HARMONIC ANALYSIS IN MULTILEVEL INVERTER USING HYBRID PWM TECHNIQUE

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HARMONIC ANALYSIS IN MULTILEVEL INVERTER USING HYBRID PWM TECHNIQUE

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for the award of the Bachelor of
Electrical Engineering with Honours

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FEBRUARY 2022

ACKNOWLEDGEMENTS

Praise and thanks to God who has granted countless blessing, knowledge, guidance and opportunity during the journey of completing this thesis, where it is one of the most challenging times of my life. Without His will and power, I am nothing.

Deepest sense of gratitude to my project supervisor, Dr. Nur Huda Binti Ramlan, who has review, guide and helped me throughout the project. Not only that, she also helped me to clear a lot of my confusion on problems that I have faced.

I would like to thank Final Year Coordinator, Dr. Ikhwan and Dr. Nur Huda for their support and assistance as well as Dr. Shafie for his building comments and suggestion during the progress presentation session.

Lastly and the most importantly, I wish to thank my parents for showering me with their love, support and encouragement, without them, I would never experience many opportunities.

ABSTRAK

Pada dekad awal, Multilevel Inverter (MLI) hanya mampu melakukan penukaran DC kepada DC tetapi dalam era baru ini, multilevel inverter digunakan secara meluas untuk mendapatkan output yang dikehendaki daripada voltan DC kepada sumber voltan AC. Objektif kerja penyelidikan ini adalah untuk mereka bentuk dan mensimulasikan pelbagai teknik Hybrid Pulse Width Modulation (PWM) untuk penyongsang bertingkat dan kemudian menganalisis prestasinya dengan membandingkannya dengan teknik PWM pelupusan fasa konvensional (PD) dari segi peratusan harmonik (THD). Kerja penyelidikan ini menggunakan MATLAB SIMULINK dengan sumber DC 200V yang melaksanakan 18 jenis PWM hibrid daripada beberapa jenis teknik modulasi lebar nadi (PWM) yang biasa untuk meningkatkan voltan keluaran dengan mengurangkan Herotan Harmonik (THD) pada inverter pelbagai peringkat dan modeling cascaded H-bridge inverter pelbagai peringkat (CHMI) telah digunakan. Disebabkan beberapa teknik PWM konvensional masih menyebabkan kehilangan kuasa tambahan kerana nilai herotan harmonik yang tinggi dan teknik PWM Hibrid mampu mengurangkan masalah ini. Hasil daripada kerja penyelidikan dibandingkan dengan peratusan dari segi nilai THD. Secara keseluruhan, semua kaedah lain yang telah dibangunkan semuanya di bawah 5% daripada had standard. Namun begitu, dua daripada kaedah tersebut telah menghasilkan nilai THD terendah iaitu 0.88% iaitu kaedah hibrid PS-PD PWM dan PS-POD PWM pada jalur frekuensi pembawa tinggi.

ABSTRACT

In earlier decade, the Multilevel Inverter (MLI) has only able to perform on conversion of DC to DC but in this new era, the multilevel inverter is widely being used to gained the desired output from DC voltage to AC voltage source. The objective of this research work is to design and simulate multiple Hybrid Pulse Width Modulation (PWM) technique for multilevel inverter and then analyse its performance by compare it with the conventional phase disposition (PD) PWM technique in terms of harmonic (THD) percentage. This research work is develop using MATLAB SIMULINK with 200V of DC source that implement the 18 types of hybrid PWM from some common type of pulse width modulation (PWM) technique to improve the output voltage by decrease the Harmonic Distortion (THD) of the multilevel inverter which is the cascaded H-bridge multilevel inverter (CHMI) is being used. Due to some of the conventional PWM technique are still causing an extra loss of power cause by high harmonic distortion value. Therefore, Hybrid PWM techniques are able to mitigate this problem. The result from the research work is compared in terms of percentage of THD values. Overall, all of the other method that has been developed was all below 5% of standard limit. However, two of the methods that generated lowest THD values at 0.88% are PS-PD PWM and PS-POD PWM hybrid methods in high carrier frequency bands switching technique.

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
PWM	Pulse Width Modulation
MLI	Multilevel Inverter Topologies
DCMI	Diode-Clamp Multilevel Inverter
FCMI	Flying-Capacitor Multilevel Inverter
CHMI	Cascaded H-Bridge Multilevel Inverter
PSPWM	Phase Shift Pulse Width Modulation
PDPWM	Phase Disposition Pulse Width Modulation
PODPWM	Phase Opposition Disposition Pulse Width Modulation
APODPWM	Alternative Phase Opposition Disposition Pulse Width Modulation
THD	Total Harmonic Distortion
EMI	Electromagnetic Interference
R	Resistor
L	Inductor
C	Capacitor
LCFB	Low Carrier Frequency Band
HCFB	High Carrier Frequency Band
VCFB	Variable Carrier Frequency Band
V	Voltage

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Eelectrical transmissions has been categories into two that is alternating current (AC) and direct current (DC). AC is the flow of the charge that changes it direction periodically which lead to the reverses the voltage level along the current. AC is usually that used to deliver the power to consumer such as residential, industrial and so on. DC is to the sources that provides a constant voltage and current. Each this type has its advantage and disadvantage such as the DC is mostly known to be able to provide more efficient in terms of power consume but it has a limit to transmit power over a long distance unlike AC current. Meanwhile, AC current can be step up or down the voltage to fulfil the requirement during transmission and distribution. So, can be seen that both AC and DC are play they own role in provides the advantages for people to make use of the different application for different purpose.

