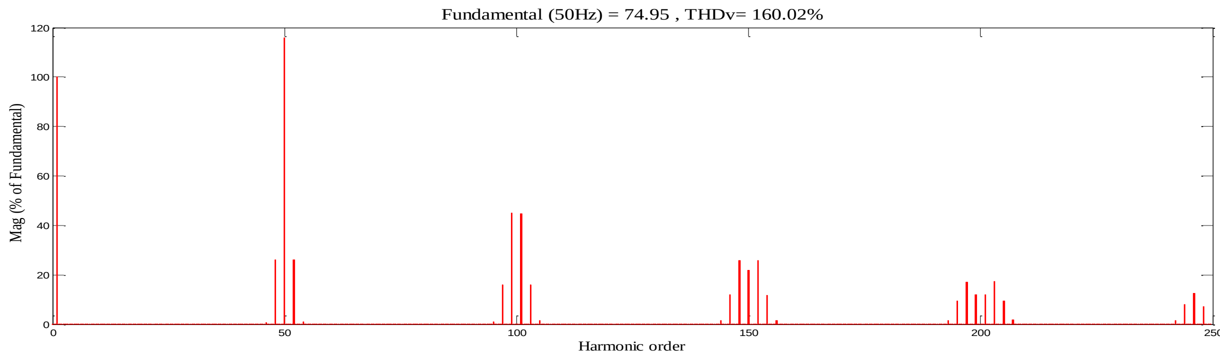

Figure 4.32 : Bipolar voltage harmonic for RL load

4.2.3.3 Single Phase Bipolar Inverter for RC Load

In RC load, the bipolar current and voltage waveform are shown in Figure 4.33 and Figure 4.34 respectively. The current waveform is like a sinusoidal shape while voltage waveform is same as the R and RL load of bipolar inverter.

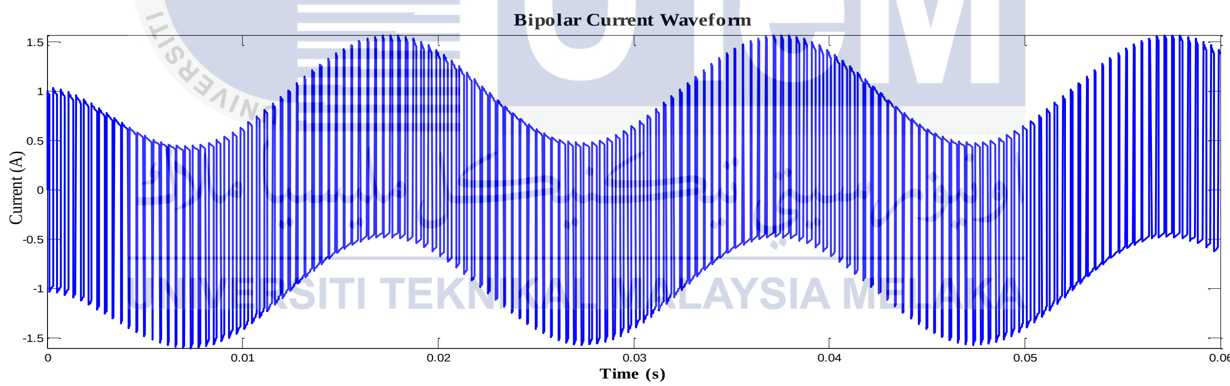

Figure 4.33 : Bipolar current waveform for RC load

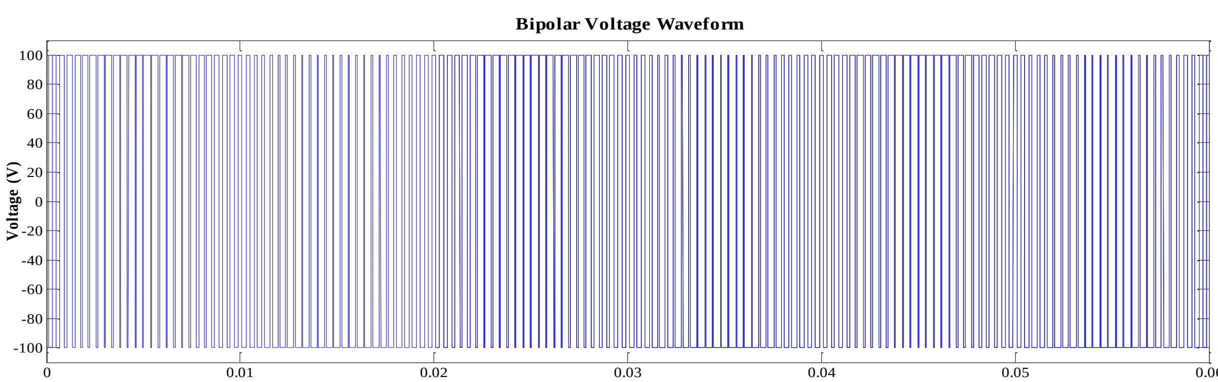

Figure 4.34 : Bipolar voltage waveform for RC load

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Figure 4.35 and Figure 4.36 respectively show the percentage of harmonic versus the harmonic order for current and voltage of RC load. The THD of current and voltage can be obtained from the figures below which are 264.40 % and 160.01 %.

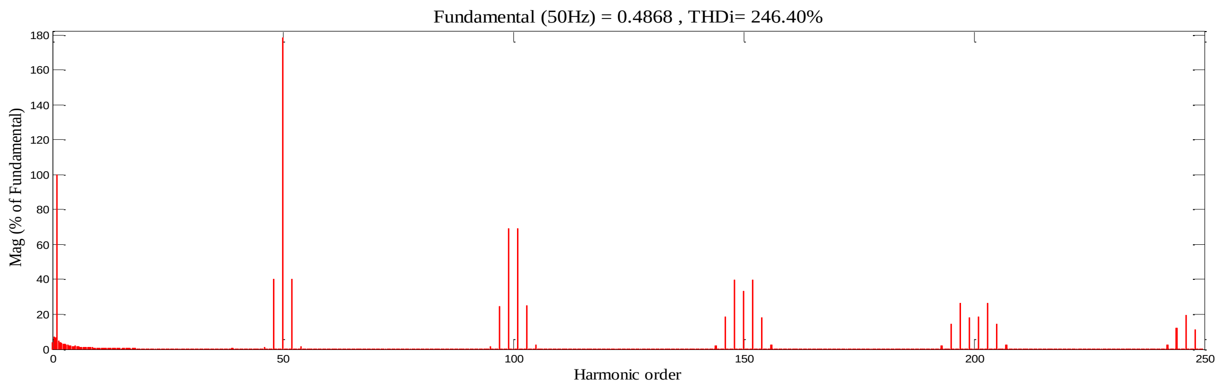

Figure 4.35 : Bipolar current harmonic for RC load

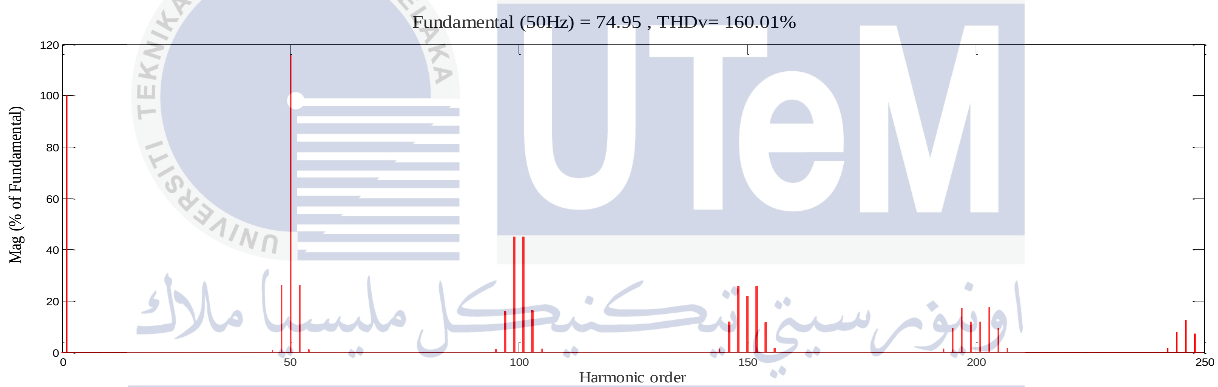

Figure 4.36 : Bipolar voltage harmonic for RC load

4.2.4 Single Phase Selective Harmonic Elimination-Pulse Width Modulation Inverter

The current and voltage waveform obtained for SHE-PWM inverter of R, RL and RC loads are shown as following. In addition, the total harmonic distortion (THD) and percentage of harmonic are also shown in following figures.

4.2.4.1 Single Phase Selective Harmonic Elimination-Pulse Width Modulation Inverter for R Load

By using R load, the current and voltage waveform produced in SHE-PWM are shown in Figure 4.37 and Figure 4.38 respectively. The shapes of the both waveforms are same. For SHE-PWM current and voltage waveform, the pulse is according to the switching scheme in SHE-PWM.

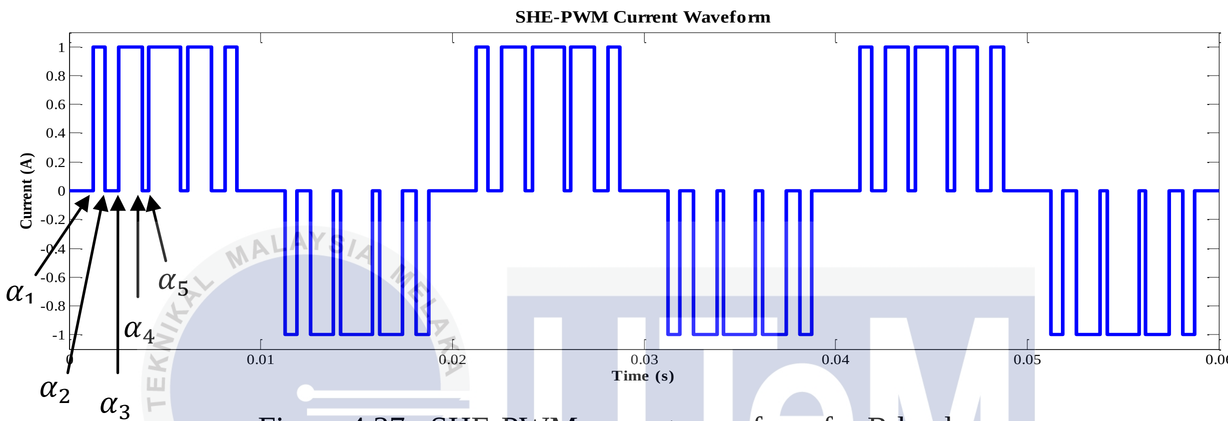

Figure 4.37 : SHE-PWM current waveform for R load

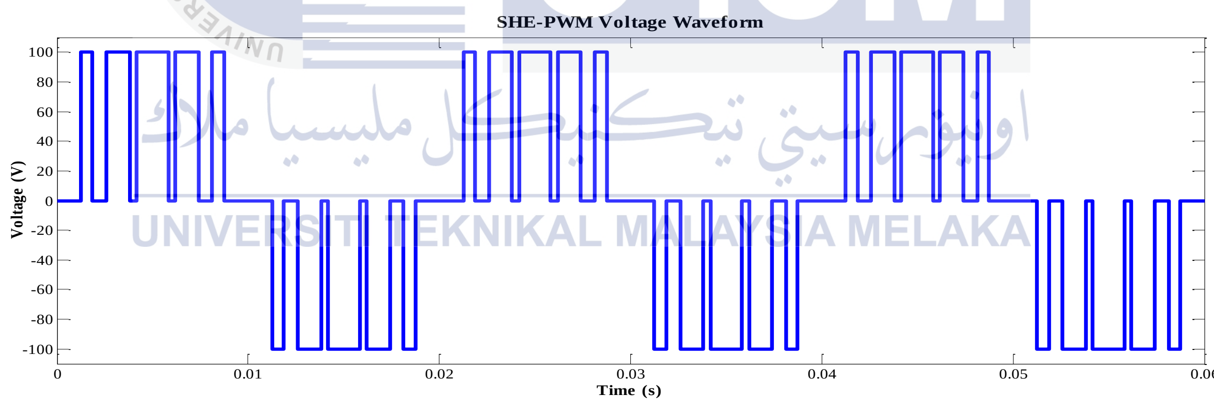

Figure 4.38 : SHE-PWM voltage waveform for R load

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Figure 4.39 and Figure 4.40 show the percentage of harmonic versus the harmonic order for current and voltage of R load. The THD of current and voltage can be obtained from the figures below. The THDi is same as the THDv which is 68.09 %. The switching angles of $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5 is used to eliminate the harmonic at 3^{rd}, 5^{th}, 7^{th} and 9^{th} harmonic order.

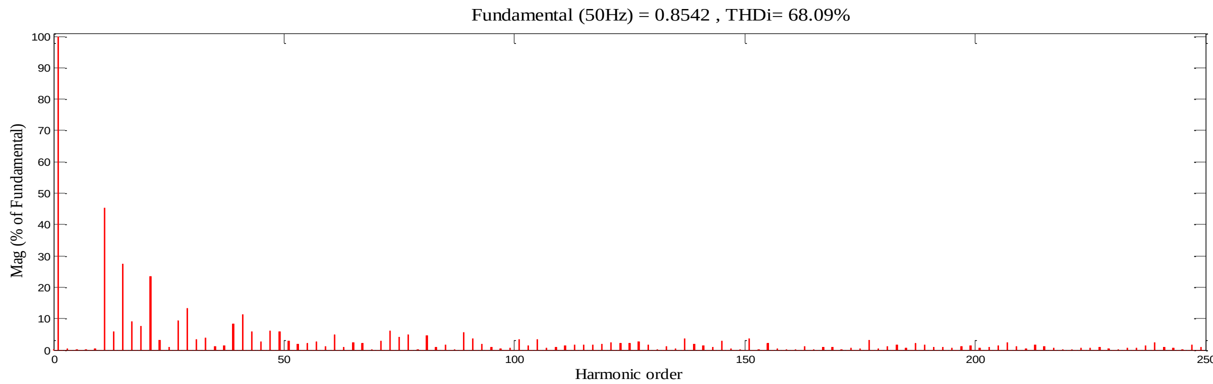

Figure 4.39 : SHE-PWM current harmonic for R load

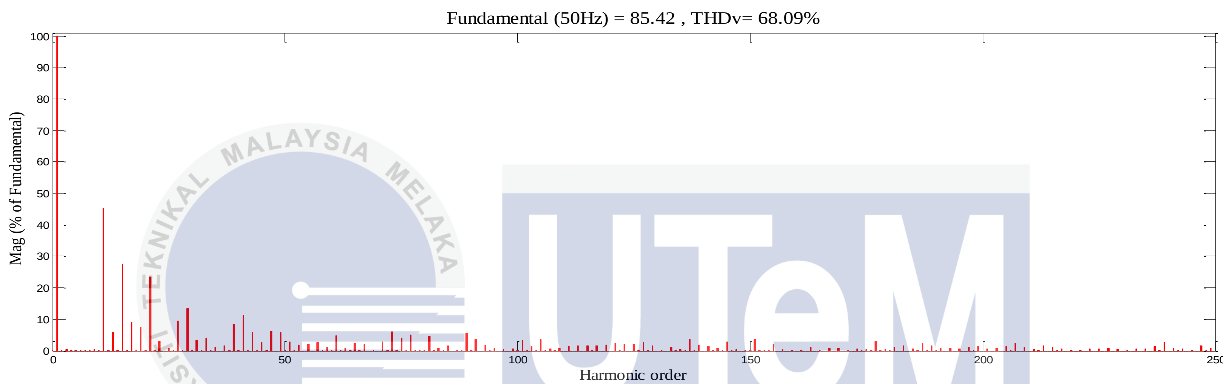

Figure 4.40 : SHE-PWM voltage harmonic for R load

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4.2.4.2 Single Phase Selective Harmonic Elimination-Pulse Width Modulation Inverter for RL Load

In RL load, the shape current waveform is different from R load which its will become a not smooth sinusoidal shape due to the current is whereas the voltage waveform is same as R load which is shown in Figure 4.41 and Figure 4.42. The shape of current waveform changed due to the presence of inductance in load.

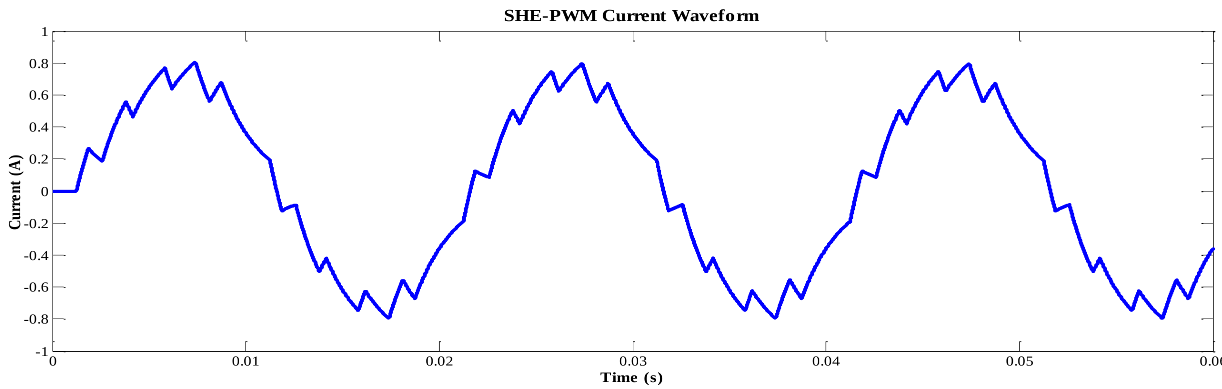

Figure 4.41 : SHE-PWM current waveform for RL load

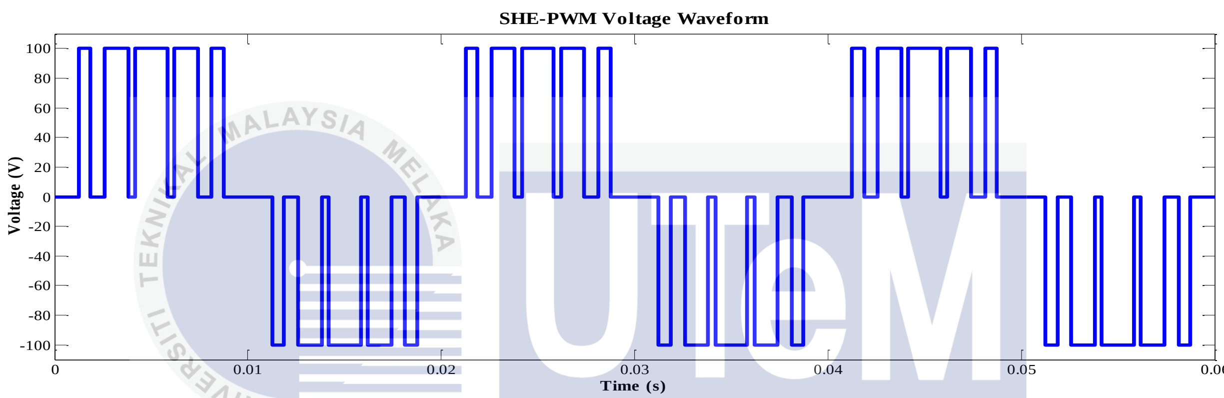

Figure 4.42 : SHE-PWM voltage waveform for RL load

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Figure 4.43 and Figure 4.44 show the percentage of harmonic versus the harmonic order for current and voltage of RL load. The THD of current and voltage can be obtained from the figures below. The THDi is 9.66 % whereas the THDv is same as the R load that is 68.09 %. The switching angles of $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5 is used to eliminate the harmonic of voltage at 3rd, 5th, 7th and 9th harmonic order.