Inverting is known as the changing process of the DC to AC that this process is complete by using the inverter. Inverter is a device that changes the dc input to the desired ac output voltage. Inverters nowadays are widely used in the application drives for industrial usually, in power supplies such as PV system and Distribution system. Inverters also has been categorized into two that are single phase and three phase inverters which its usage is beyond the types of application needed.(MOHD HAZMAN BIN IDROS, 2012) In the purpose on increased the power rating, reduce the electromagnetic interference and improve in the harmonic (THD) performance the multilevel inverters (MLIs) has used widely nowadays. Multilevel inverter is the inverter that is switched at low switching frequency if compare to the two-level inverters. Multilevel inverter also been famous in the power industry since it is able to fulfil the requirement of high power of the high-power applications in the industrial. This multilevel inverter has to be fulfilled the requirements that it is used to achieve a pure sinusoidal output voltage and the inverter output current should be low total harmonic distortion (THD) (Adem, 2018). Since there is a different application voltage requirement so to control the output voltage the pulse width modulation (PWM) technique is used. PWM technique is choose to be used for MLIs because it can control the ON and OFF of the switch that can implement to the different applications. (Karthik et al., 2015)

In this project, the PWM multilevel inverter will be used which the output voltage will control by the PWM technique. If compare to the conventional inverter, the PWM multilevel inverter has much more advantages in term of harmonic. PWM multilevel inverter has much lower order of harmonic than the others.

1.2 PROBLEM STATEMENT

Different PWM technique will result in different value of THD (%). The most commonly used PWM technique is the sinusoidal PWM that has two categories which are bipolar and unipolar. Under this technique also has been categories to four common method that is PSPWM, PDPWM, PODPWM and APODPWM. The thing that make this four-method different is it will generate different value of the harmonic (THD).

Since the conventional PWM technique still causes extra losses of power so in the afford to overcome this problem the implementation in minimizing the distortion is by designing a hybrid PWM technique and inject back to inverter. There are two ways to obtain better result in output signal of the inverter such as proposed new topologies of the inverter and the other one is by improving the switching techniques.

Because of the PWM technique has four categories with different value of THD (%) the right choice for the hybrid process is also importance to achieve better output.

1.3 OBJECTIVE

- To design and simulate multiple Hybrid Pulse Width Modulation (PWM) technique for multilevel inverter.

- To analyse the performance of multiple hybrid PWM technique and compare with the conventional phase disposition (PD) PWM technique in terms of the harmonic (THD) percentage.

1.4 SCOPE

First, design and simulate multiple Hybrid PWM using MATLAB SIMULINK. After complete the development and simulation of the Hybrid PWM then analyse and compare the performance of six type of hybrid PWM technique such as PS-PD, PS-POD, PS-APOD, PD-POD, PD-APOD and POD-APOD in three switching technique which is low carrier frequency band, high carrier frequency band and variable carrier frequency band in term of harmonic (THD) percentage.

1.5 THESIS OUTLINE

In this thesis consist of five chapters which in Chapter 1 discussed about the project background, problem statement, objective and scope of the research work.

Next, Chapter 2 will discuss about the literature review on multilevel inverter and the pulse width modulation that referred and used throughout the research work.

In Chapter 3, methodology of the research work will introduce including the method of solution for the stated problem, development of Hybrid PWM, parameters setting and all the details of the system for further analysis.

Meanwhile, in Chapter 4, result obtained by the simulation of the designed system will be discuss and analyse. On the other hand, Chapter 5 will conclude all the finding of the research work and recommendation for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The multilevel inverter was invented according to the demand on the high voltage and the high power with the available switching devices and better output waveforms that increase from time to time. Multilevel inverter was usually used in the high-power system applications such as static reactive power compensation and adjustable speed drives. Based on different demand or scenario, there are main three multilevel inverters have been developed which is diode-clamped, flying-capacitor, cascaded H-bridge multilevel inverter. All this multilevel inverter has one goal which is to achieve the automatic voltage balance of each dc voltage without any additional balancing circuits.

In earlier decade, the initial aims of developing the multilevel inverter is applied to the high voltage and high-power applications such as FACTs devices and voltage drives such as applied to dc-to-dc conversion that use to decrease the magnetic inductors and achieving high power density also the efficiency. This dc-to-dc converter has a feature of small size, light weight and high efficiency. A 55KW multilevel dc-dc converter has been demonstrated that suited for power density applications such as the voltage boost in plug in hybrid electric vehicle (HEVs). The latest advance proposed multilevel modular capacitor-clamped dc-dc converter has been developed and demonstrate in the aims to achieve the higher voltage boost ratio and to reduce the number of devices. Since it is zero-current switching version utilizing stray inductance can reduces the required capacitance more efficient and raise in its efficiency also power density.

2.2 MULTILEVEL INVERTERS (MLI TOPOLOGIES)

The conversion of the dc to ac power to a desired output voltage and frequency using the power electronic devices has been known as inverter. The conversion using the inverter usually will deliver an output voltage and current in two different levels of positive and negative voltage that known as two level inverters. This inverter was working with high switching frequency, high switching loses, high power and voltage applications rating constraints. Using this conventional inverter also will facing the high level in total harmonic distortion, electromagnetic interference (EMI) and high voltage differential ($\frac{dv}{dt}$) pressure(Krishna & Suresh, 2016). It was challenging to assemble the power electronic switches directly to high and medium voltage grid that lead to the development of different topology of multilevel inverter. In earlier 1975, the multilevel inverter topology has been invented with three level converters that able to rise the inverter power rating with high number of voltage levels but its devices rating is decrease and it produces a smooth sinusoidal waveform from different level of dc voltage as input.

Follow by the improvement in multilevel inverter nowadays, it has become a popular part in the high power and voltages ranges of industrial applications. It also much simple to develop together with renewable energy sources for several high-power applications. This inverter has some advantages that it able to decrease the harmonic distortion, high number of voltage level, staircase waveform quality, low switching losses, better electromagnetic compatibility, higher power quality and this inverter also can run at both fundamental and high switching frequency of pulse width modulation. Besides, this inverter also has a disadvantage that it requires a large number of power electronic switches. Since it was using the semiconductor switches so a gate driver circuit will increase the complication or difficulty to the system that made it become more expensive so nowadays mostly researcher was focus on decreasing the complication of the circuit by reduce the number of power electronic switches and gate driver circuits.

There are some advantages that can obviously see on using the multilevel inverter compare to conventional inverter which is the number of the devices on implement the multilevel inverter is less than the conventional inverters. Other than that, the multilevel inverter also more reliable and cost competitive compare to the conventional two-level inverter.

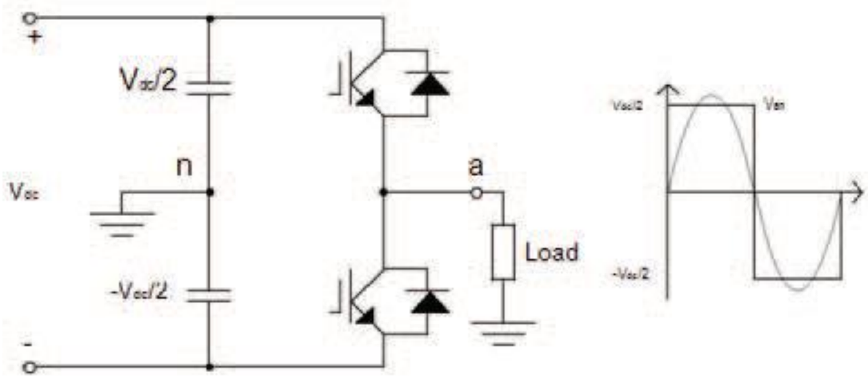

Figure 1 Single Phase Leg of Two-Level Inverter without PWM

Figure 1 shows the conventional two-level inverter that produce the output AC voltage from the input DC voltage without the pulse width modulation switching meanwhile the Figure 2 shows the AC output voltage of the inverter that is with the PWM switching circuit.

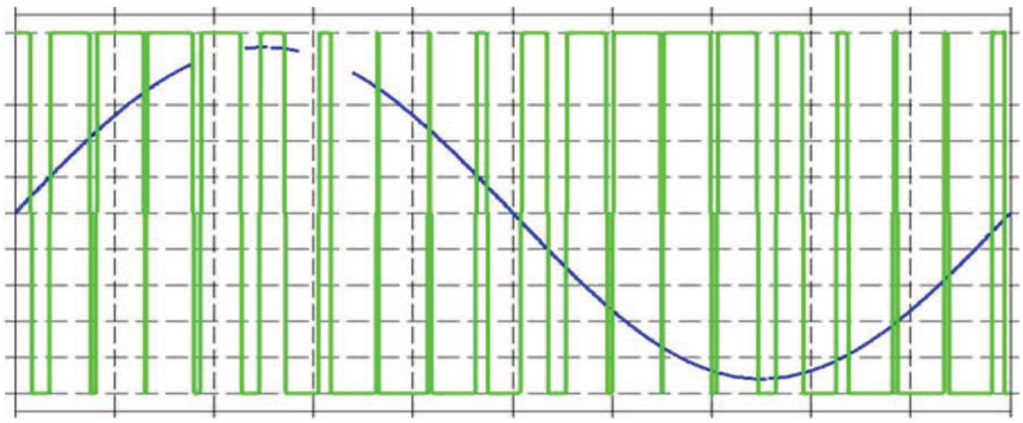

Figure 2 Pulse Width Modulation Output

In the Multilevel inverter topology (MLI), different level DC voltage has been added to the circuit to produce a smoother output waveform that has a lower ($\frac{dv}{dt}$) and harmonic distortions. The circuit design was difficult because of increase in voltage levels and it required a complex switching controller circuit to run.

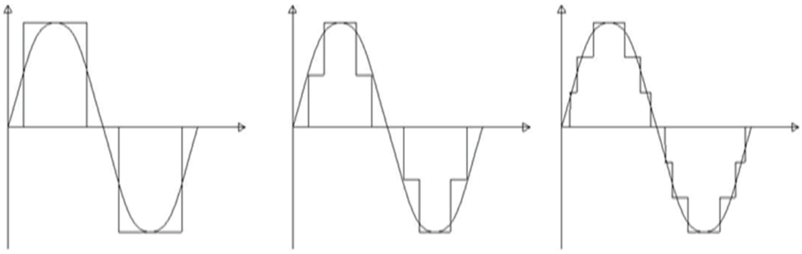

Figure 3 Three Level, Five Level and Seven Level Output Waveform in Basic Switching