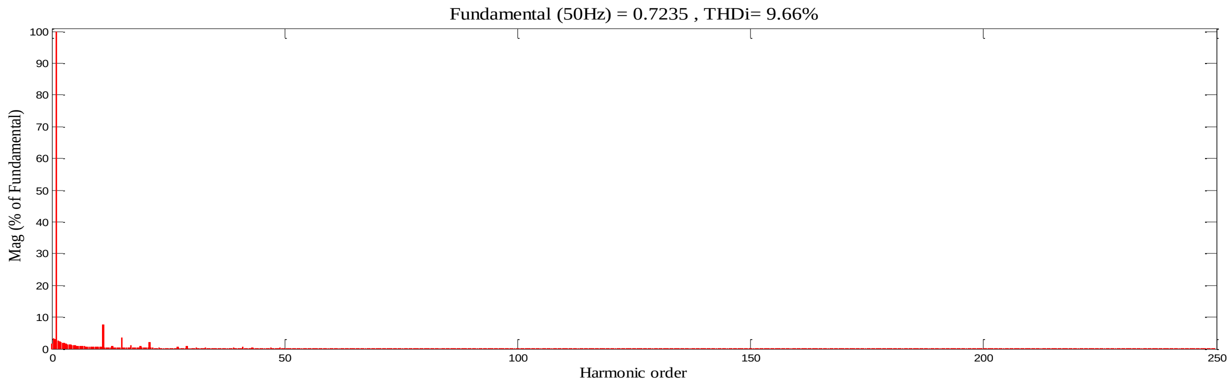

Figure 4.43 : SHE-PWM current harmonic for RL load

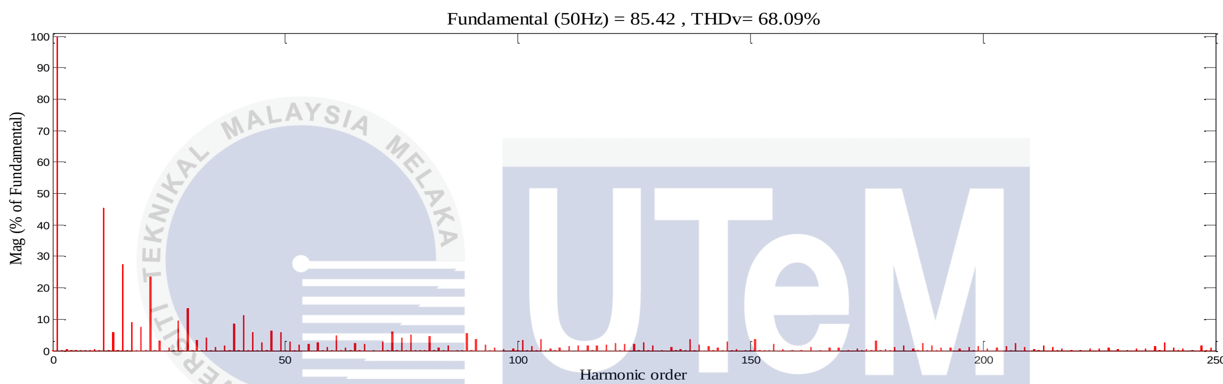

Figure 4.44 : SHE-PWM voltage harmonic for RL load

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4.2.4.3 Single Phase Selective Harmonic Elimination-Pulse Width Modulation Inverter for RC Load

In RC load, the bipolar current and voltage waveform are shown in Figure 4.45 and Figure 4.46. The current is discharged and the waveform shape is not smooth and in shape of curve while the voltage waveform is same as the R and RL load of SHE-PWM inverter. The current waveform is changed because of the presence of capacitance in the load.

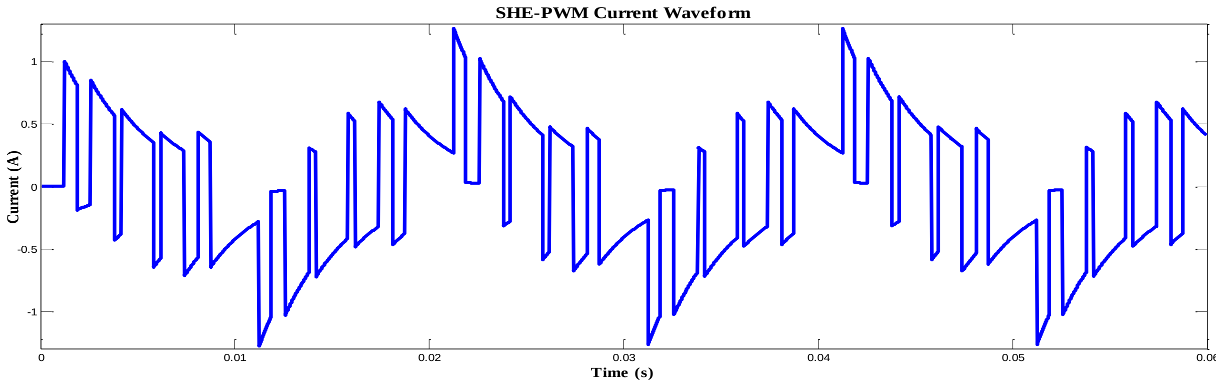

Figure 4.45 : SHE-PWM current waveform for RC load

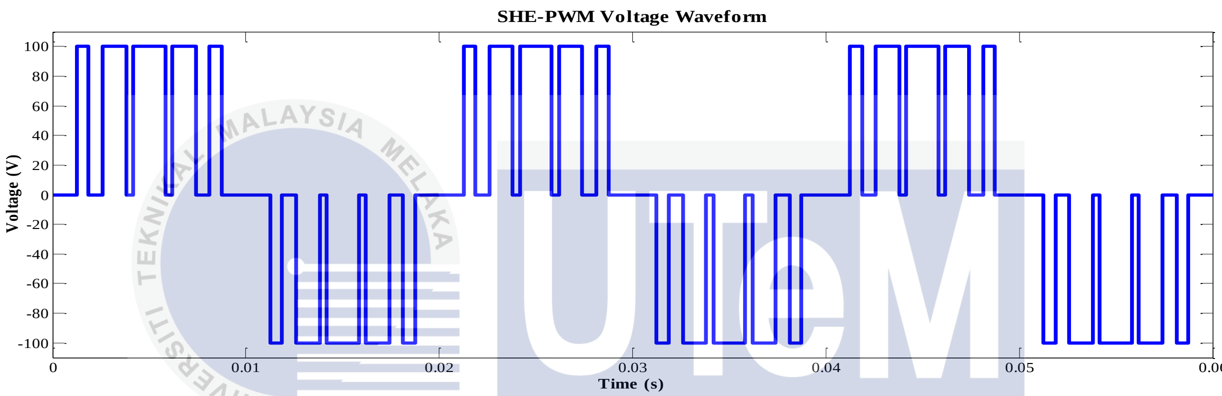

Figure 4.46 : SHE-PWM voltage waveform for RC load

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Figure 4.47 and Figure 4.48 respectively show the percentage of harmonic versus the harmonic order for current and voltage of RC load. The THD of current and voltage can be obtained from the figures below which are 104.69 % and 68.09 %. The value of THDv is same as R load and RL load of SHE-PWM inverter. The switching angles of $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5 is used to eliminate the voltage harmonic at 3rd, 5th, 7th and 9th harmonic order.

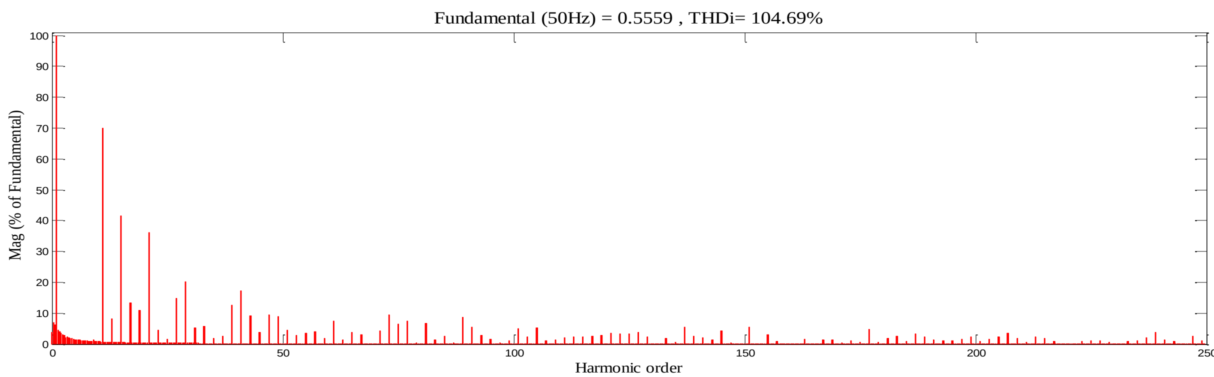

Figure 4.47 : SHE-PWM current harmonic for RC load

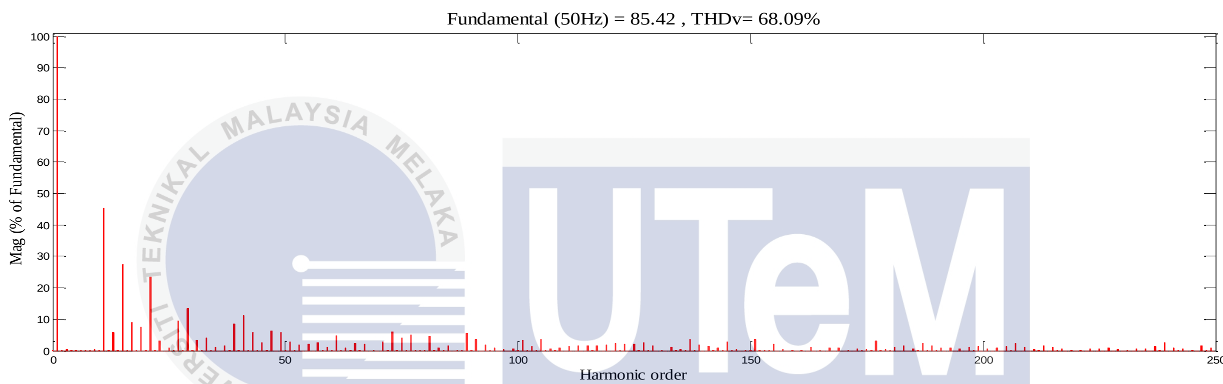

Figure 4.48 : SHE-PWM voltage harmonic for RC load

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4.3 Three Phase Simulation Results

After the set up the three phase simulink block using MATLAB program, the single phase waveform results is obtained and shown in scope. By using the Fast Fourier Transform (FFT) analysis, the waveforms and harmonics obtained are shown as below for different types of inverter of several loads R, RL and RC.

4.3.1 Three Phase Seven-Level Selective Harmonic Elimination-Pulse Width Modulation Inverter

The current and voltage waveform obtained for three phase SHE-PWM inverter of R, RL and RC loads are shown as following. In addition, the total harmonic distortion (THD) and percentage of harmonic are also shown in following figures.

Figure 4.49 shows the switching waveform for angles $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5 while the Figure 4.50 shows the switching waveform of angles $\beta_1, \beta_2, \beta_3, \beta_4$ and β_5.

Figure 4.49 : The switching waveform for angles $\boldsymbol{\alpha_1, \alpha_2, \alpha_3, \alpha_4}$ **and** $\boldsymbol{\alpha_5}$

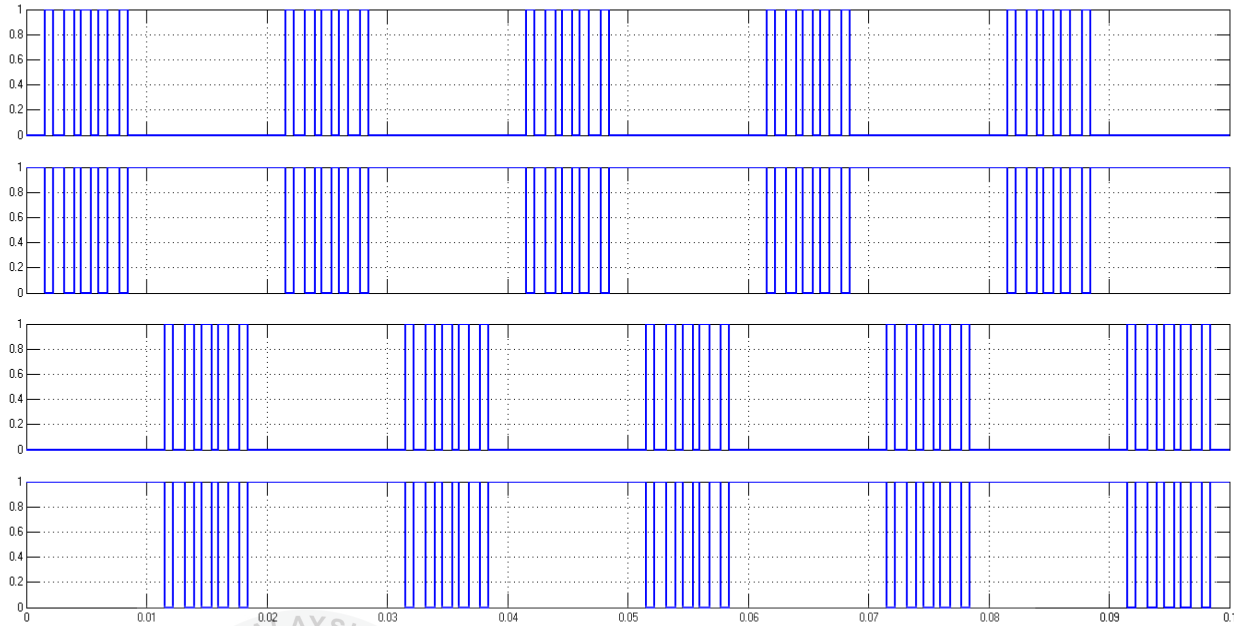

Figure 4.50 : The switching waveform of angles $\boldsymbol{\beta_1, \beta_2, \beta_3, \beta_4}$ **and** $\boldsymbol{\beta_5}$

4.3.1.1 Three Phase Seven-Level Selective Harmonic Elimination-Pulse-Width Modulation Inverter for R Load

By using R load, the phase-current waveform produced in SHE-PWM is shown in Figure 4.51, Figure 4.52 and Figure 4.53 respectively.

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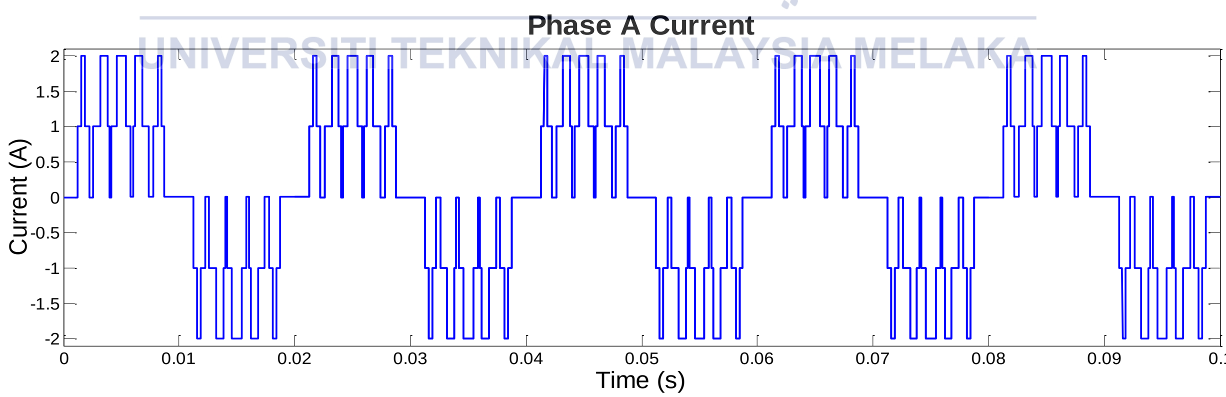

Figure 4.51 : Waveform of phase A current

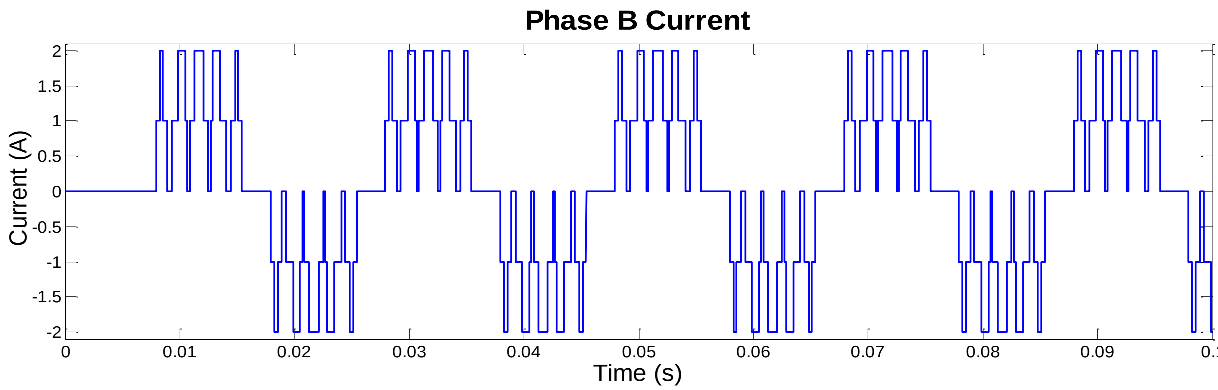

Figure 4.52 : Waveform of phase B current

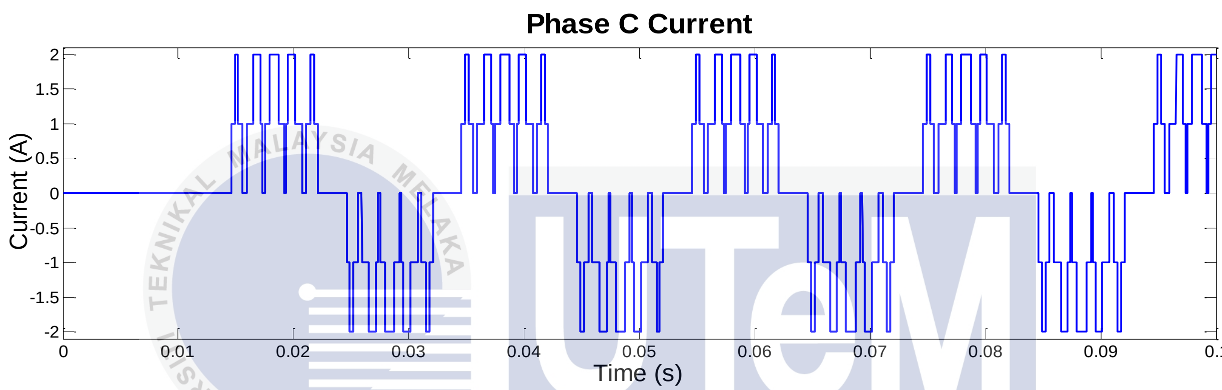

Figure 4.53: Waveform of phase C current

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By using R load, the phase-voltage waveform produced in SHE-PWM is shown in Figure 4.54, Figure 4.55 and Figure 4.56 respectively.

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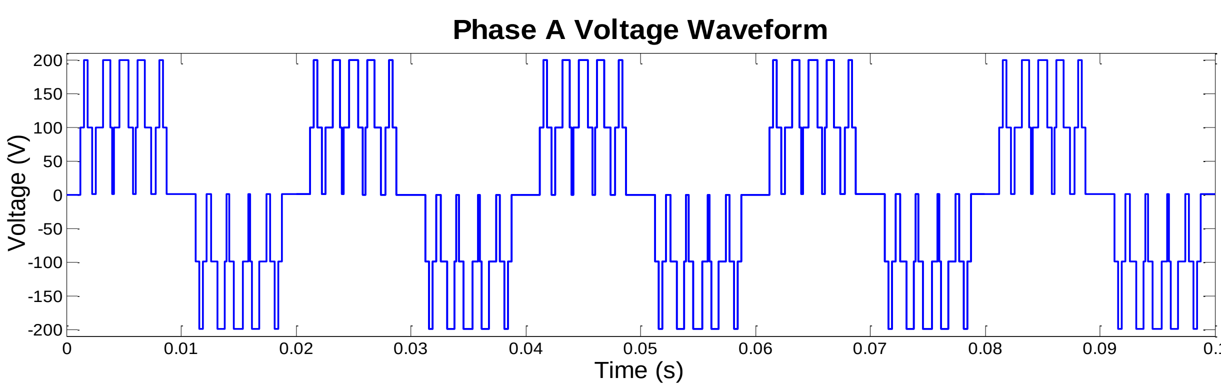

Figure 4.54 : Waveform of phase A voltage

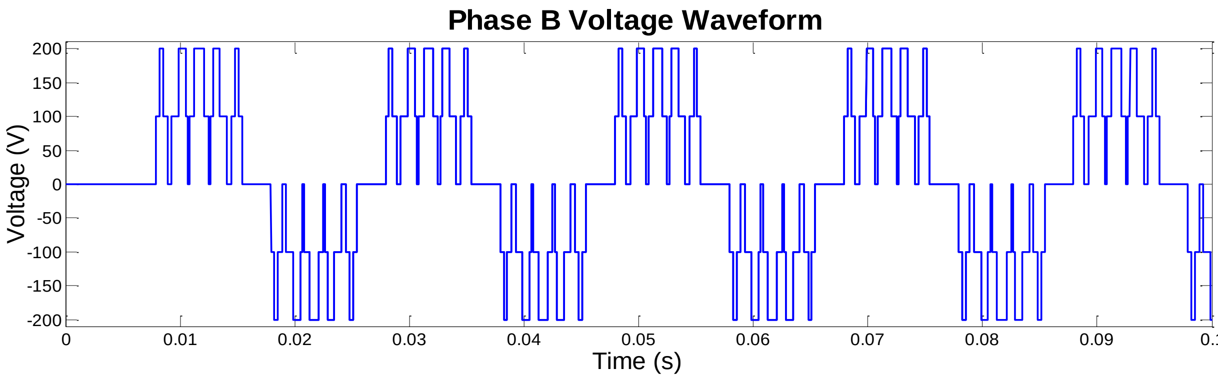

Figure 4.55 : Waveform of phase B voltage

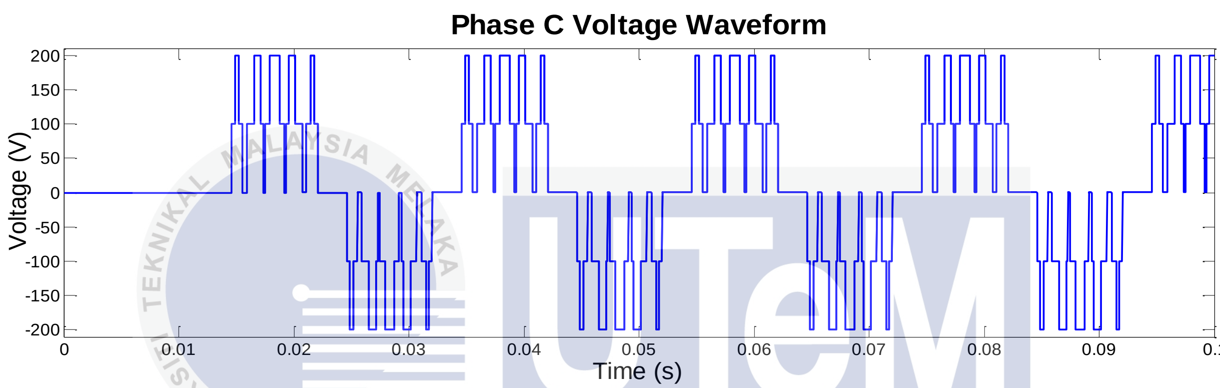

Figure 4.56 : Waveform of phase C voltage

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By using R load, the line-voltage waveform produced in SHE-PWM is shown in Figure 4.57, Figure 4.58 and Figure 4.59 respectively. The figures show the seven-level line-voltage waveform.