The multilevel inverter has been classified into several categories since there is a difference demand by the different applications that show in Figure 4 below. As the information, there are three main topologies of MLI that usually used which is diode clamped inverter, flying capacitor inverter and the cascaded H-bridge inverter. (Rathore et al., 2015)

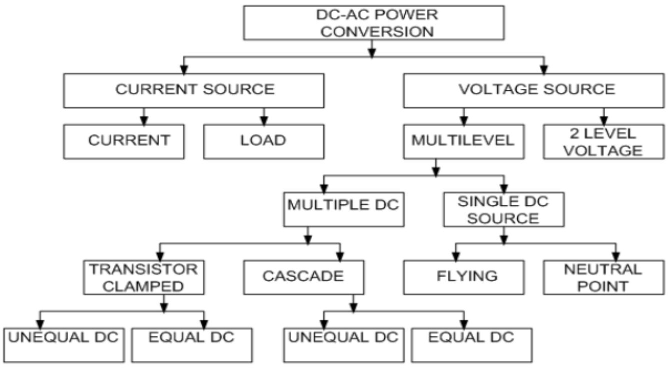

Figure 4 Multilevel Inverter Categories

Table 1 Comparison of Conventional Inverter and Multilevel Inverter

No	Conventional Inverter	Multilevel Inverter
1	THD high in the output waveform.	THD low in the output waveform.
2	High switching stresses	Low switching stresses
3	Not for high voltage application	For high voltage application
4	Cannot generate high voltage levels	Can generate high voltage levels
5	High dv/dt and EMI	Low dv/dt and EMI
6	High switching frequency and high switching losses	Low switching frequency and low switching losses

2.2.1 DIODE-CLAMPED MULTILEVEL INVERTER (DCMI)

Diode clamped inverter is an inverter that also known as Neutral Point Clamped inverter (NPC). This inverter was use to solve the problem when the maximum output voltage is half of the input DC voltage by increase the number switches and the diodes. The clamping diode is used to limit the voltage stress of power electronic devices. This diode clamped multilevel inverter is much easier to control because it controls technique is simple and if when the number of the level increases then its distortion or THD is reduced but if the number of the level is higher than it will need or require more clamping diodes in the system. Its capacitance is low and are recharged and its efficiency also high for the fundamental frequency. For this inverter, if the control and monitoring not accurate then the DC level will be released and this topology also has a obstacle in conversion of high power because it requires high speed of clamping diodes that lead to reverse recovery stress.

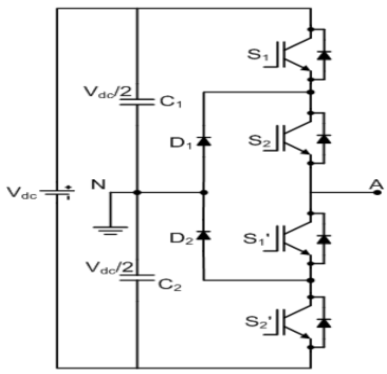

Figure 5 Three Level Diode Clamped Multilevel Inverter

In this inverter, during the positive voltage injected into the system, the S1 and S2 will be ON state while S_1' and S_2' will be ON state during the negative voltage is injected. When the no voltage injected, the S2 and S_1' will be in the ON state. This switching pattern is shown as Table 2 below:

Table 2 DCMI Switching Pattern

Output Voltage	Switching State			
	S_1	S_2	S_1'	S_2'
Vdc / 2	1	1	0	0
0	0	1	1	0
-Vdc / 2	0	0	1	1

2.2.2 FLYING-CAPACITOR MULTILEVEL INVERTER (FCMI)

Flying Capacitor Multilevel inverter is the inverter that known as the Capacitor Clamped Inverter. Its circuit design actually is same as the diode clamped inverter just the two clamping diodes are replaced by one flying capacitor. In this inverter, the capacitor is used to limit the voltage. This inverter able to controlling for both active and reactive power flow in the system. This inverter has eliminated the needs of filter for the system and also it can handle a large amount of the packing capacity. But this inverter voltage control across all capacitor is much complex so it become a bit difficult to used and it switching losses also high. Since there are additional switching states that help the inverter to maintain the charge balance in the capacitors but it switching efficiency is low.

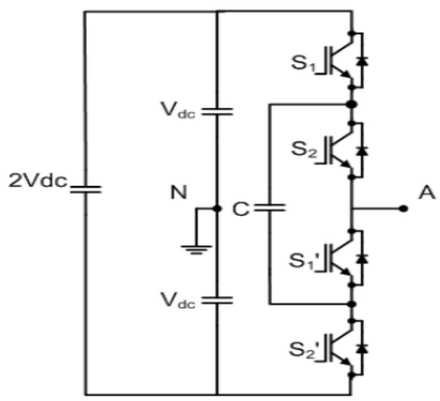

Figure 6 Three Level Flying Capacitor Multilevel Inverter

In this inverter, during the positive voltage injected into the system, the S1 and S2 will be ON state while S_1' and S_2' will be ON state during the negative voltage is injected. When the no voltage injected, the S1 and S_1' ON state and it also can be S2 and S_2' in ON state. This switching pattern is shown as Table 3 below:

Table 3 FCMLI Switching Pattern

Output Voltage	Switching State			
	S_1	S_2	S_1'	S_2'
Vdc	1	1	0	0
0	1	0	1	0
	0	1	0	1
-Vdc	0	0	1	1

2.2.3 CASCADED H-BRIDGED MULTILEVEL INVERTER (CHMI)

For the three level of the cascaded H-bridge multilevel inverter is build up by combination of single H bridge with the series power conversion. Cascaded H-Bridge Multilevel inverter is much better if compare to both diodes clamped and flying capacitors multilevel inverter since it only requires a smaller number of components on switching levels. This CHMLI is build up using single DC voltages sources and a group of switches and capacitors for H-bridge. This inverter able to reduce the harmonic distortion better than DCMLI and FCMLI inverter. But this inverter is required an isolated DC voltages sources for its system and more complex controller is required due to the amount of the capacitor that used in the inverter.