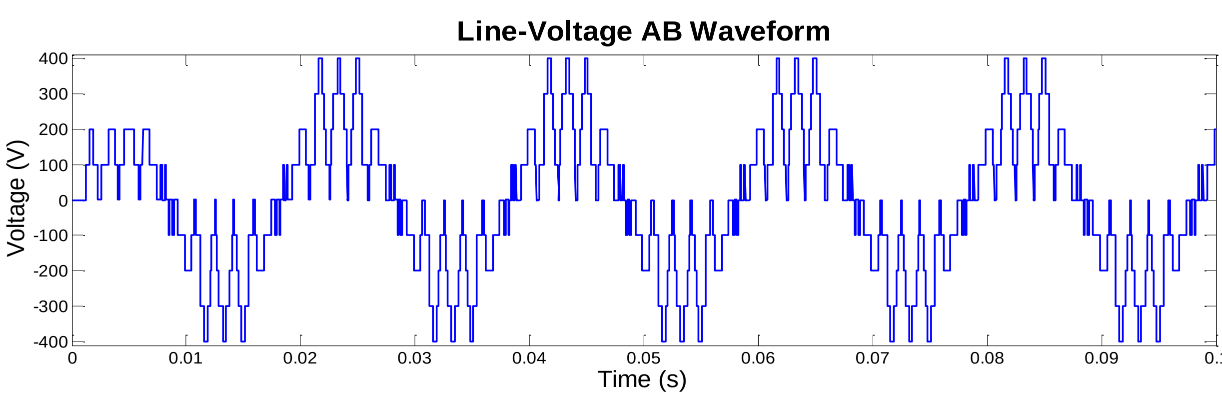

Figure 4.57 : Waveform of line AB voltage

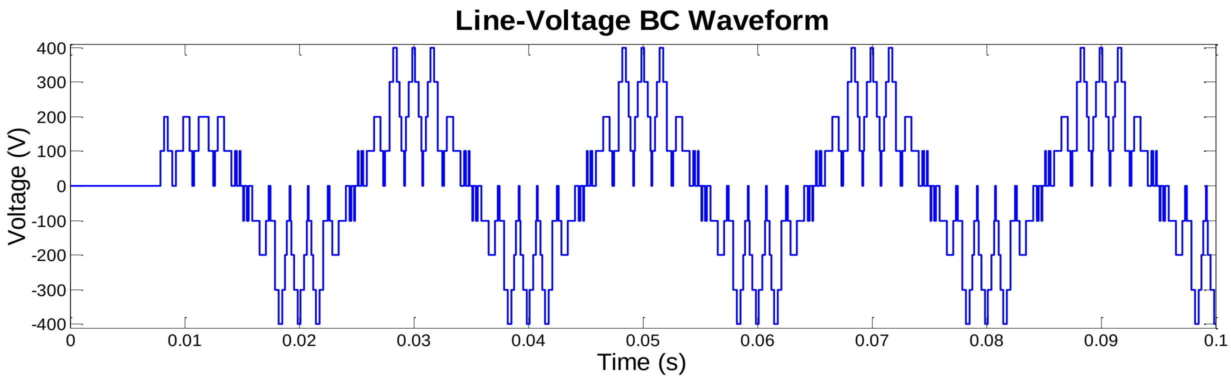

Figure 4.58 : Waveform of line BC voltage

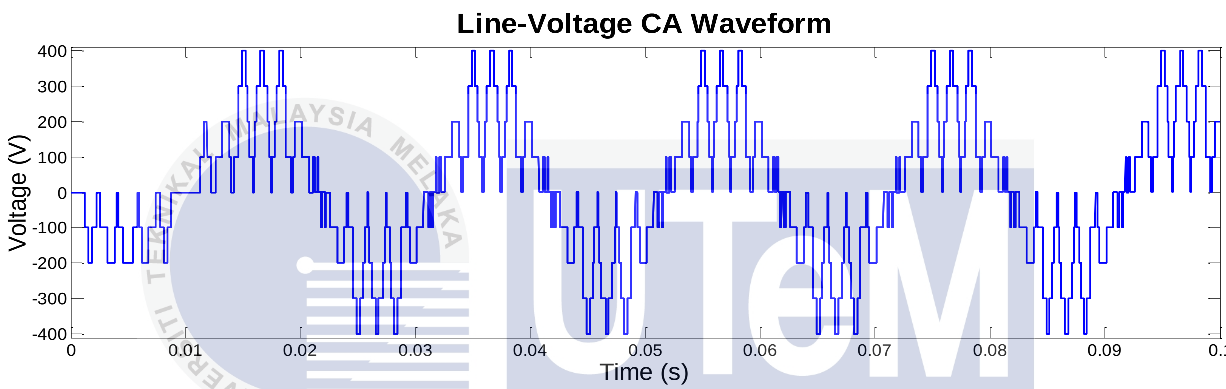

Figure 4.59 : Waveform of line CA voltage

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The total harmonic distortion for current and voltage are shown in Figure 4.60, Figure 4.61 and Figure 4.62 respectively. The THDi for seven-level SHE-PWM is 60.52% and THDv of phase-voltage is 60.52%. The THDv of seven-level line-voltage for SHE-PWM is 35.79%. The switching angles of $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5 with the $\beta_1, \beta_2, \beta_3, \beta_4$ and β_5 angles are used to eliminate the voltage harmonic at 3^{rd}, 5^{th}, 7^{th} and 9^{th} harmonic order for seven-level inverter.

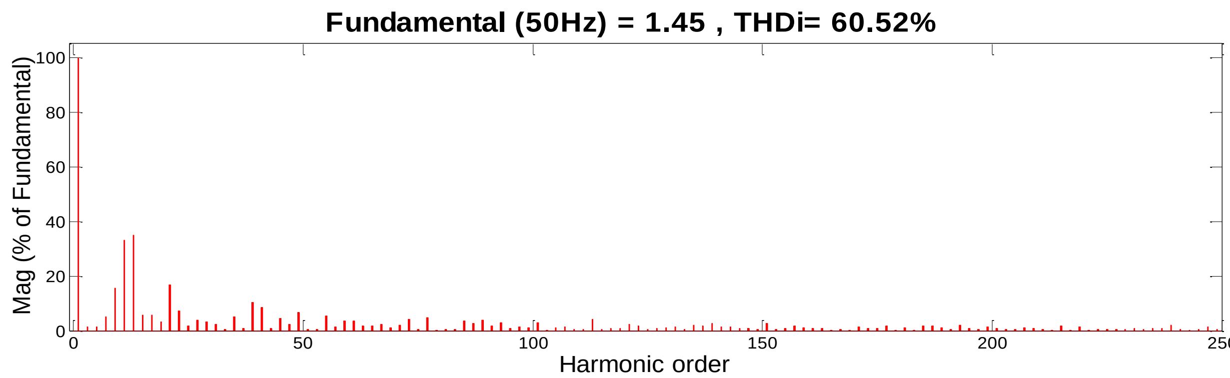

Figure 4.60 : Total Harmonic Distortion of current

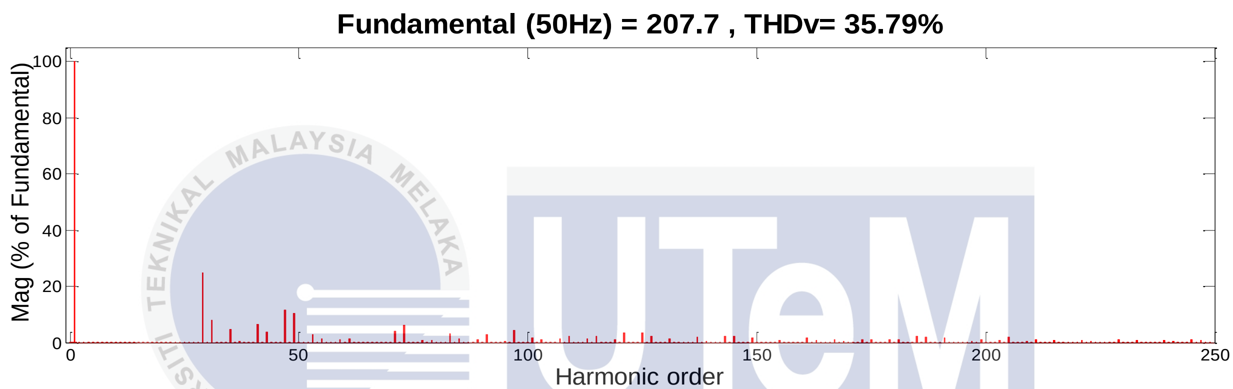

Figure 4.61 :Total Harmonic Distortion of line-voltage

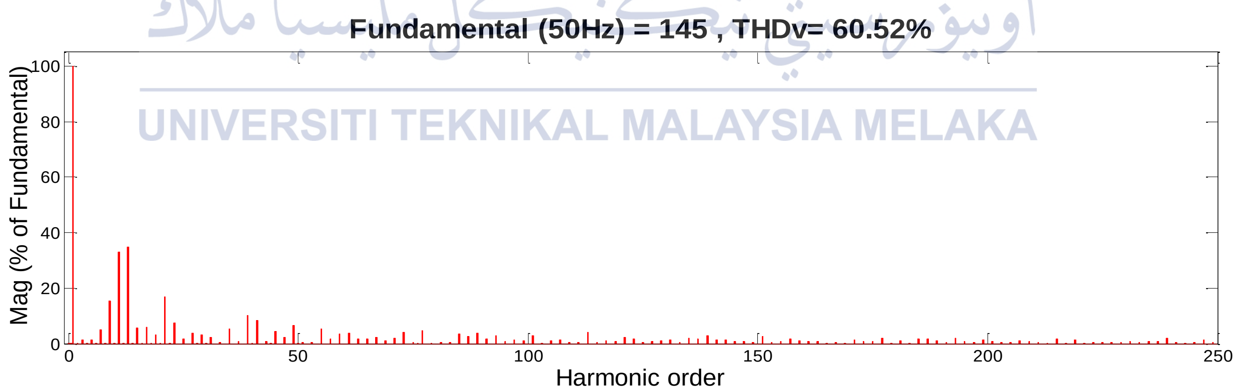

Figure 4.62 : Total Harmonic Distortion of phase voltage

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4.3.1.2 Three Phase Seven- Level Selective Harmonic Elimination-Pulse-Width Modulation Inverter for RL Load

By using RL load, the phase-current waveform produced in SHE-PWM is shown in Figure 4.63, Figure 4.64 and Figure 4.65 respectively. The current waveform of SHE-PWM inverter is become sinusoidal waveform due to the presence of the inductance in load.

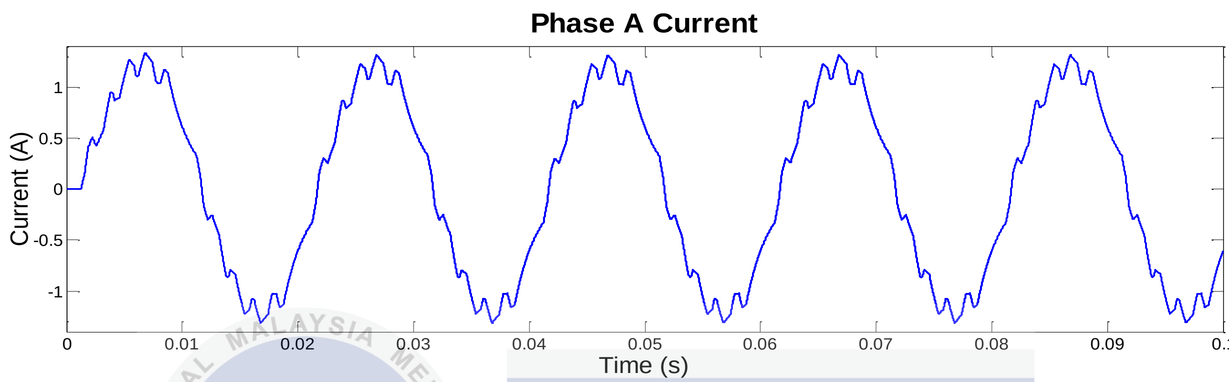

Figure 4.63 : Waveform of phase A current

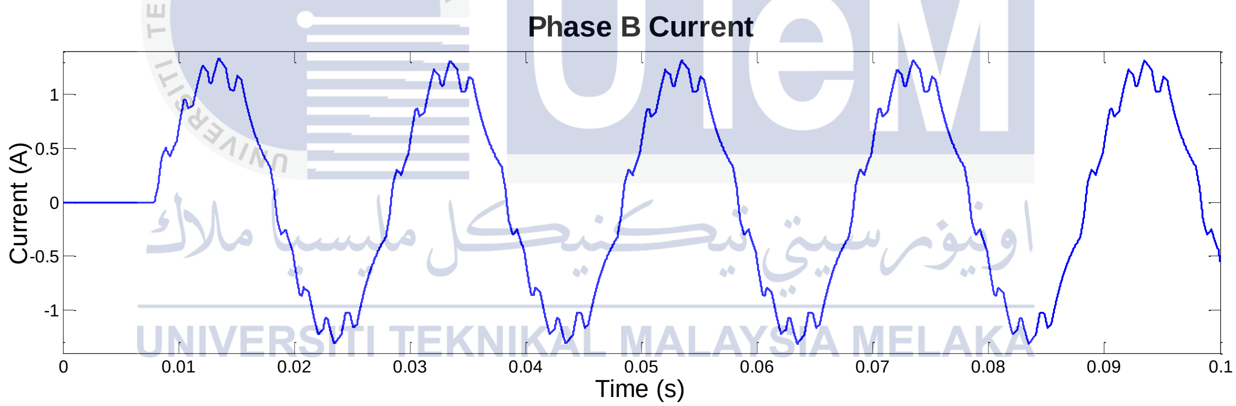

Figure 4.64 : Waveform of phase B current

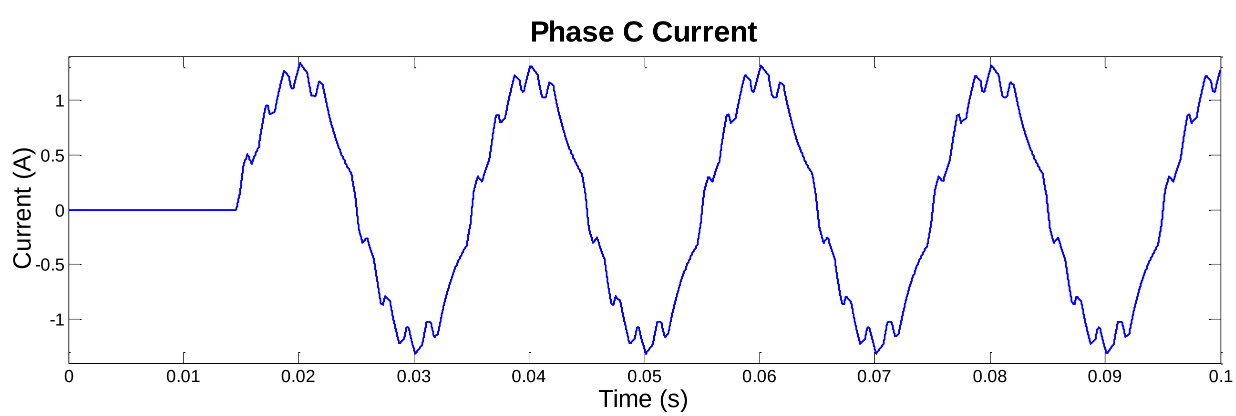

Figure 4.65 : Waveform of phase C current

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By using RL load, the phase-voltage waveform produced in SHE-PWM is shown in Figure 4.66, Figure 4.67 and Figure 4.68 respectively. The shape of the waveform is same as the R load.

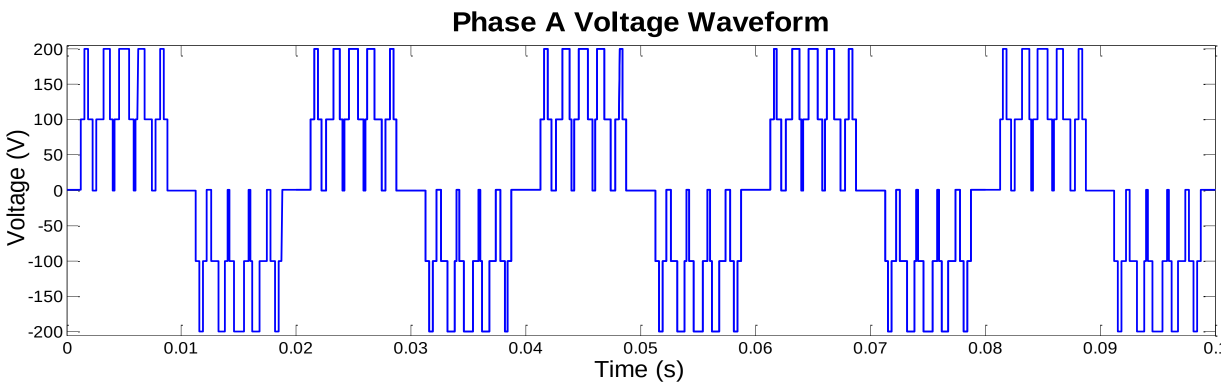

Figure 4.66 : Waveform of phase A voltage

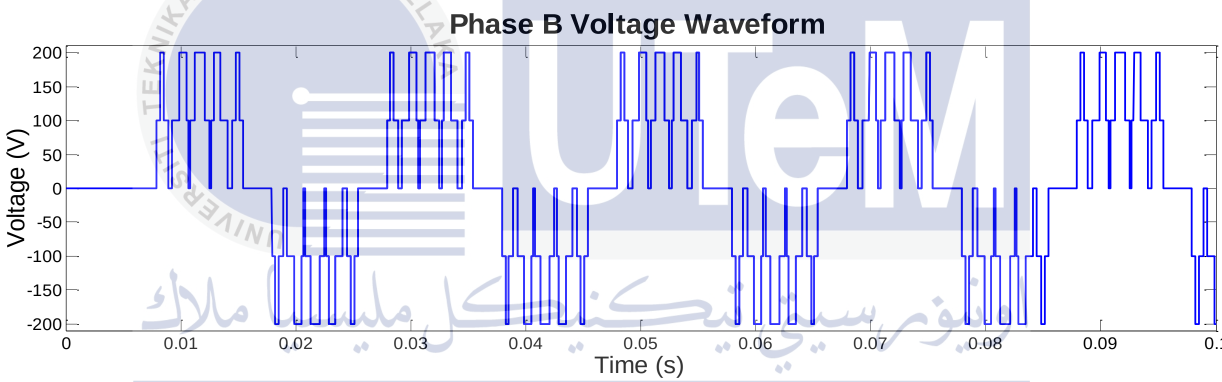

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Figure 4.67 : Waveform of phase B voltage

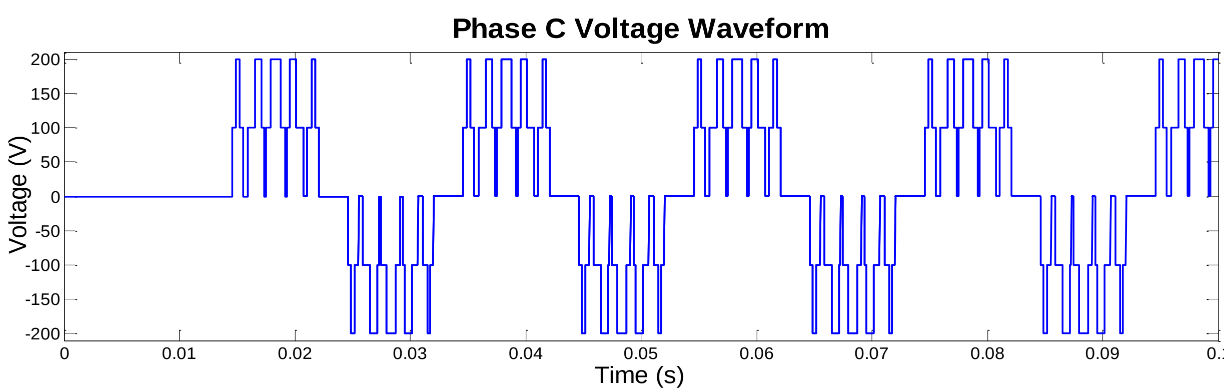

Figure 4.68 : Waveform of phase C voltage

By using RL load, the line-voltage waveform produced in SHE-PWM is shown in Figure 4.69, Figure 4.70 and Figure 4.71 respectively. The figures show the seven-level line-voltage waveform.

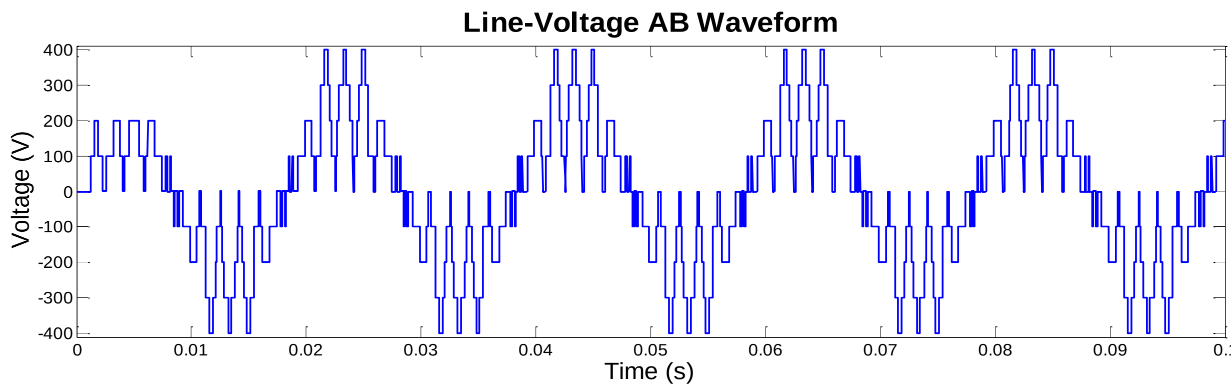

Figure 4.69 : Waveform of line AB voltage

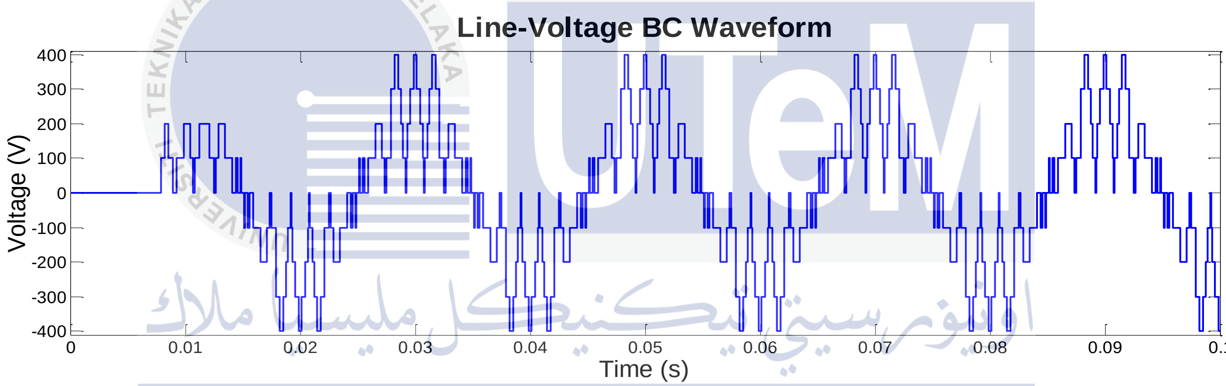

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Figure 4.70 : Waveform of line BC voltage

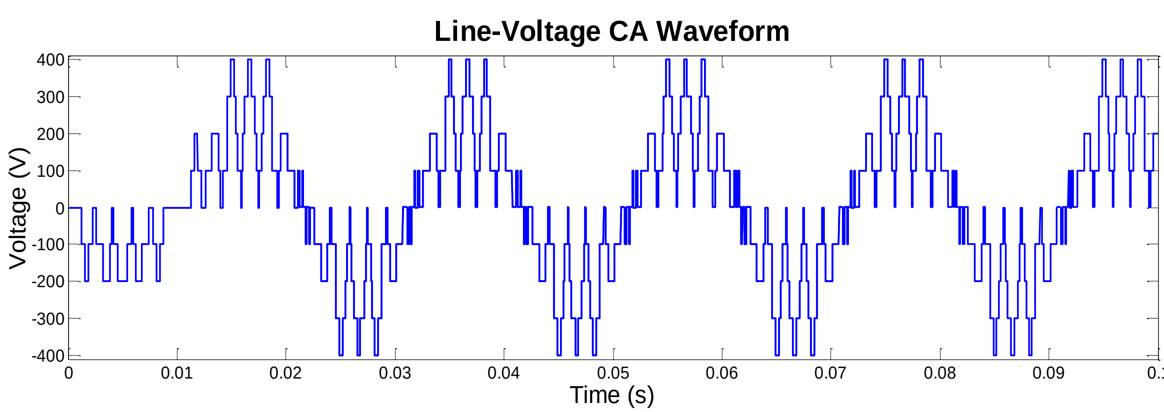

Figure 4.71 : Waveform of line CA voltage

The total harmonic distortion for current and voltage are shown in Figure 4.72, Figure 4.73 and Figure 4.74 respectively. The THDi for seven-level SHE-PWM is 8.59% and THDv of phase-voltage is 60.52%. The THDv of seven-level line-voltage for SHE-PWM is 35.80%. The switching angles of $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5 with the $\beta_1, \beta_2, \beta_3, \beta_4$ and β_5 angles are used to eliminate the voltage harmonic at 3rd, 5th, 7th and 9th harmonic order for seven-level inverter.

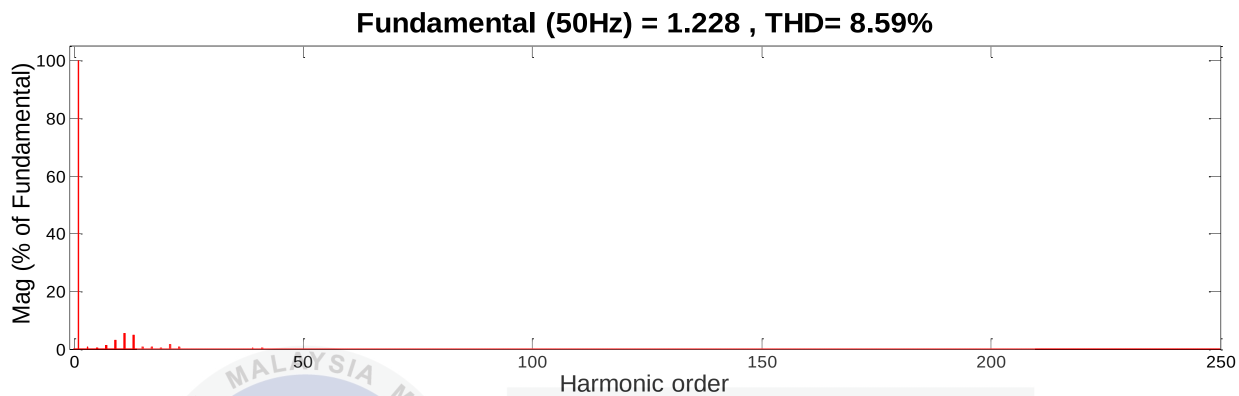

Figure 4.72 : Total Harmonic Distortion of current

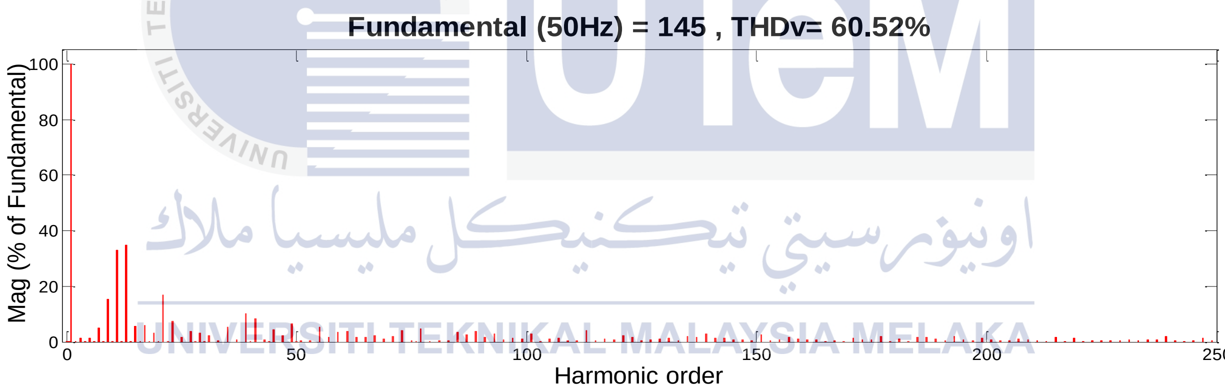

Figure 4.73 : Total Harmonic Distortion of phase-voltage

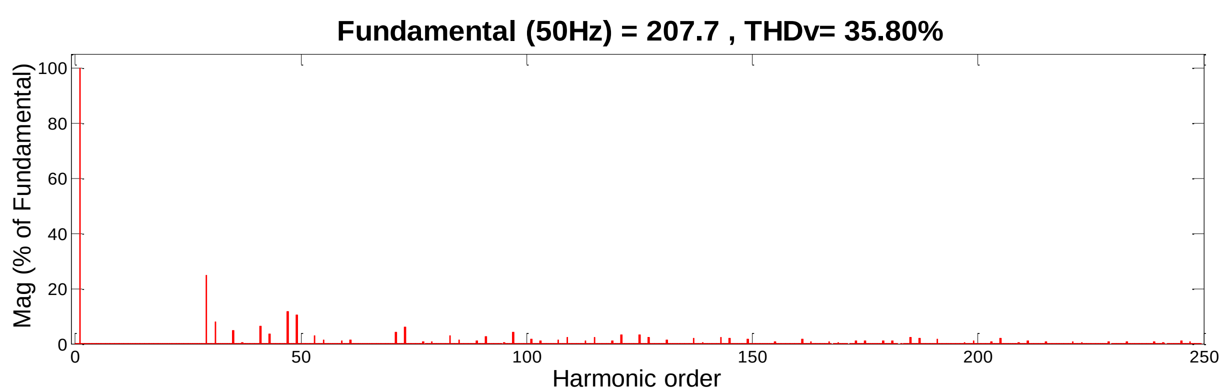

Figure 4.74 : Total Harmonic Distortion of line-voltage

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4.3.1.3 Three Phase Seven-Level Selective Harmonic Elimination-Pulse-Width Modulation Inverter for RC Load

By using RC load, the phase-current waveform produced in SHE-PWM is shown in Figure 4.75, Figure 4.76 and Figure 4.77 respectively. The shape of the waveform is different from R and RL load because there is a capacitance added in the load. The presence of the capacitance will affect the shape of current waveform.

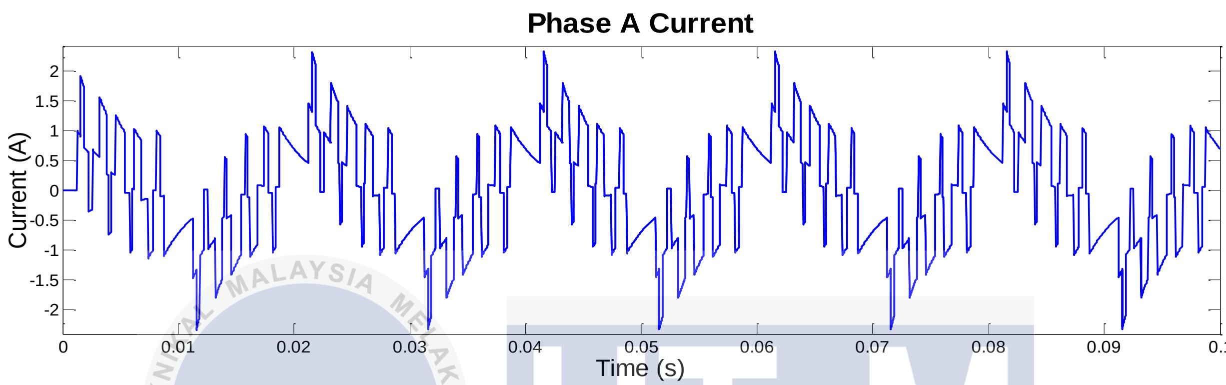

Figure 4.75 : Waveform of phase A current

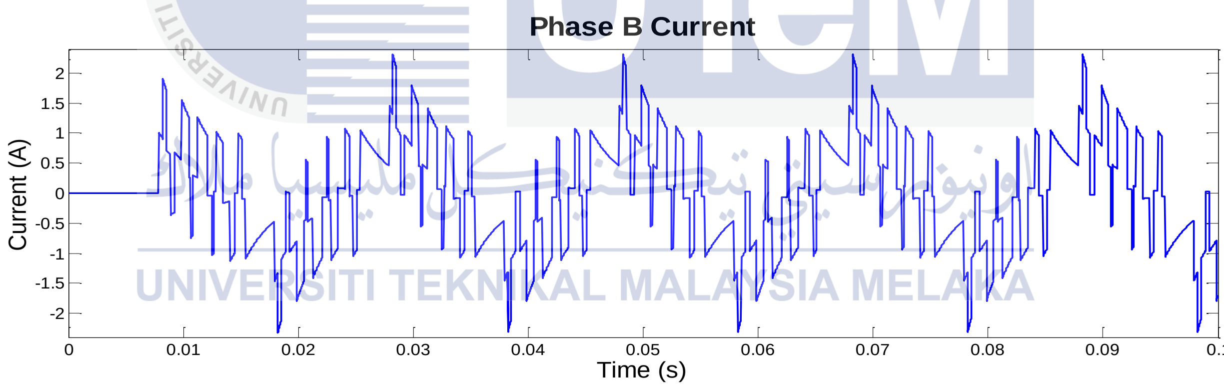

Figure 4.76 : Waveform of phase B current

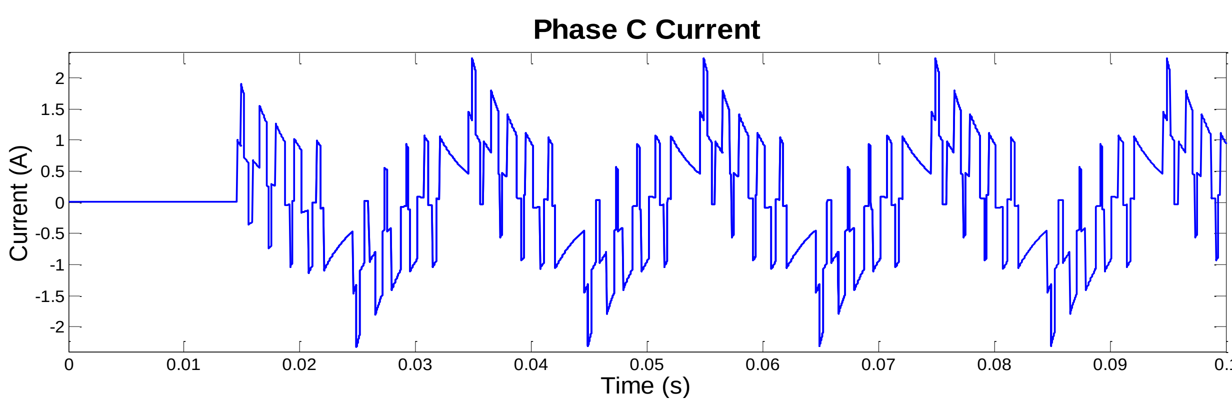

Figure 4.77 : Waveform of phase C current

By using RC load, the phase-voltage waveform produced in SHE-PWM is shown in Figure 4.78, Figure 4.79 and Figure 4.80 respectively. The waveform has no change and same as the R and RL load.

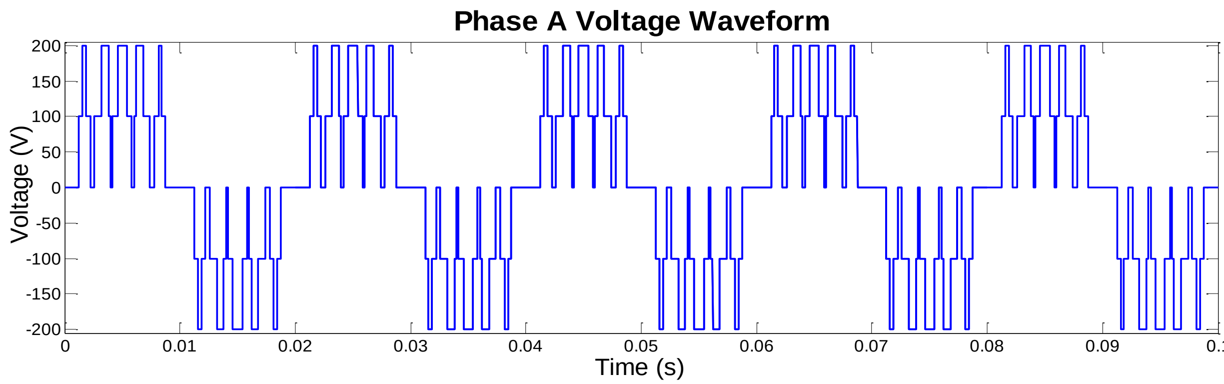

Figure 4.78 : Waveform of phase A voltage

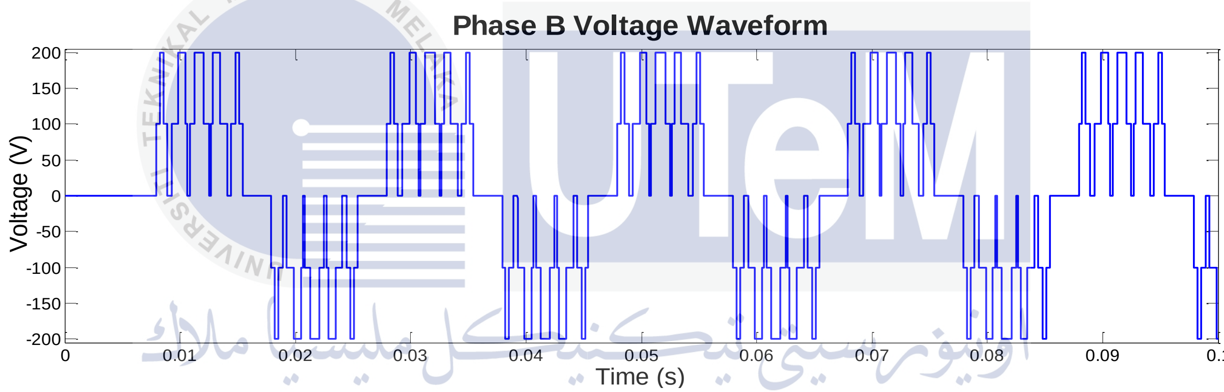

Figure 4.79 : Waveform of phase B voltage

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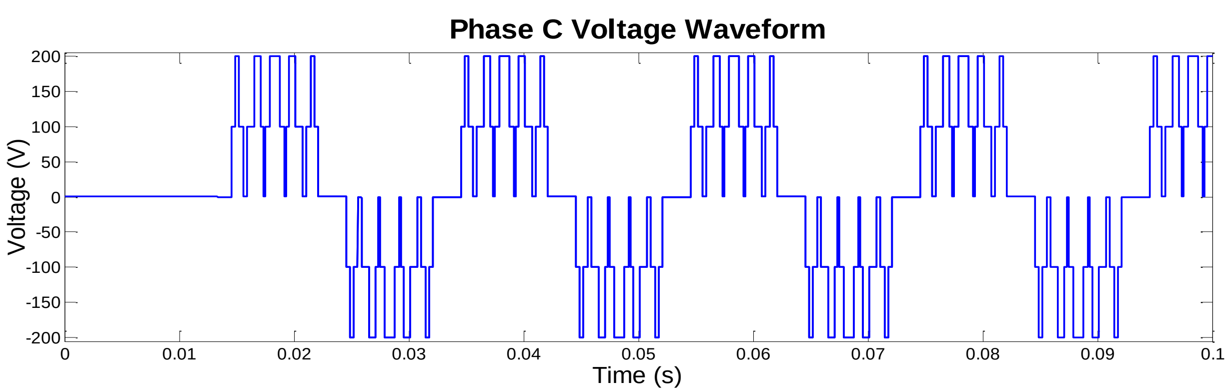

Figure 4.80 : Waveform of phase C voltage

By using RC load, the line-voltage waveform produced in SHE-PWM is shown in Figure 4.81, Figure 4.82 and Figure 4.83 respectively. The figures show the seven-level line-voltage waveform.