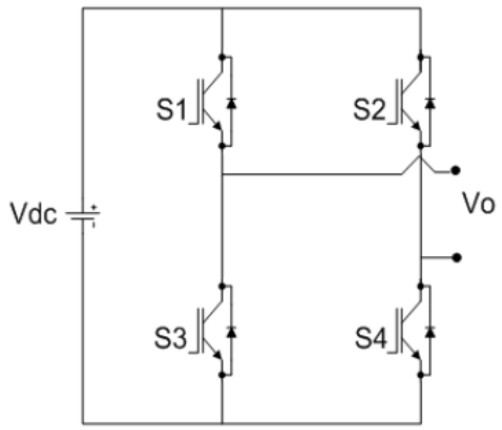

Figure 7 Three Level Cascaded H-Bridge Multilevel Inverter

In this inverter, during the positive voltage injected into the system, the S1 and S4 will be ON state while S3 and S2 will be ON state during the negative voltage is injected. When the no voltage injected, the S1 and S2 ON state and it also can be S3 and S4 in ON state.(Rathore et al., 2015) This switching pattern is shown as Table 2 below:

Table 4 CHB MLI Switching Pattern

Output Voltage	Switching State			
	S_1	S_2	S_3	S_4
Vdc	1	0	0	1
0	1	1	0	0
	0	0	1	1
-Vdc	0	1	1	0

2.2.4 SIGNIFICANCE OF THE 5-LEVEL CHMI

For five levels of the cascaded H-bridge multilevel inverter is build up by combination of double H bridge with the series power conversion at each H-bridge which mean that it consists of two dc input voltage. There is three level of outputs that generate by each of this single-phase H-bridge inverter which is +Vdc, 0 and -Vdc. The output voltage in each bridge is the summation of the voltage that is generated by each of the dc voltage. In each of the H-bridge is working with four switches that is S1, S2, S3 and S4 so for the five level H-bridge will consist eight switches since it is built from combination of double H-bridge.(Javvaji, 2013)

The cascaded H-bridge multilevel inverter is capable of producing the total voltage in both positive and negative half cycles. (Mauryan & Institutions, 2020) This inverter usually use modulation with fundamental switching frequency or high switching frequency pulse width modulation technique for obtaining a better output voltage response with minimum harmonic distortions. For this cascaded inverter, the different PWM technique was being injected to the inverter to generate out a better quality of output voltage and current waveform that with less harmonic distortion.

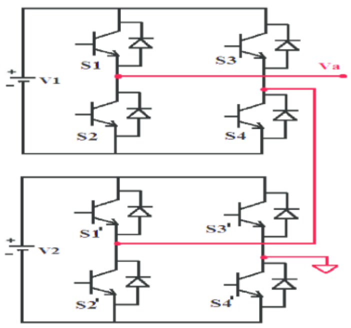

Figure 8 5-Level Cascaded H-Bridge Multilevel Inverter (Palanisamy et al., 2016)

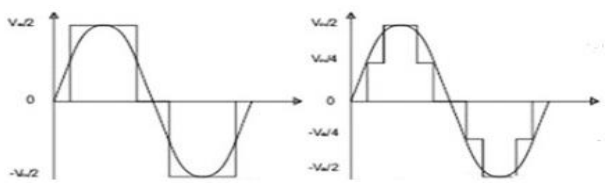

Figure 9 Input Waveform and Output 5- Level Waveform

2.3 PULSE WIDTH MODULATION (PWM) TECHNIQUE

Pulse width modulation (PWM) is a modulation technique that produce the variable-width pulses to achieve the amplitude of the analogue or sinusoidal signal and off more of the time for a low amplitude signal. In the application in inverters the PWM technique is a technique used to control the duty cycle of the switches and give steady output voltage with the reduction of the harmonics. PWM is comparing it reference signal with the carrier signal to regulate the amplitude and the frequency in inverter (Shaiful & Karim, 2019). This PWM technique is switching by adjust the frequency low and high. The switching frequency of this technique is must be more than 1kHz. In PWM technique, if the reference signal is higher than the carrier signal, the PWM output will become high then if the reference signal is lower than carrier signal then the output will be lower. The PWM Technique has been classified into several categories and it was shown Figure 10 below:

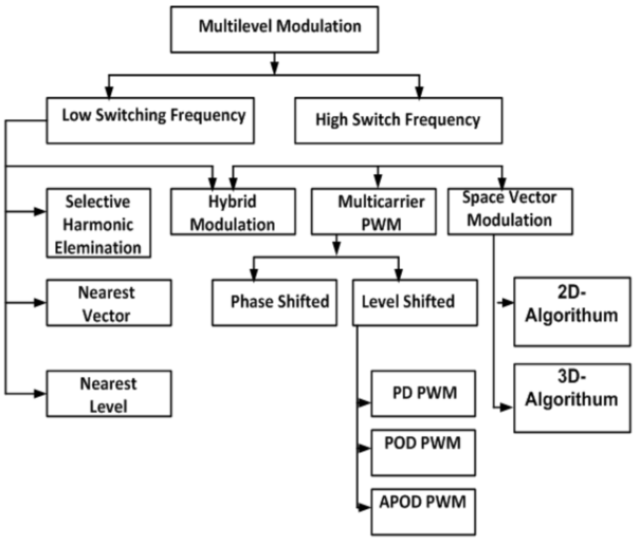

Figure 10 Pulse Width Modulation Technique Categories

2.3.1 PHASE SHIFT PWM TECHNIQUE (PS PWM)

The phase shift PWM is use to achieve the zero-voltage turn-on on power switches and also enhance the efficiency generate by the converter and this PSPWM is usually apply at input side. In the PS PWM, its triangular carriers have the same frequency and peak to peak amplitude. In bipolar, for the m, voltage levels (m-1) of carrier signals are needed and it will phase shifted by the angle of (360°/ (m-1)).

The Figure 11 shows the gate signal that produce together with analysing of the carrier wave and modulating signal. (Devi & Srivani, 2017)

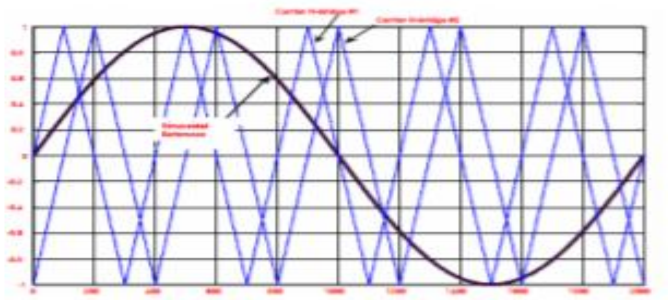

Figure 11 PS PWM Input signal

2.3.2 PHASE DISPOSITION PWM TECHNIQUE (PD PWM)

This PDPWM technique usually is used several triangular carriers with only one modulation wave for the bipolar PWM. In phase disposition PWM all of it carrier signals are in the same phase and its carriers is below the zero-reference line. This PDPWM are generally used since it can provide the lower harmonic distortion of load voltage and current. (Rathore et al., 2015)

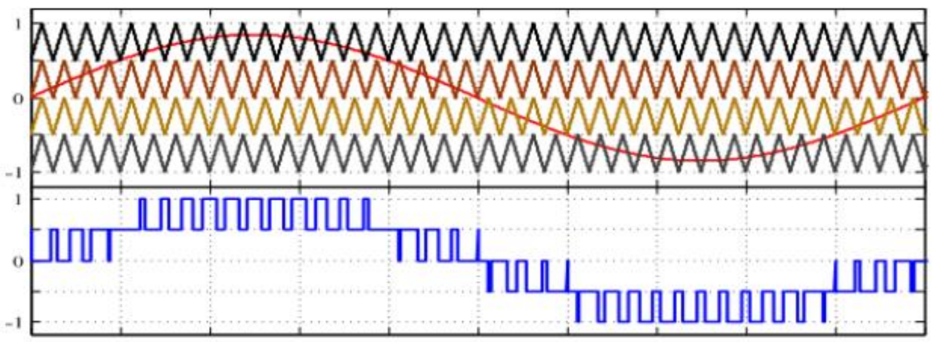

Figure 12 PDPWM Input and Output Waveform

2.3.3 PHASE OPPOSITION DISPOSITION PWM TECHNIQUE (POD PWM)

For POD PWM technique, all of it carriers signal above the zero line of reference voltage or sinusoidal modulation waveform out of phase with those below the zero by 180°.

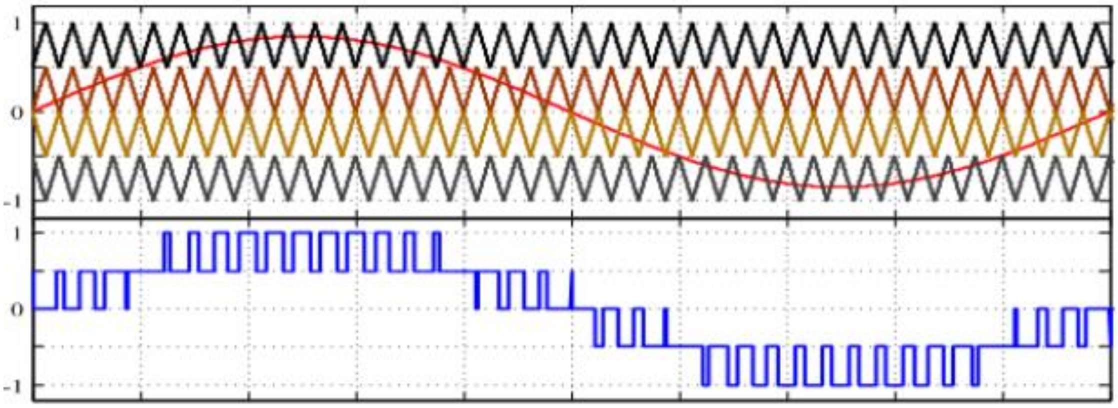

Figure 13 POD PWM Input and Output Waveform

2.3.4 ALTERNATIVE PHASE OPPOSITION DISPOSITION PWM TECHNIQUE (APOD PWM)

For APOD PWM technique, all of the adjacent carrier signals are put of the phase by 180°, in the other word its carrier signal is phase shifted by 180° from the adjacent carriers. This technique will generate almost the same result as the POD PWM technique. (Mandal & Nigam, 2018)