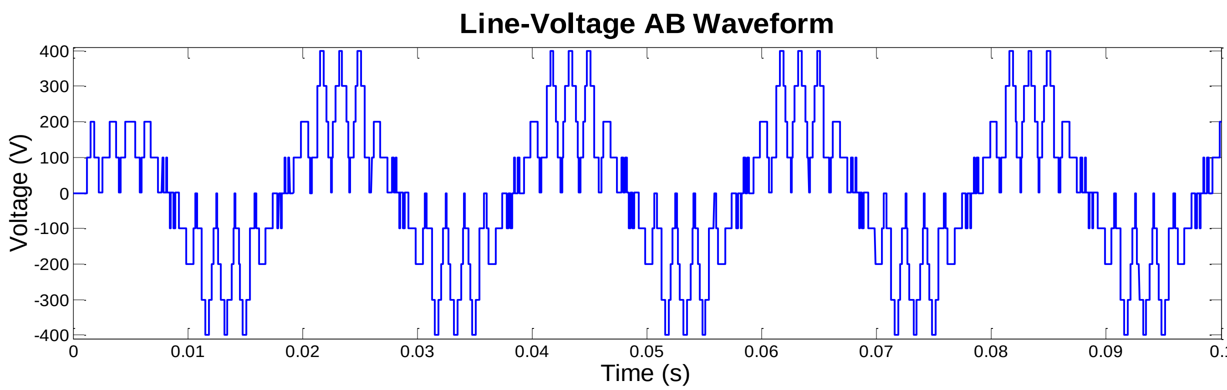

Figure 4.81 : Waveform of line AB voltage

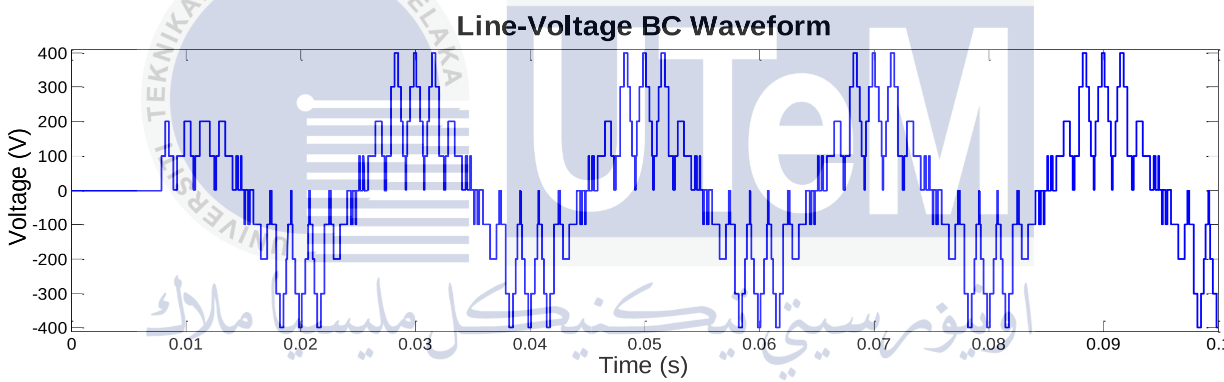

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Figure 4.82 : Waveform of line BC voltage

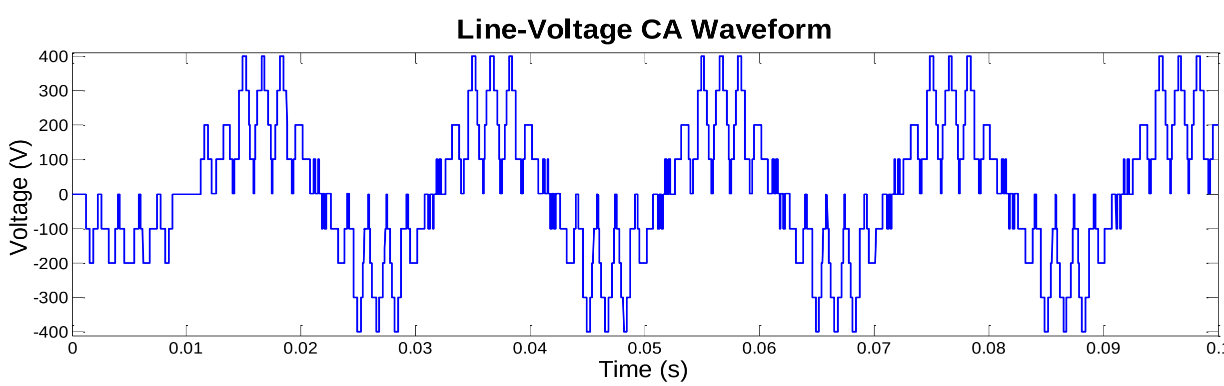

Figure 4.83 : Waveform of line CA voltage

The total harmonic distortion for current and voltage are shown in Figure 4.84, Figure 4.85 and Figure 4.86 respectively. The THDi for seven-level SHE-PWM is 87.95% and THDv of phase-voltage is 60.52%. The THDv of seven-level line-voltage for SHE-PWM is 35.77%. The switching angles of $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5 with the $\beta_1, \beta_2, \beta_3, \beta_4$ and β_5 angles are used to eliminate the voltage harmonic at 3rd, 5th, 7th and 9th harmonic order for seven-level inverter.

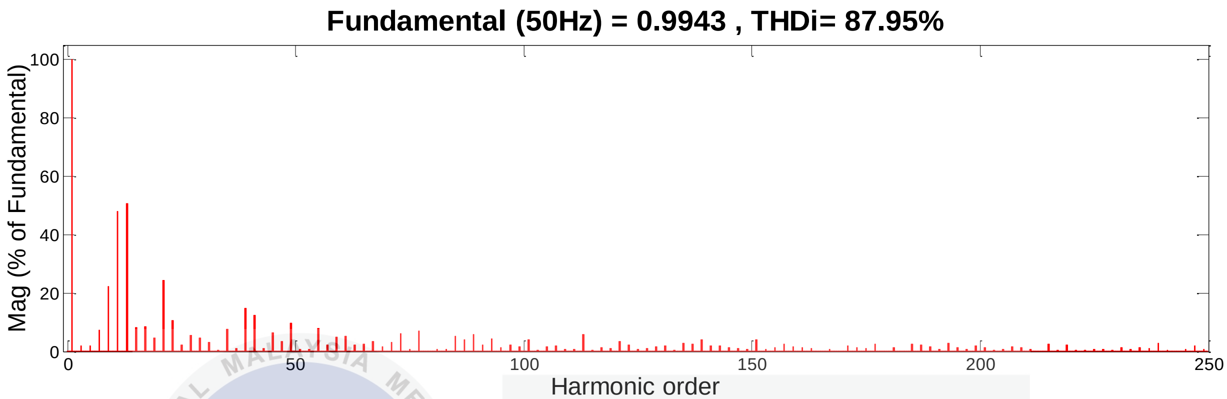

Figure 4.84 : Total harmonic distortion of current

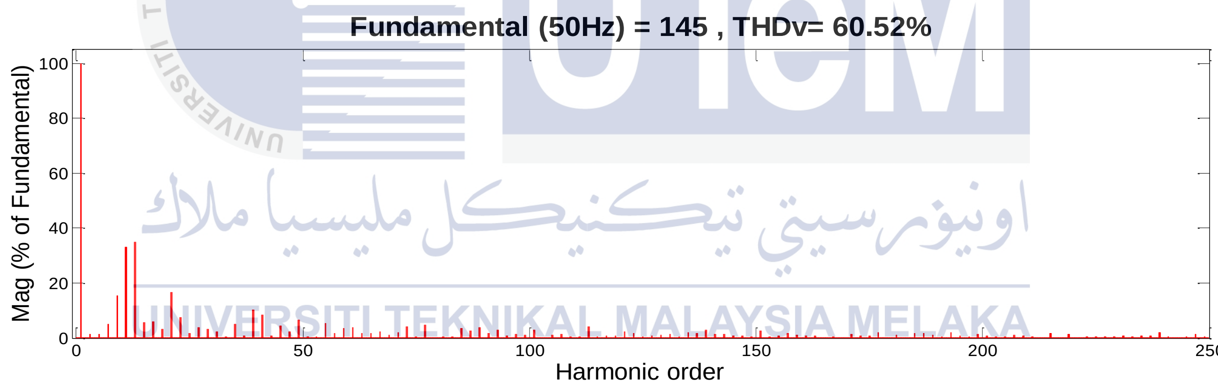

Figure 4.85 : Total harmonic distortion of phase-voltage

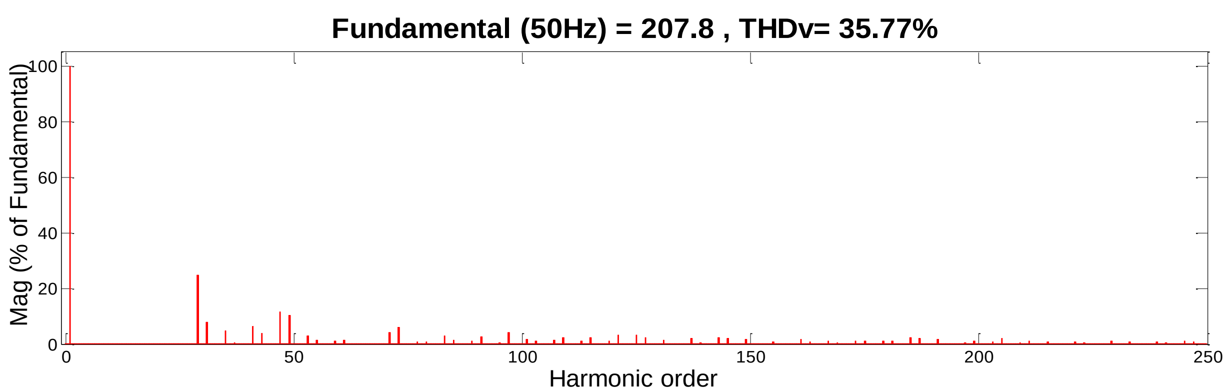

Figure 4.86 : Total harmonic distortion of line-voltage

4.3.2 Three Phase Seven-Level Trinary Multilevel Inverter

The three phase trinary inverter's current and voltage waveform for R, RL and RC loads are shown as following. In addition, the total harmonic distortion (THD) and percentage of harmonic are also shown in following figures. The trinary multilevel inverter's result will be used to compare with SHE-PWM multilevel inverter.

4.3.2.1 Three Phase Seven-Level Trinary Multilevel Inverter for R Load

The phase current waveforms of three phase trinary inverter using R load are shown in Figure 4.87, Figure 4.88 and Figure 4.89 respectively.

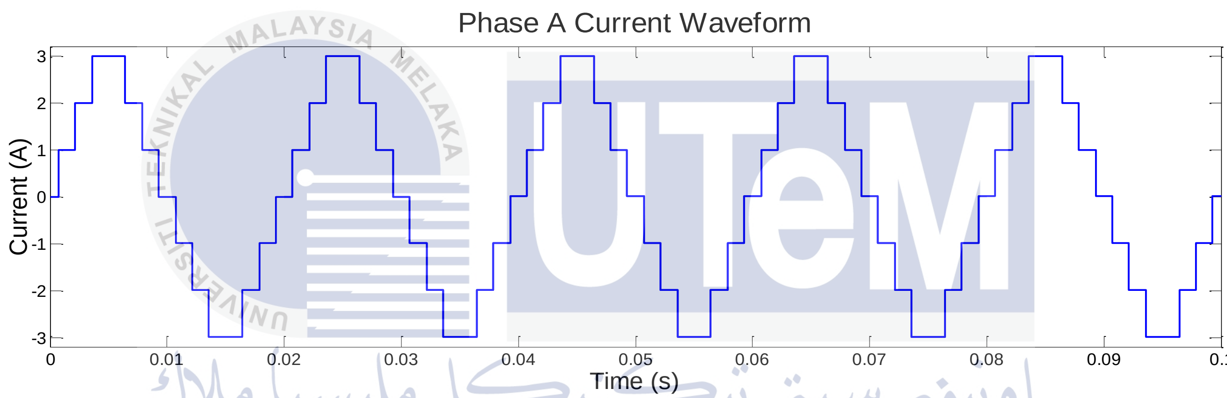

Figure 4.87 : Waveform of phase A current

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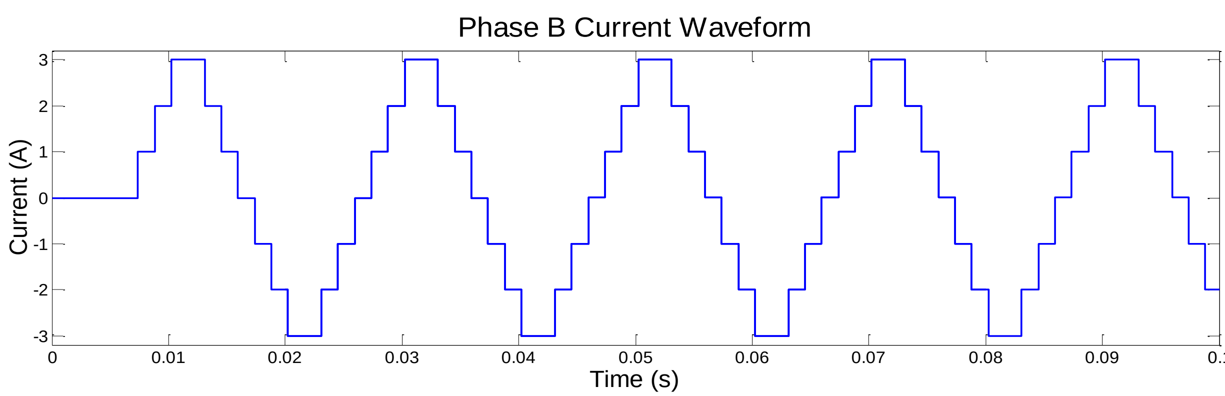

Figure 4.88 : Waveform of phase B current

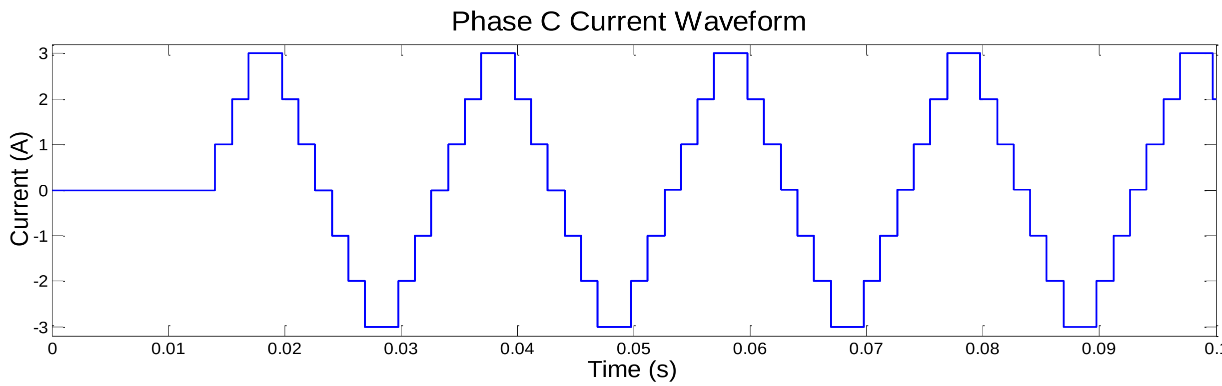

Figure 4.89 : Waveform of phase C current

The voltage waveforms of three phase trinary inverter are shown in Figure 4.90, Figure 4.91 and Figure 4.92 respectively.

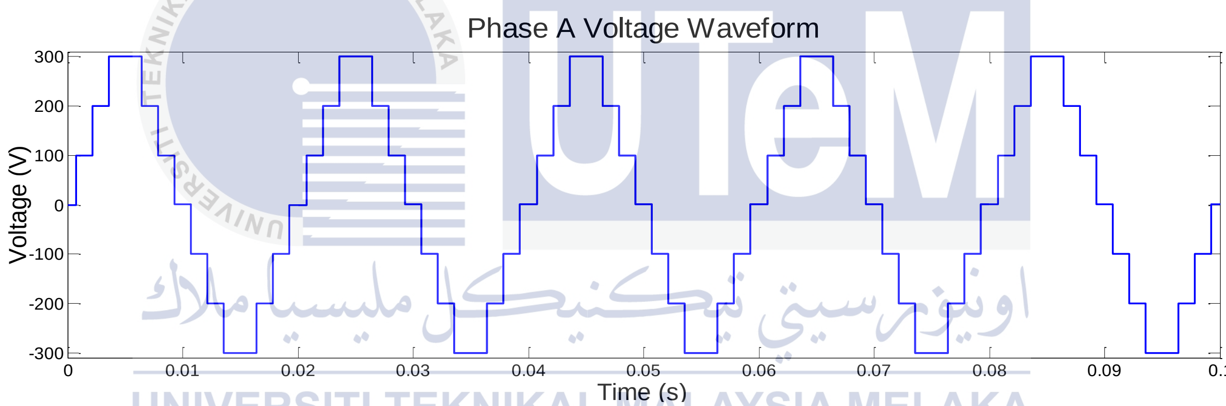

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Figure 4.90 : Waveform of phase A voltage

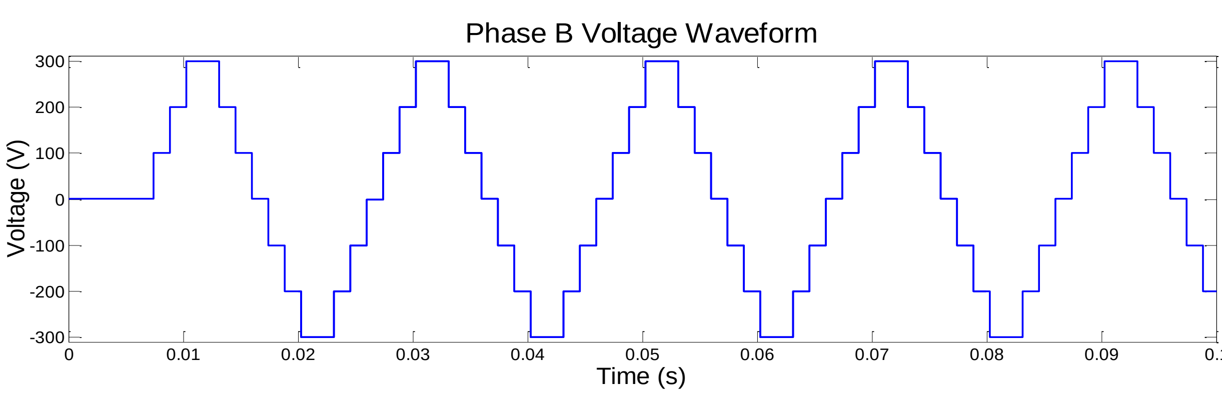

Figure 4.91 : Waveform of phase B voltage

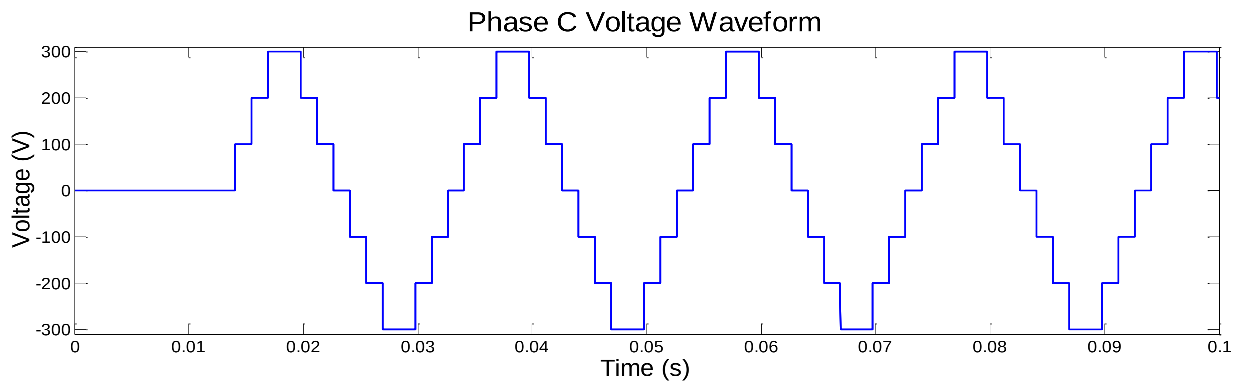

Figure 4.92 : Waveform of phase C voltage

The total harmonic distortion for current and voltage of R load for three phase trinary inverter are shown in Figure 4.93 and Figure 4.94 respectively. The THDi for seven-level trinary inverter is 16.83% and THDv of phase-voltage is 16.83%.

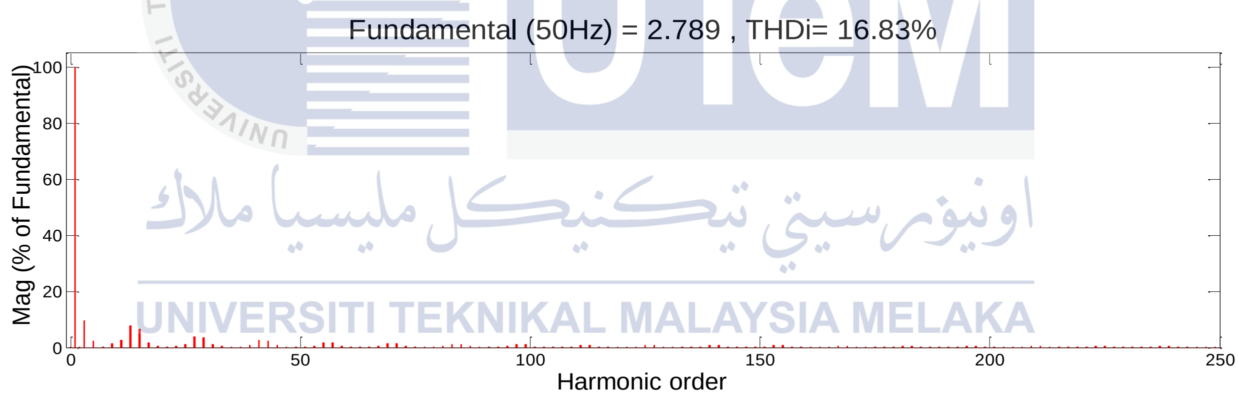

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Figure 4.93 : Total harmonic distortion of current

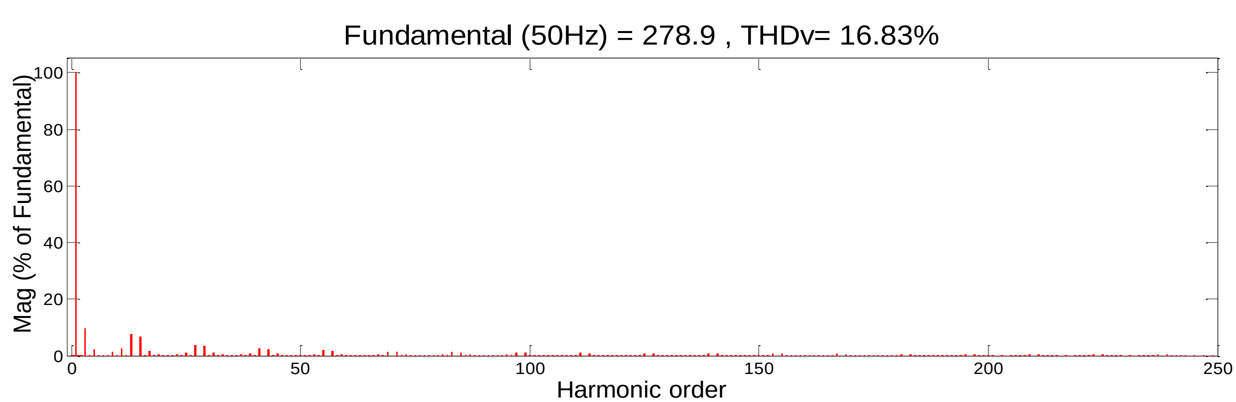

Figure 4.94 : Total harmonic distortion of voltage

4.3.2.2 Three Phase Seven-Level Trinary Multilevel Inverter for RL Load

The three phase trinary inverter current and voltage waveforms of RL load are shown in Figure 4.95, Figure 4.96 and Figure 4.97 respectively. The current waveform of seven-level trinary inverter is a sinusoidal shape due to the presence of inductance in the load.

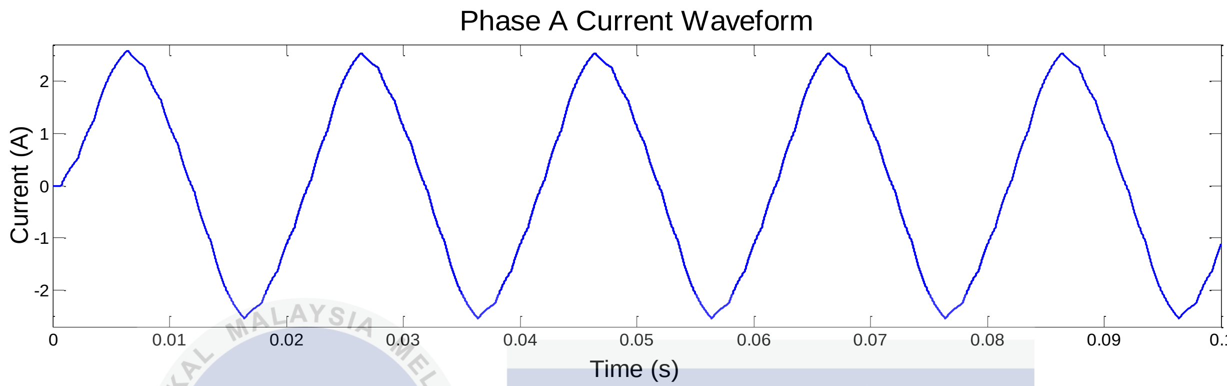

Figure 4.95 : Waveform of phase A current

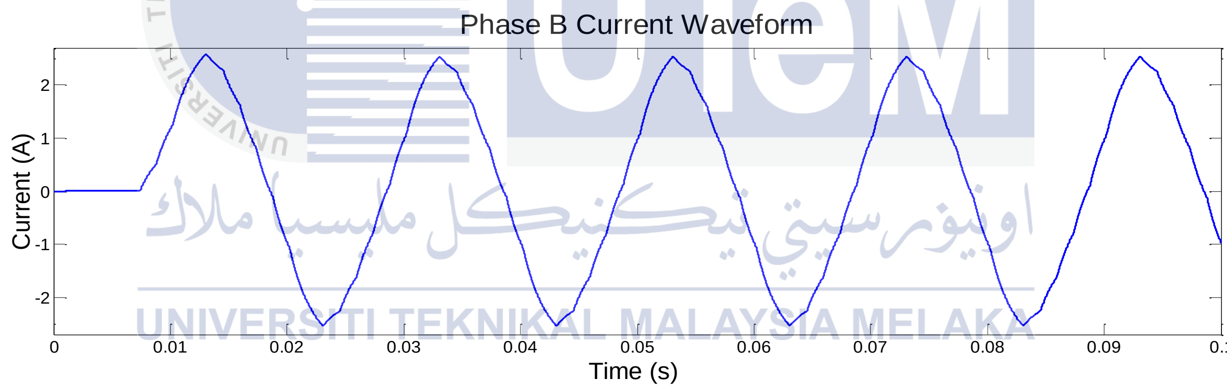

Figure 4.96 : Waveform of phase B current

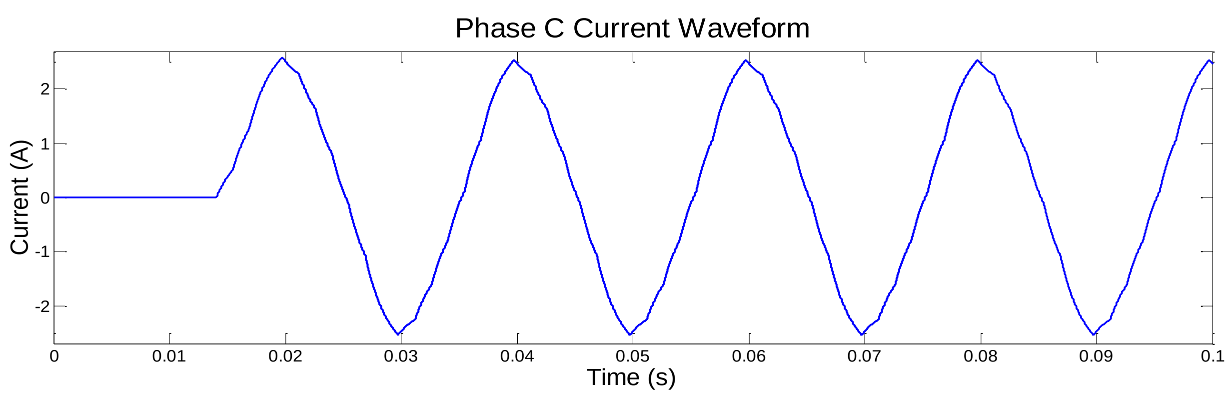

Figure 4.97 : Waveform of phase C current

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The voltage waveforms of three phase trinary inverter are shown in Figure 4.98, Figure 4.99 and Figure 4.100 respectively. It is same as the R load voltage waveform.

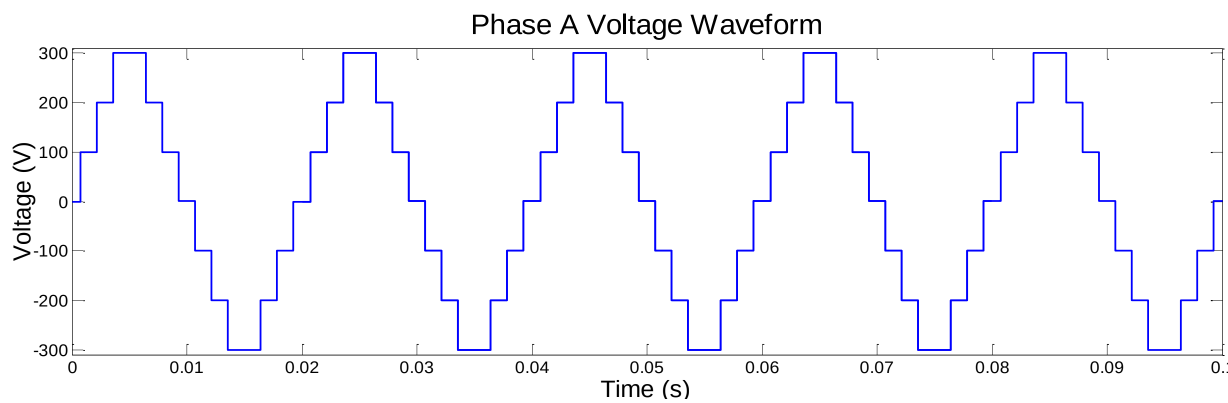

Figure 4.98 : Waveform of phase A voltage

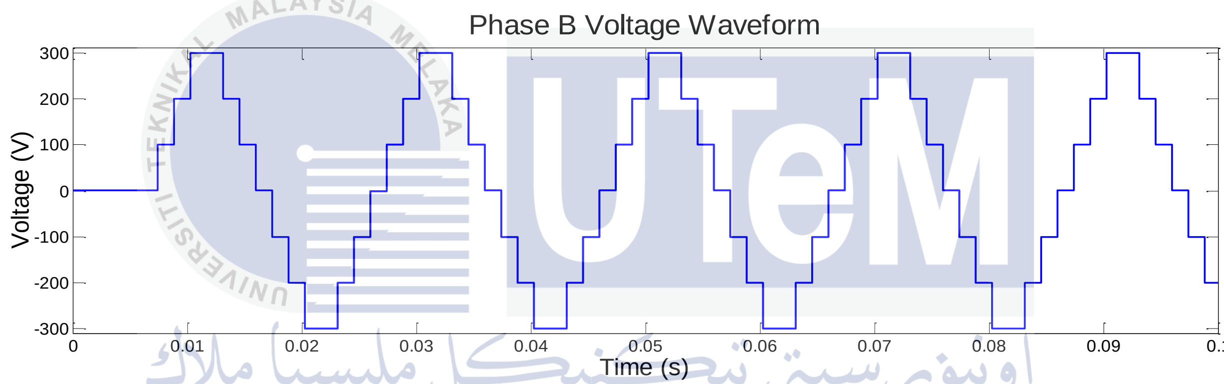

Figure 4.99 : Waveform of phase B voltage

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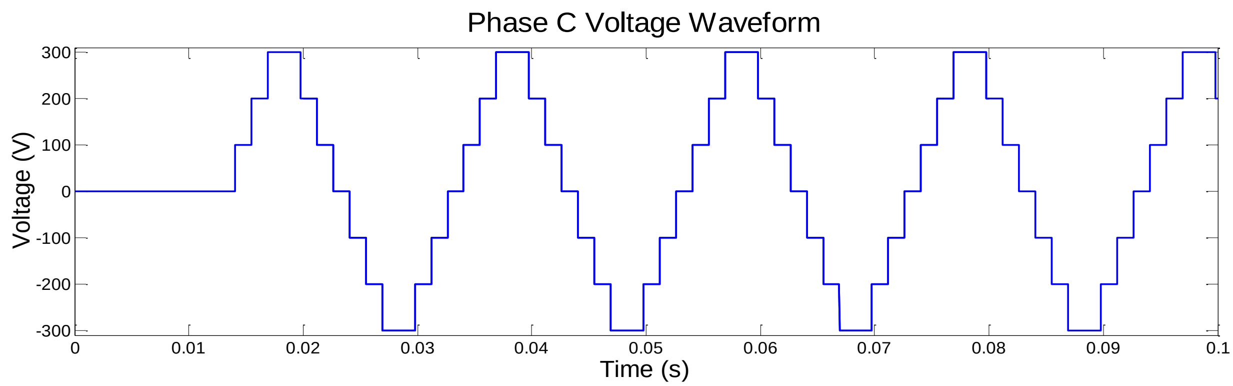

Figure 4.100 : Waveform of phase C voltage

The total harmonic distortion for current and voltage of RL load for three phase trinary inverter are shown in Figure 4.101 and Figure 4.102 respectively. The THDi for seven-level trinary inverter is 5.55% and THDv of phase-voltage is 16.83%.

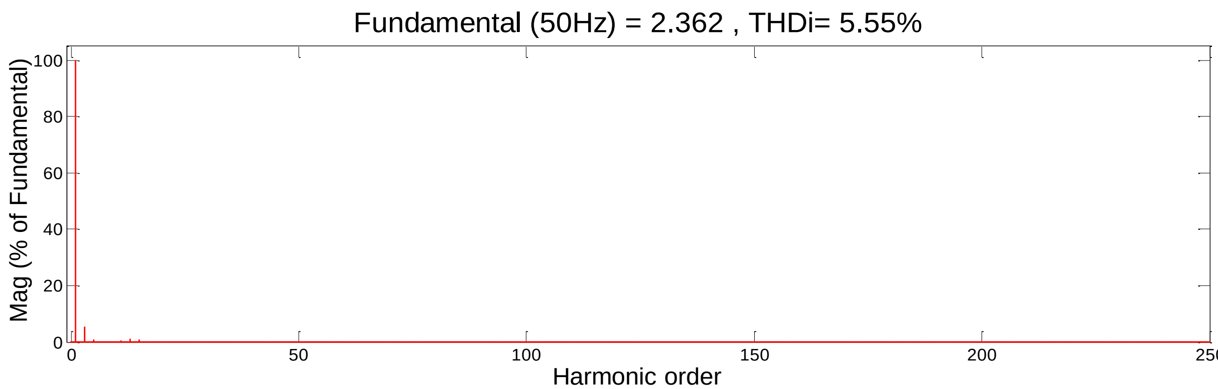

Figure 4.101 : Total harmonic distortion of current

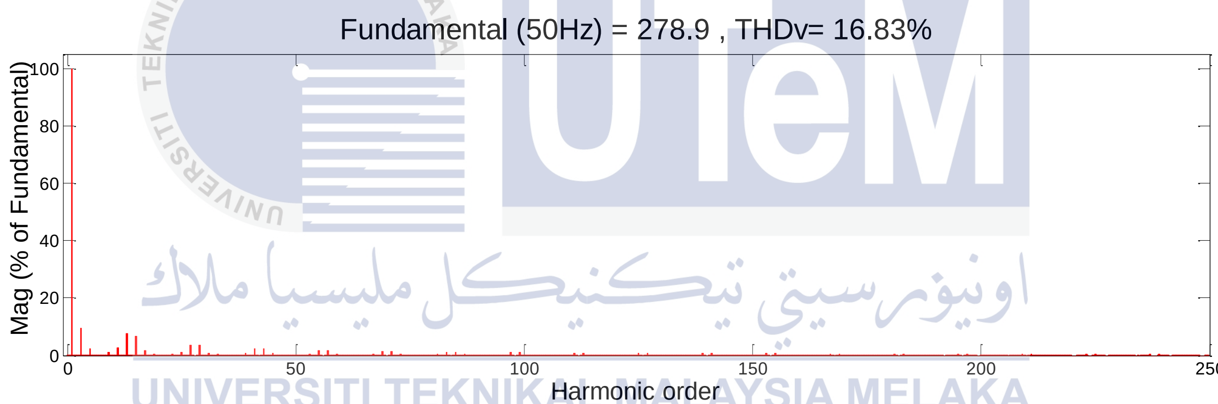

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Figure 4.102: Total harmonic distortion of voltage

4.3.2.3 Three Phase Seven-Level Trinary Multilevel Inverter for RC Load

The phase current waveforms of three phase trinary inverter are shown in Figure 4.103, Figure 4.104 and Figure 4.105 respectively. The current waveform shape is change because the capacitance is added in the load.

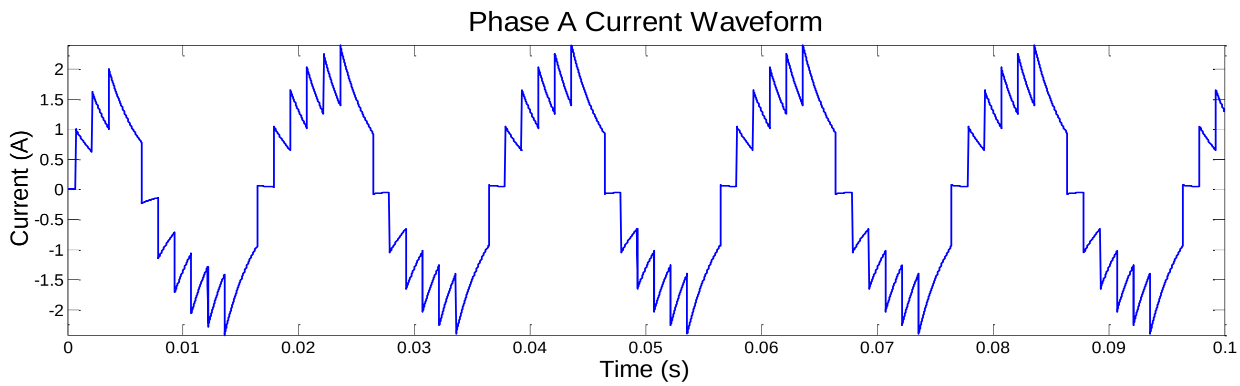

Figure 4.103 : Waveform of phase A current

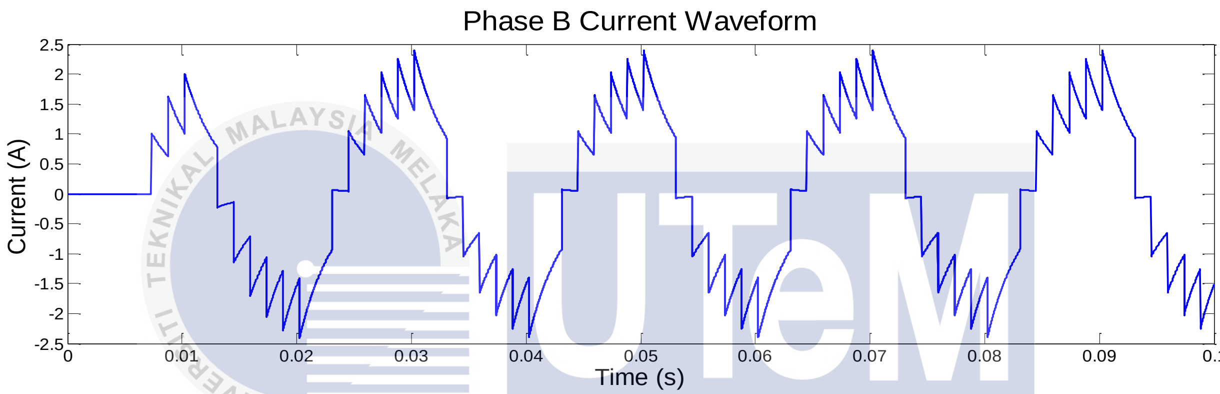

Figure 4.104 : Waveform of phase B current

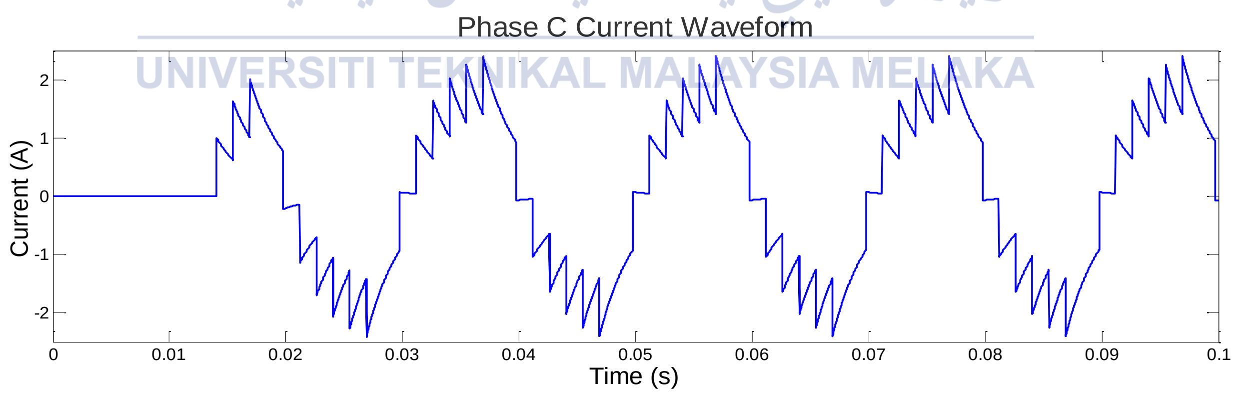

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Figure 4.105 : Waveform of phase C current

The voltage waveforms of three phase trinary inverter are shown in Figure 4.106, Figure 4.107 and Figure 4.108 respectively.