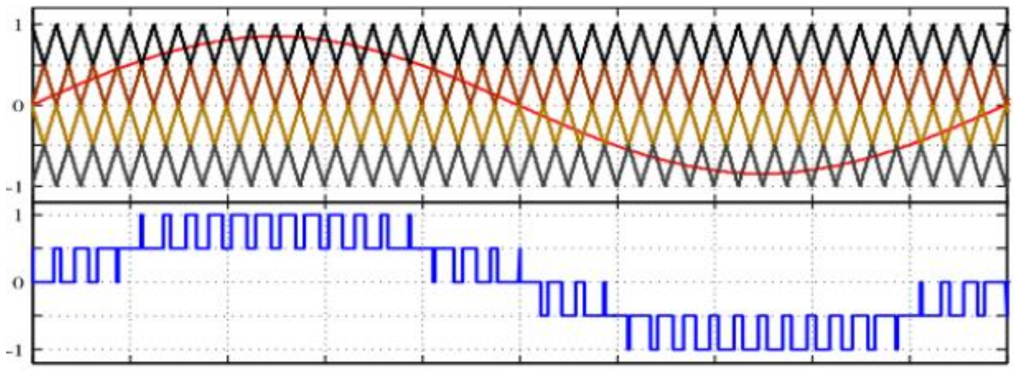

Figure 14 APOD PWM Technique Input and Output Waveform

CHAPTER 3

METHODOLOGY

3.1 Introduction

The work for this project started from the process of designing the five-level CHMI and follow by the process of applying the PWM technique to the inverter. Once the process of designing the CHMI and PWM circuit is finish, the simulation for testing the circuit is being done to make sure there is no error or problem is detected in the circuit then the PWM technique for the circuit is being hybrid to obtain the better result of total harmonic distortion (THD). Lastly, the result that being generate from the hybrid PWM Technique five level CHMI with the amplitude for the sine wave to achieve the better result. Other than that, the comparison of THD output between different method of Hybrid PWM technique is being analysed. After all the comparison between method then all the method then compare with the conventional Phase Disposition (PD) PWM. This progress during early stage can be view in the flow chart in Figure 15 below:

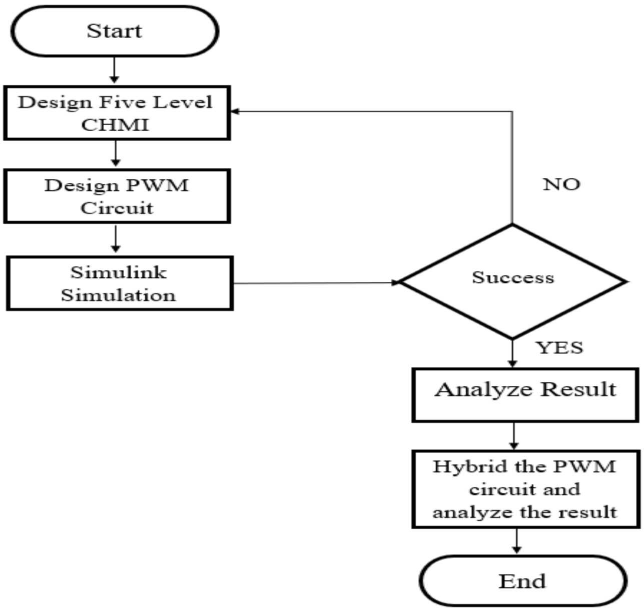

Figure 15 Flow Chart of Early Stage

3.2 Proposed Solution

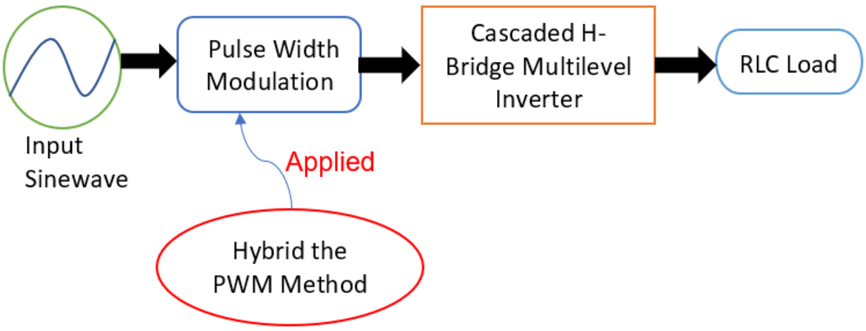

Figure 16 Block Diagram of Proposed Solution

In conventional method of the system, it consists of PWM circuit that receive an input sinewave as reference then from PWM circuit connect to the five level Cascaded H-Bridge Multilevel Inverter circuit and finally the RLC load. So, for the proposed solution it all similar to the conventional system connection it just has an improvement at PWM circuit by hybrid every two-difference type of PWM technique to achieve the low harmonic distortion output if possible. After complete hybrid the PWM technique then all the result of the hybrid method and pattern will be compared with the conventional phase disposition (PD) PWM.