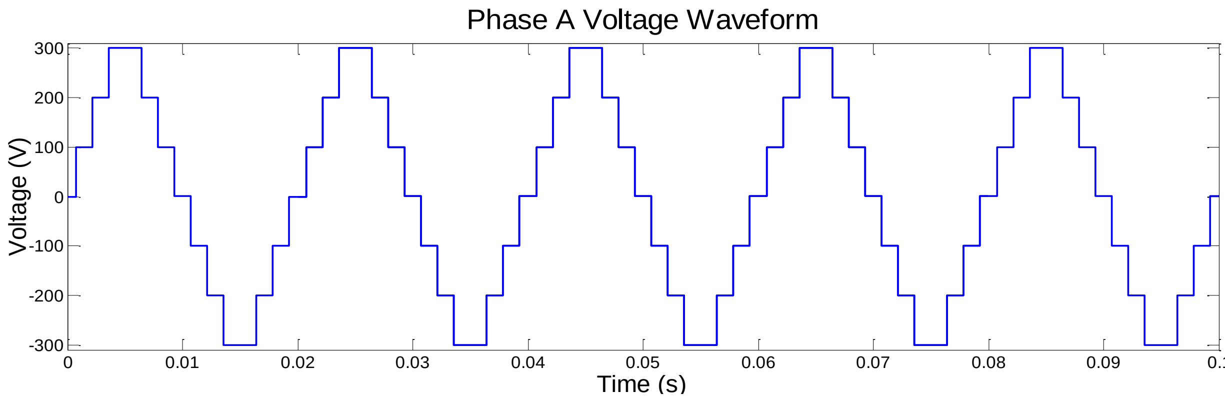

Figure 4.106 : Waveform of phase A voltage

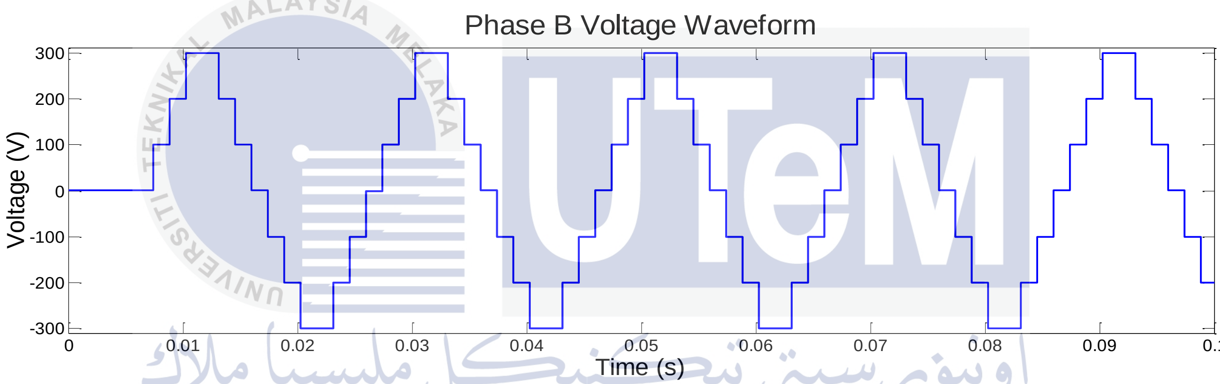

Figure 4.107 : Waveform of phase B voltage

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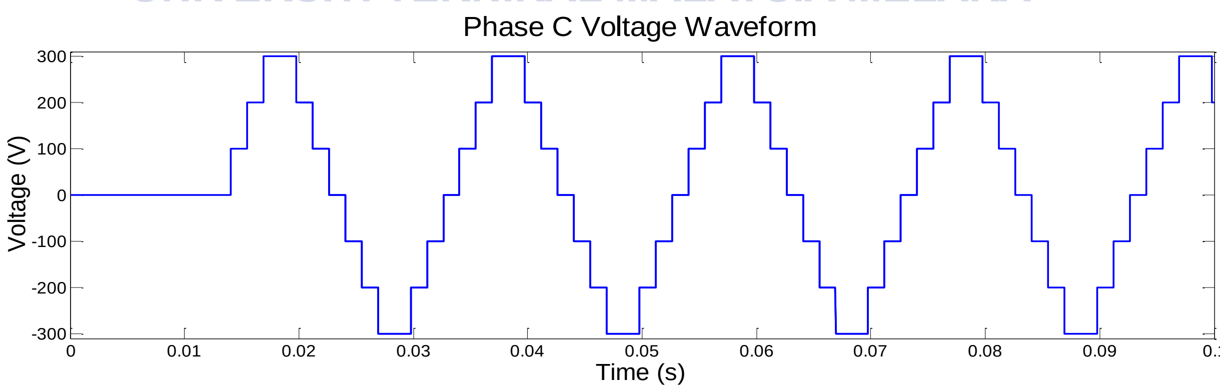

Figure 4.108 : Waveform of phase C voltage

The total harmonic distortion for current and voltage of RC load for three phase trinary inverter are shown in Figure 4.109 and Figure 4.110 respectively. The THDi for seven-level trinary inverter is 24.05% and THDv of phase-voltage is 16.82%.

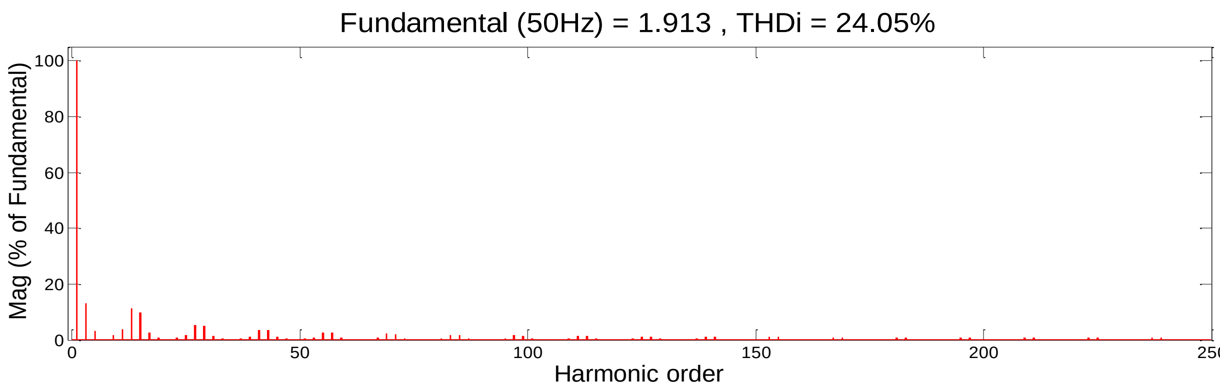

Figure 4.109 : Total harmonic distortion of current

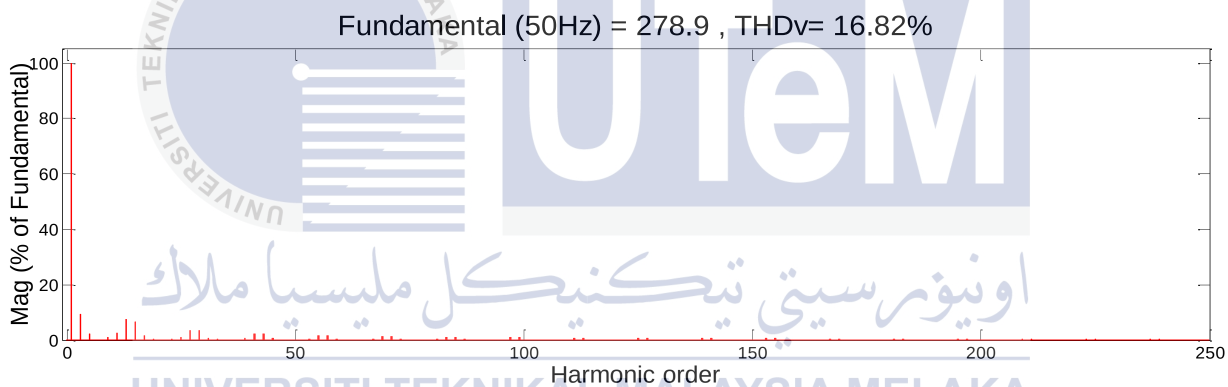

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Figure 4.110 : Total harmonic distortion of voltage

4.4 Total Harmonic Distortion

THD is defined as the ratio of the powers for all harmonic components to the power for the fundamental frequency. The THD for current (THDi) and voltage (THDv) of R, RL and RC loads that produced by different types of single phase inverters is shown in the Table 4.1. On the other hand, Table 4.2 shows the THD for current and voltage of R, RL and RC load for three phase SHE-PWM inverter.

Table 4.1: THD of current and voltage for several loads of single phase inverter

LOAD	Square Wave		Unipolar		Bipolar		SHE-PWM	
	THDi	THDv	THDi	THDv	THDi	THDv	THDi	THDv
R	48.34%	48.34%	83.54%	83.54%	160.01%	160.01%	68.09%	68.09%
RL	21.52%	48.34%	21.67%	207.33%	6.35%	160.02%	9.66%	68.09%
RC	66.59%	48.34%	111.86%	71.95%	246.40%	160.01%	104.69%	68.09%

The table above shows the total harmonic distortion (THD) of current and voltage for the different types of inverters with three types of loads. From the table, the square wave inverter has the lowest percentage of THDi and THDv among the inverters. However, its percentage of THDi for RL load is the highest compared to the bipolar and SHE-PWM inverter which is 21.52%. In RL load, bipolar inverter has the lowest percentage of THDi which is 6.35 %. All the inverters have constant percentage of THDv for R, RL and RC loads except unipolar inverter. Unipolar inverter has the highest percentage of THDv for RL load which is 207.33% among all the inverters. Besides that, all the percentages of THDi are reduced when the load has added an inductance whereas percentages of THDi for all inverters are increased when a capacitance is added in the load.

Table 4.2 : THD for current and voltage of three phase SHE-PWM inverter

Type of Multilevel Inverter	R Load		RL Load		RC Load	
	THDi	**THDv**	**THDi**	**THDv**	**THDi**	**THDv**
SHE-PWM	60.52%	35.79%	8.59%	35.80%	87.95%	35.77%
Trinary	16.83%	16.83%	5.55%	16.83%	24.05%	16.82%

The Table 4.2 shows the total harmonic distortion (THD) of current and voltage for three phase SHE-PWM inverter and three phase trinary inverter of several loads. The THDi for RC load is the highest for both inverters which are 87.95% and 16.83% respectively while the THDi for RL load of both inverters are the lowest that are only 8.59% and 5.55% respectively. The THDi for R load of SHE-PWM inverter is 60.52% and THDi for R load of trinary inverter is 16.83%%. This had proved that the passive components which are inductor and capacitor will affect the THD for current. This is because the inductance can act as a passive filter and reduce the harmonic at high frequency but the percentage of THDi is increase when the capacitance is added in the load. Next, the THDv for R load and RL load of three phase SHE-PWM inverter is same which has 53.84%. There is 53.81% of THDv for RC load. Furthermore, the THDv for three phase trinary inverter of R and RL loads also same which is 16.83%. The RC load's THDv for trinary inverter is 16.82%.

4.5 Percentage of Harmonic for Low and High Harmonic Order

The percentages of harmonic for different types of inverters are compared in the tables below. They are categorised in two groups that are low harmonic order which are 3^{rd}, 5^{th}, 7^{th} and 9^{th} and high harmonic order which are 99^{th} to 105^{th} and 199^{th} to 205^{th}.

4.5.1 Single Phase Inverter

The percentage of harmonic for low harmonic order such as 3^{rd}, 5^{th}, 7^{th} and 9^{th} is shown in Table 4.3 for single phase inverters. On the other hand, Table 4.4 and Table 4.5 show the percentage of harmonic for high harmonic order. The high orders that had been chosen are 99^{th} to 105^{th} and 199^{th} to 205^{th}.

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Table 4.3 : Percentage of harmonic at low harmonic order

Load	**R**				**RL**				**RC**			
Harmonic Order	3rd	5th	7th	9th	3rd	5th	7th	9th	3rd	5th	7th	9th
Square Wave	33.33%	20.00%	14.29%	11.11%	18.64%	7.39%	3.97%	2.51%	45.82%	28.52%	20.59%	16.09%
Unipolar	0.07%	0.14%	0.09%	0.05%	20.08%	6.29%	2.31%	1.23%	8.30%	2.19%	1.06%	0.77%
Bipolar	0.02%	0.16%	0.09%	0.00%	1.66%	1.08%	0.79%	0.62%	2.54%	1.84%	1.02%	0.90%
SHE-PWM	0.34%	0.07%	0.06%	0.30%	1.54%	1.02%	0.73%	0.60%	1.99%	1.44%	1.19%	1.31%

Table 4.4: Percentage of harmonic at 99th to 105th harmonic order

Load	**R**				**RL**				**RC**			
Harmonic Order	99th	101th	103th	105th	99th	101th	103th	105th	99th	101th	103th	105th
Square Wave	1.01%	0.99%	0.97%	0.95%	0.10%	0.10%	0.10%	0.09%	1.47%	1.44%	1.42%	1.39%
Unipolar	45.02%	44.89%	16.10%	1.43%	1.96%	1.73%	0.55%	0.06%	54.10%	54.56%	22.17%	4.01%
Bipolar	45.08%	44.88%	16.09%	1.49%	0.85%	0.84%	0.30%	0.06%	69.32%	69.18%	24.85%	2.37%
SHE-PWM	0.63%	3.32%	1.41%	3.44%	0.06%	0.08%	0.06%	0.09%	1.05%	5.03%	2.24%	5.36%

Table 4.5 : Percentage of harmonic at 199th to 205th harmonic order

Load	**R**				**RL**				**RC**			
Harmonic Order	199th	201th	203th	205th	199th	201th	203th	205th	199th	201th	203th	205th
Square Wave	0.50%	0.50%	0.49%	0.49%	0.05%	0.05%	0.05%	0.05%	0.73%	0.73%	0.72%	0.71%
Unipolar	11.97%	12.02%	17.24%	9.51%	0.25%	0.26%	0.33%	0.17%	13.48%	13.61%	21.31%	12.65%
Bipolar	11.94%	12.01%	17.32%	9.55%	0.11%	0.12%	0.16%	0.09%	18.34%	18.53%	26.63%	14.66%
SHE-PWM	1.47%	0.56%	0.96%	1.46%	0.03%	0.03%	0.03%	0.03%	2.30%	0.82%	1.51%	2.28%

From the tables shown above, the square wave has high percentage of harmonic at low harmonic order among the types of inverter. However, it has the lowest percentage of harmonic at high harmonic order for R, RL and RC loads. In unipolar and bipolar inverter, the percentage of harmonic at low frequency is small and almost zero but at high harmonic order, the percentage of harmonic is large compare to the square wave and SHE-PWM inverter. This has lead to the high THD in unipolar and bipolar inverter. Besides that, the SHE-PWM inverter has low percentage of harmonic at low and high harmonic order compared to unipolar and bipolar. In low harmonic order, SHE-PWM has the low percentage of harmonic that almost near to zero. It is better than square wave which it had eliminated the low harmonic at 3rd, 5th, 7th and 9th order.

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4.5.2 Three Phase Seven-Level Inverter

The percentage of harmonic for three phase SHE-PWM and trinary inverter at low order is shown at Table 4.6. On the other hand, Table 4.7 and 4.8 shows the percentage of harmonic at higher orders which are 99th to 105th and 199th to 205th for three phase SHE-PWM inverter.

Table 4.6 : Percentage of harmonic at low harmonic order

Load	**R**				**RL**				**RC**			
Harmonic Order	3rd	5th	7th	9th	3rd	5th	7th	9th	3rd	5th	7th	9th
SHE-PWM	0.00%	0.01%	0.01%	0.00%	0.00%	0.01%	0.01%	0.00%	0.02%	0.02%	0.01%	0.01%
Trinary	9.54%	2.20%	0.01%	1.22%	9.54%	2.19%	0.01%	1.22%	9.54%	2.19%	0.01%	1.22%

Table 4.7 : Percentage of harmonic at 99th to 105th harmonic order

Harmonic Order	99th	101th	103th	105th	99th	101th	103th	105th	99th	101th	103th	105th
SHE-PWM	0.02%	1.64%	1.17%	0.00%	0.02%	1.64%	1.17%	0.00%	0.02%	1.64%	1.17%	0.00%
Trinary	1.01%	0.28%	0.10%	0.01%	1.01%	0.28%	0.10%	0.01%	1.01%	0.28%	0.10%	0.01%

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Table 4.8 : Percentage of harmonic at 199th to 205th harmonic order

Load	**R**				**RL**				**RC**			
Harmonic Order	199th	201th	203th	205th	199th	201th	203th	205th	199th	201th	203th	205th
SHE-PWM	1.07%	0.01%	0.64%	2.10%	1.07%	0.01%	0.64%	2.10%	1.07%	0.02%	0.62%	2.12%
Trinary	0.14%	0.05%	0.01%	0.06%	0.14%	0.05%	0.01%	0.06%	0.14%	0.05%	0.01%	0.06%

From the tables above, the triplen harmonic of SHE-PWM inverter had been eliminated. The percentage of harmonic for 5th and 7th order also eliminated which is only 0.01% for both of the order. R and RL loads have the same percentage of harmonic for 5th and 7th harmonic order. The RC load has different percentage compare to R and RL loads but is nearer to zero. This had shown that the SHE-PWM technique can be use to eliminate the chosen lower harmonic order. For trinary inverter, the 3rd order has 9.54% of harmonic and 5th order of has 2.20% of harmonic. Next, the 7th and 9th order of trinary inverter have 0.01% and 1.22% of harmonic respectively. This shows the harmonic at low harmonic order for trinary inverter is higher than SHE-PWM inverter. This trinary technique cannot eliminate the harmonic at low order.

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CHAPTER 5

CONCLUSION

5.1 Conclusion

In conclusion, the simulation result has proved that the SHE-PWM technique can eliminated the harmonic for selected order. SHE-PWM can eliminates the low switching frequency harmonic that is difficult to filter by passive filter. Among the four single phase inverter, SHE-PWM inverter is a good technique to be chosen because it has low percentage harmonic in low and high harmonic order compared to square wave, unipolar and bipolar. SHE-PWM has the advantages which it can eliminate the harmonic at low frequency. The harmonic at low frequency should be eliminated because mostly equipments are sensitive with the harmonic at low frequency. Furthermore, the switching frequency of unipolar and bipolar is high and the THD is low but this result in higher power losses. SHE-PWM has low switching frequency and same THD as unipolar and bipolar which lead to low power losses. It is due to the change of switching frequency will affect the power losses. Either single phase or three phase of SHE-PWM multilevel inverter, the percentage of harmonic for selected of low harmonic order can be eliminated by using this technique.

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5.2 Recommendation

The SHE-PWM technique can be used for improving the hardware in the future. Since the simulation results had proved the harmonic at low harmonic order can be eliminated, thus the harmonic in the equipment can be reduced by using SHE-PWM technique.

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PUBLICATION

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APPENDICES

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APPENDIX A

The coding of the calculation for switching angle α single phase SHE-PWM using m-file is shown as following. The alpha, α angles is used to control the switching of H-bridge. The alpha angles obtained from the coding are shown as following:

$$\alpha_1 = 22.5833$$
$$\alpha_2 = 33.6015$$
$$\alpha_3 = 46.6430$$
$$\alpha_4 = 68.4979$$
$$\alpha_5 = 75.0974$$

For the equation that used to obtain the matrix y is

$$y = \frac{\pi}{4}M$$

where M is the modulation index which the value used in this calculation is 0.85.

```
clear;
y=[ 0.6676
   0
   0
   0
   0];
t=0.000001;

alpha1=20; %20deg
alpha2=30; %30deg
alpha3=50; %50deg
alpha4=70; %70deg
alpha5=80; %80deg

a1=(alpha1*pi)/180; %change angle from degree to radian form
a2=(alpha2*pi)/180;
a3=(alpha3*pi)/180;
a4=(alpha4*pi)/180;
a5=(alpha5*pi)/180;

x=[alpha1
```

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```
    alpha2
    alpha3
    alpha4
    alpha5];

for i=1:10
    J(1,1)=(cos(a1)-cos(a2)+cos(a3)-cos(a4)+cos(a5));
    J(2,1)=(cos(3*a1)-cos(3*a2)+cos(3*a3)-cos(3*a4)+cos(3*a5));
    J(3,1)=(cos(5*a1)-cos(5*a2)+cos(5*a3)-cos(5*a4)+cos(5*a5));
    J(4,1)=(cos(7*a1)-cos(7*a2)+cos(7*a3)-cos(7*a4)+cos(7*a5));
    J(5,1)=(cos(9*a1)-cos(9*a2)+cos(9*a3)-cos(9*a4)+cos(9*a5));
end
for j=1:10
    K=[-sin(a1) +sin(a2) -sin(a3) +sin(a4) -sin(a5)
    -(3*sin(3*a1)) +(3*sin(3*a2)) -(3*sin(3*a3)) +(3*sin(3*a4)) -(3*sin(3*a5))
    -(5*sin(5*a1)) +(5*sin(5*a2)) -(5*sin(5*a3)) +(5*sin(5*a4)) -(5*sin(5*a5))
    -(7*sin(7*a1)) +(7*sin(7*a2)) -(7*sin(7*a3)) +(7*sin(7*a4)) -(7*sin(7*a5))
    -(9*sin(9*a1)) +(9*sin(9*a2)) -(9*sin(9*a3)) +(9*sin(9*a4)) -(9*sin(9*a5))];
end
J
K
da=inv(K)*(y-J);
da
A=radtodeg(da);
A
B=x+A;
B

x=B;
b1=(x(1,1)*pi)/180;
b2=(x(2,1)*pi)/180;
b3=(x(3,1)*pi)/180;
b4=(x(4,1)*pi)/180;
b5=(x(5,1)*pi)/180;

for i=1:10
    J(1,1)=(cos(b1)-cos(b2)+cos(b3)-cos(b4)+cos(b5));
    J(2,1)=(cos(3*b1)-cos(3*b2)+cos(3*b3)-cos(3*b4)+cos(3*b5));
    J(3,1)=(cos(5*b1)-cos(5*b2)+cos(5*b3)-cos(5*b4)+cos(5*b5));
    J(4,1)=(cos(7*b1)-cos(7*b2)+cos(7*b3)-cos(7*b4)+cos(7*b5));
    J(5,1)=(cos(9*b1)-cos(9*b2)+cos(9*b3)-cos(9*b4)+cos(9*b5));
end
for j=1:10
    K=[-sin(b1) +sin(b2) -sin(b3) +sin(b4) -sin(b5)
    -(3*sin(3*b1)) +(3*sin(3*b2)) -(3*sin(3*b3)) +(3*sin(3*b4)) -(3*sin(3*b5))
    -(5*sin(5*b1)) +(5*sin(5*b2)) -(5*sin(5*b3)) +(5*sin(5*b4)) -(5*sin(5*b5))
    -(7*sin(7*b1)) +(7*sin(7*b2)) -(7*sin(7*b3)) +(7*sin(7*b4)) -(7*sin(7*b5))
    -(9*sin(9*b1)) +(9*sin(9*b2)) -(9*sin(9*b3)) +(9*sin(9*b4)) -(9*sin(9*b5))];
end
J
K
```

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```
da=inv(K)*(y-J);
da
C=radtodeg(da);
C
D=x+C;

w=D
c1=(w(1,1)*pi)/180;
c2=(w(2,1)*pi)/180;
c3=(w(3,1)*pi)/180;
c4=(w(4,1)*pi)/180;
c5=(w(5,1)*pi)/180;

for i=1:10
   J(1,1)=(cos(c1)-cos(c2)+cos(c3)-cos(c4)+cos(c5));
   J(2,1)=(cos(3*c1)-cos(3*c2)+cos(3*c3)-cos(3*c4)+cos(3*c5));
   J(3,1)=(cos(5*c1)-cos(5*c2)+cos(5*c3)-cos(5*c4)+cos(5*c5));
   J(4,1)=(cos(7*c1)-cos(7*c2)+cos(7*c3)-cos(7*c4)+cos(7*c5));
   J(5,1)=(cos(9*c1)-cos(9*c2)+cos(9*c3)-cos(9*c4)+cos(9*c5));
end
for j=1:10
   K=[-sin(c1) +sin(c2) -sin(c3) +sin(c4) -sin(c5)
   -(3*sin(3*c1)) +(3*sin(3*c2)) -(3*sin(3*c3)) +(3*sin(3*c4)) -(3*sin(3*c5))
   -(5*sin(5*c1)) +(5*sin(5*c2)) -(5*sin(5*c3)) +(5*sin(5*c4)) -(5*sin(5*c5))
   -(7*sin(7*c1)) +(7*sin(7*c2)) -(7*sin(7*c3)) +(7*sin(7*c4)) -(7*sin(7*c5))
   -(9*sin(9*c1)) +(9*sin(9*c2)) -(9*sin(9*c3)) +(9*sin(9*c4)) -(9*sin(9*c5))];
end

J
K
da=inv(K)*(y-J);
da
O=radtodeg(da);
O
P=w+O;
P

z=P;
d1=(z(1,1)*pi)/180;
d2=(z(2,1)*pi)/180;
d3=(z(3,1)*pi)/180;
d4=(z(4,1)*pi)/180;
d5=(z(5,1)*pi)/180;

for i=1:10
   J(1,1)=(cos(d1)-cos(d2)+cos(d3)-cos(d4)+cos(d5));
   J(2,1)=(cos(3*d1)-cos(3*d2)+cos(3*d3)-cos(3*d4)+cos(3*d5));
   J(3,1)=(cos(5*d1)-cos(5*d2)+cos(5*d3)-cos(5*d4)+cos(5*d5));
   J(4,1)=(cos(7*d1)-cos(7*d2)+cos(7*d3)-cos(7*d4)+cos(7*d5));
   J(5,1)=(cos(9*d1)-cos(9*d2)+cos(9*d3)-cos(9*d4)+cos(9*d5));
end
```

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```
for j=1:10
   K=[-sin(d1) +sin(d2) -sin(d3) +sin(d4) -sin(d5)
   -(3*sin(3*d1)) +(3*sin(3*d2)) -(3*sin(3*d3)) +(3*sin(3*d4)) -(3*sin(3*d5))
   -(5*sin(5*d1)) +(5*sin(5*d2)) -(5*sin(5*d3)) +(5*sin(5*d4)) -(5*sin(5*d5))
   -(7*sin(7*d1)) +(7*sin(7*d2)) -(7*sin(7*d3)) +(7*sin(7*d4)) -(7*sin(7*d5))
   -(9*sin(9*d1)) +(9*sin(9*d2)) -(9*sin(9*d3)) +(9*sin(9*d4)) -(9*sin(9*d5))];
end

J
K
da=inv(K)*(y-J);
da
E=radtodeg(da);
E
F=z+E;
F

k=F;
e1=(k(1,1)*pi)/180;
e2=(k(2,1)*pi)/180;
e3=(k(3,1)*pi)/180;
e4=(k(4,1)*pi)/180;
e5=(k(5,1)*pi)/180;

for i=1:10
   J(1,1)=(cos(e1)-cos(e2)+cos(e3)-cos(e4)+cos(e5));
   J(2,1)=(cos(3*e1)-cos(3*e2)+cos(3*e3)-cos(3*e4)+cos(3*e5));
   J(3,1)=(cos(5*e1)-cos(5*e2)+cos(5*e3)-cos(5*e4)+cos(5*e5));
   J(4,1)=(cos(7*e1)-cos(7*e2)+cos(7*e3)-cos(7*e4)+cos(7*e5));
   J(5,1)=(cos(9*e1)-cos(9*e2)+cos(9*e3)-cos(9*e4)+cos(9*e5));
end
for j=1:10
   K=[-sin(e1) +sin(e2) -sin(e3) +sin(e4) -sin(e5)
   -(3*sin(3*e1)) +(3*sin(3*e2)) -(3*sin(3*e3)) +(3*sin(3*e4)) -(3*sin(3*e5))
   -(5*sin(5*e1)) +(5*sin(5*e2)) -(5*sin(5*e3)) +(5*sin(5*e4)) -(5*sin(5*e5))
   -(7*sin(7*e1)) +(7*sin(7*e2)) -(7*sin(7*e3)) +(7*sin(7*e4)) -(7*sin(7*e5))
   -(9*sin(9*e1)) +(9*sin(9*e2)) -(9*sin(9*e3)) +(9*sin(9*e4)) -(9*sin(9*e5))];
end

J
K
da=inv(K)*(y-J);
da
G=radtodeg(da);
G
H=k+G;
H

m=H;
f1=(m(1,1)*pi)/180;
f2=(m(2,1)*pi)/180;
```

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```
f3=(m(3,1)*pi)/180;
f4=(m(4,1)*pi)/180;
f5=(m(5,1)*pi)/180;

for i=1:10
   J(1,1)=(cos(f1)-cos(f2)+cos(f3)-cos(f4)+cos(f5));
   J(2,1)=(cos(3*f1)-cos(3*f2)+cos(3*f3)-cos(3*f4)+cos(3*f5));
   J(3,1)=(cos(5*f1)-cos(5*f2)+cos(5*f3)-cos(5*f4)+cos(5*f5));
   J(4,1)=(cos(7*f1)-cos(7*f2)+cos(7*f3)-cos(7*f4)+cos(7*f5));
   J(5,1)=(cos(9*f1)-cos(9*f2)+cos(9*f3)-cos(9*f4)+cos(9*f5));
end
for j=1:10
   K=[-sin(f1) +sin(f2) -sin(f3) +sin(f4) -sin(f5)
   -(3*sin(3*f1)) +(3*sin(3*f2)) -(3*sin(3*f3)) +(3*sin(3*f4)) -(3*sin(3*f5))
   -(5*sin(5*f1)) +(5*sin(5*f2)) -(5*sin(5*f3)) +(5*sin(5*f4)) -(5*sin(5*f5))
   -(7*sin(7*f1)) +(7*sin(7*f2)) -(7*sin(7*f3)) +(7*sin(7*f4)) -(7*sin(7*f5))
   -(9*sin(9*f1)) +(9*sin(9*f2)) -(9*sin(9*f3)) +(9*sin(9*f4)) -(9*sin(9*f5))];
end
J
K
da=inv(K)*(y-J);
da
L=radtodeg(da);
L
M=m+L;
M
```

APPENDIX B

The coding of the calculation for switching angles α and β of three phase seven-level SHE-PWM inverter using m-file is shown as following. The alpha, α angles is used to control the first H-bridge in each phase while the beta, β angle is calculated to control the switching of second H-bridge in each phase. The alpha angles that obtained from calculation are shown as following.

$$\alpha_1 = 22.5833$$
$$\alpha_2 = 33.6015$$
$$\alpha_3 = 46.6430$$
$$\alpha_4 = 68.4979$$
$$\alpha_5 = 75.0974$$

For the beta angles which obtained from the coding is shown as below.

$$\beta_1 = 28.0924$$
$$\beta_2 = 40.1222$$
$$\beta_3 = 57.5705$$
$$\beta_4 = 71.7976$$
$$\beta_5 = 82.5487$$

For the equation that used to obtain the matrix y is

$$y = \frac{\pi}{4}M$$

where M is the modulation index which the value used in this calculation is 0.85.

```
clear;
y=[ 0.6676
    0
    0
    0
    0];
```

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```
t=0.000001;

alpha1=20; %20deg
alpha2=30; %30deg
alpha3=50; %50deg
alpha4=70; %70deg
alpha5=80; %80deg

a1=(alpha1*pi)/180; %change angle from degree to radian form
a2=(alpha2*pi)/180;
a3=(alpha3*pi)/180;
a4=(alpha4*pi)/180;
a5=(alpha5*pi)/180;

x=[alpha1
   alpha2
   alpha3
   alpha4
   alpha5];


for i=1:10
   J(1,1)=(cos(a1)-cos(a2)+cos(a3)-cos(a4)+cos(a5));
   J(2,1)=(cos(3*a1)-cos(3*a2)+cos(3*a3)-cos(3*a4)+cos(3*a5));
   J(3,1)=(cos(5*a1)-cos(5*a2)+cos(5*a3)-cos(5*a4)+cos(5*a5));
   J(4,1)=(cos(7*a1)-cos(7*a2)+cos(7*a3)-cos(7*a4)+cos(7*a5));
   J(5,1)=(cos(9*a1)-cos(9*a2)+cos(9*a3)-cos(9*a4)+cos(9*a5));
end
for j=1:10
   K=[-sin(a1) +sin(a2) -sin(a3) +sin(a4) -sin(a5)
   -(3*sin(3*a1)) +(3*sin(3*a2)) -(3*sin(3*a3)) +(3*sin(3*a4)) -(3*sin(3*a5))
   -(5*sin(5*a1)) +(5*sin(5*a2)) -(5*sin(5*a3)) +(5*sin(5*a4)) -(5*sin(5*a5))
   -(7*sin(7*a1)) +(7*sin(7*a2)) -(7*sin(7*a3)) +(7*sin(7*a4)) -(7*sin(7*a5))
   -(9*sin(9*a1)) +(9*sin(9*a2)) -(9*sin(9*a3)) +(9*sin(9*a4)) -(9*sin(9*a5))];
end

J
K
da=inv(K)*(y-J);
da
A=radtodeg(da);
A
B=x+A;
B

x=B;
b1=(x(1,1)*pi)/180;
b2=(x(2,1)*pi)/180;
b3=(x(3,1)*pi)/180;
b4=(x(4,1)*pi)/180;
b5=(x(5,1)*pi)/180;
```

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```
for i=1:10
   J(1,1)=(cos(b1)-cos(b2)+cos(b3)-cos(b4)+cos(b5));
   J(2,1)=(cos(3*b1)-cos(3*b2)+cos(3*b3)-cos(3*b4)+cos(3*b5));
   J(3,1)=(cos(5*b1)-cos(5*b2)+cos(5*b3)-cos(5*b4)+cos(5*b5));
   J(4,1)=(cos(7*b1)-cos(7*b2)+cos(7*b3)-cos(7*b4)+cos(7*b5));
   J(5,1)=(cos(9*b1)-cos(9*b2)+cos(9*b3)-cos(9*b4)+cos(9*b5));
end
for j=1:10
   K=[-sin(b1) +sin(b2) -sin(b3) +sin(b4) -sin(b5)
   -(3*sin(3*b1)) +(3*sin(3*b2)) -(3*sin(3*b3)) +(3*sin(3*b4)) -(3*sin(3*b5))
   -(5*sin(5*b1)) +(5*sin(5*b2)) -(5*sin(5*b3)) +(5*sin(5*b4)) -(5*sin(5*b5))
   -(7*sin(7*b1)) +(7*sin(7*b2)) -(7*sin(7*b3)) +(7*sin(7*b4)) -(7*sin(7*b5))
   -(9*sin(9*b1)) +(9*sin(9*b2)) -(9*sin(9*b3)) +(9*sin(9*b4)) -(9*sin(9*b5))];
end

J
K
da=inv(K)*(y-J);
da
C=radtodeg(da);
C
D=x+C;

w=D
c1=(w(1,1)*pi)/180;
c2=(w(2,1)*pi)/180;
c3=(w(3,1)*pi)/180;
c4=(w(4,1)*pi)/180;
c5=(w(5,1)*pi)/180;

for i=1:10
   J(1,1)=(cos(c1)-cos(c2)+cos(c3)-cos(c4)+cos(c5));
   J(2,1)=(cos(3*c1)-cos(3*c2)+cos(3*c3)-cos(3*c4)+cos(3*c5));
   J(3,1)=(cos(5*c1)-cos(5*c2)+cos(5*c3)-cos(5*c4)+cos(5*c5));
   J(4,1)=(cos(7*c1)-cos(7*c2)+cos(7*c3)-cos(7*c4)+cos(7*c5));
   J(5,1)=(cos(9*c1)-cos(9*c2)+cos(9*c3)-cos(9*c4)+cos(9*c5));
end
for j=1:10
   K=[-sin(c1) +sin(c2) -sin(c3) +sin(c4) -sin(c5)
   -(3*sin(3*c1)) +(3*sin(3*c2)) -(3*sin(3*c3)) +(3*sin(3*c4)) -(3*sin(3*c5))
   -(5*sin(5*c1)) +(5*sin(5*c2)) -(5*sin(5*c3)) +(5*sin(5*c4)) -(5*sin(5*c5))
   -(7*sin(7*c1)) +(7*sin(7*c2)) -(7*sin(7*c3)) +(7*sin(7*c4)) -(7*sin(7*c5))
   -(9*sin(9*c1)) +(9*sin(9*c2)) -(9*sin(9*c3)) +(9*sin(9*c4)) -(9*sin(9*c5))];
end

J
K
da=inv(K)*(y-J);
da
O=radtodeg(da);
```

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```
O
P=w+O;
P

z=P;
d1=(z(1,1)*pi)/180;
d2=(z(2,1)*pi)/180;
d3=(z(3,1)*pi)/180;
d4=(z(4,1)*pi)/180;
d5=(z(5,1)*pi)/180;

for i=1:10
    J(1,1)=(cos(d1)-cos(d2)+cos(d3)-cos(d4)+cos(d5));
    J(2,1)=(cos(3*d1)-cos(3*d2)+cos(3*d3)-cos(3*d4)+cos(3*d5));
    J(3,1)=(cos(5*d1)-cos(5*d2)+cos(5*d3)-cos(5*d4)+cos(5*d5));
    J(4,1)=(cos(7*d1)-cos(7*d2)+cos(7*d3)-cos(7*d4)+cos(7*d5));
    J(5,1)=(cos(9*d1)-cos(9*d2)+cos(9*d3)-cos(9*d4)+cos(9*d5));
end
for j=1:10
    K=[-sin(d1) +sin(d2) -sin(d3) +sin(d4) -sin(d5)
    -(3*sin(3*d1)) +(3*sin(3*d2)) -(3*sin(3*d3)) +(3*sin(3*d4)) -(3*sin(3*d5))
    -(5*sin(5*d1)) +(5*sin(5*d2)) -(5*sin(5*d3)) +(5*sin(5*d4)) -(5*sin(5*d5))
    -(7*sin(7*d1)) +(7*sin(7*d2)) -(7*sin(7*d3)) +(7*sin(7*d4)) -(7*sin(7*d5))
    -(9*sin(9*d1)) +(9*sin(9*d2)) -(9*sin(9*d3)) +(9*sin(9*d4)) -(9*sin(9*d5))];
end

J
K
da=inv(K)*(y-J);
da
E=radtodeg(da);
E
F=z+E;
F

k=F;
e1=(k(1,1)*pi)/180;
e2=(k(2,1)*pi)/180;
e3=(k(3,1)*pi)/180;
e4=(k(4,1)*pi)/180;
e5=(k(5,1)*pi)/180;

for i=1:10
    J(1,1)=(cos(e1)-cos(e2)+cos(e3)-cos(e4)+cos(e5));
    J(2,1)=(cos(3*e1)-cos(3*e2)+cos(3*e3)-cos(3*e4)+cos(3*e5));
    J(3,1)=(cos(5*e1)-cos(5*e2)+cos(5*e3)-cos(5*e4)+cos(5*e5));
    J(4,1)=(cos(7*e1)-cos(7*e2)+cos(7*e3)-cos(7*e4)+cos(7*e5));
    J(5,1)=(cos(9*e1)-cos(9*e2)+cos(9*e3)-cos(9*e4)+cos(9*e5));
end
for j=1:10
    K=[-sin(e1) +sin(e2) -sin(e3) +sin(e4) -sin(e5)
```

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```
    -(3*sin(3*e1)) +(3*sin(3*e2)) -(3*sin(3*e3)) +(3*sin(3*e4)) -(3*sin(3*e5))
    -(5*sin(5*e1)) +(5*sin(5*e2)) -(5*sin(5*e3)) +(5*sin(5*e4)) -(5*sin(5*e5))
    -(7*sin(7*e1)) +(7*sin(7*e2)) -(7*sin(7*e3)) +(7*sin(7*e4)) -(7*sin(7*e5))
    -(9*sin(9*e1)) +(9*sin(9*e2)) -(9*sin(9*e3)) +(9*sin(9*e4)) -(9*sin(9*e5))];
end

J
K
da=inv(K)*(y-J);
da
G=radtodeg(da);
G
H=k+G;
H

m=H;
f1=(m(1,1)*pi)/180;
f2=(m(2,1)*pi)/180;
f3=(m(3,1)*pi)/180;
f4=(m(4,1)*pi)/180;
f5=(m(5,1)*pi)/180;

for i=1:10
    J(1,1)=(cos(f1)-cos(f2)+cos(f3)-cos(f4)+cos(f5));
    J(2,1)=(cos(3*f1)-cos(3*f2)+cos(3*f3)-cos(3*f4)+cos(3*f5));
    J(3,1)=(cos(5*f1)-cos(5*f2)+cos(5*f3)-cos(5*f4)+cos(5*f5));
    J(4,1)=(cos(7*f1)-cos(7*f2)+cos(7*f3)-cos(7*f4)+cos(7*f5));
    J(5,1)=(cos(9*f1)-cos(9*f2)+cos(9*f3)-cos(9*f4)+cos(9*f5));
end
for j=1:10
    K=[-sin(f1) +sin(f2) -sin(f3) +sin(f4) -sin(f5)
    -(3*sin(3*f1)) +(3*sin(3*f2)) -(3*sin(3*f3)) +(3*sin(3*f4)) -(3*sin(3*f5))
    -(5*sin(5*f1)) +(5*sin(5*f2)) -(5*sin(5*f3)) +(5*sin(5*f4)) -(5*sin(5*f5))
    -(7*sin(7*f1)) +(7*sin(7*f2)) -(7*sin(7*f3)) +(7*sin(7*f4)) -(7*sin(7*f5))
    -(9*sin(9*f1)) +(9*sin(9*f2)) -(9*sin(9*f3)) +(9*sin(9*f4)) -(9*sin(9*f5))];
end
J
K
da=inv(K)*(y-J);
da
L=radtodeg(da);
L
M=m+L;
M

N(1,1)=((M(2,1)-M(1,1))/2)+M(1,1); %calculate the beta angle
N(2,1)=((M(3,1)-M(2,1))/2)+M(2,1);
N(3,1)=((M(4,1)-M(3,1))/2)+M(3,1);
N(4,1)=((M(5,1)-M(4,1))/2)+M(4,1);
N(5,1)=((90-M(5,1))/2)+M(5,1);
N
```