3.3 Simulation Flowchart

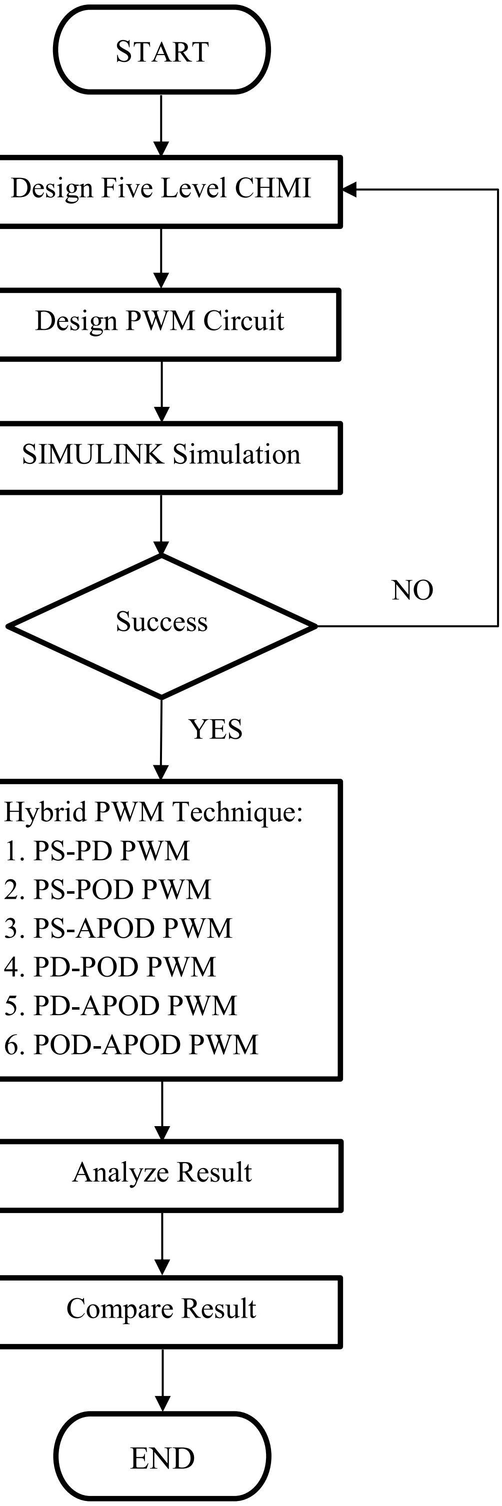

Figure 17 Simulation Flow Chart

3.4 Cascaded H-Bridge Multilevel Inverter Circuit

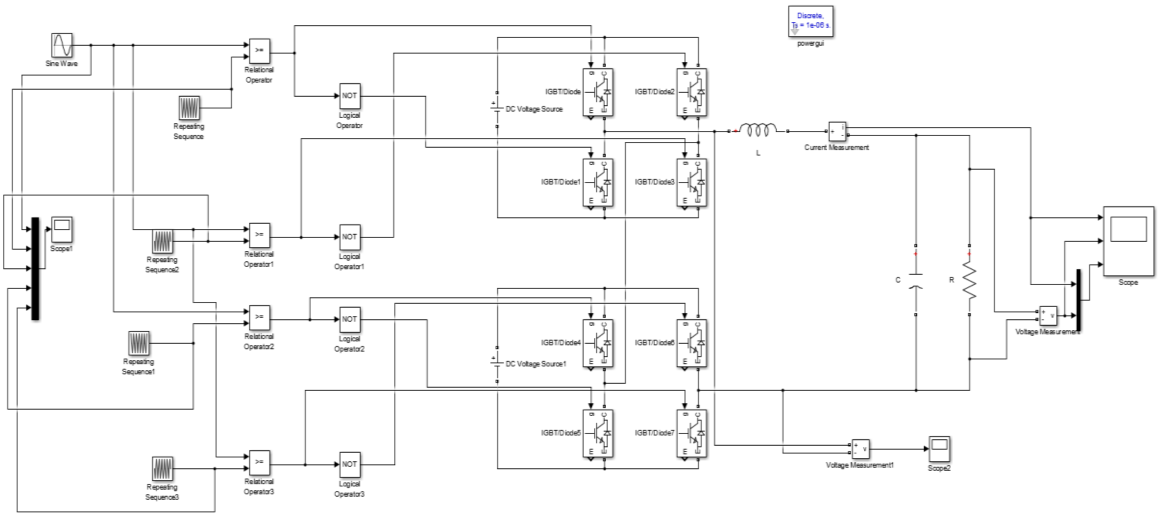

Figure 18 Five Level CHMI Using PWM Technique

The Simulink circuit design is commonly containing CHMI circuit, PWM circuit, RLC load, scope, IGBT as switches, repeat sequence block to create the carrier signal, the voltage and current measurement to measure and display the output voltage and current waveform that the complete block diagram was showing in the Figure 18 above. Note that the design of circuit for the different method of PWM as well as for the hybrid PWM is all same just has a different at the carrier signal pattern.

3.4.1 RLC Load Value

All carrier signal or also known as switching frequency used for the all method of conventional PWM and hybrid PWM technique was all set equal to 20KHz and the nominal power was expected to be 200W. Therefore, to achieve a better result, the amplitude for the reference signal or the input sine wave was being maintain at 0.9 and the input voltage at each H-bridge is 100V. So, the output voltage will be:

$$Vo = V1 + V2 = 100V + 100V = 200V \qquad (3.1)$$

Since the amplitude of the reference signal is 0.9, so the output voltage:

$$Vo = 200V\ X\ 0.9 = 180V \qquad (3.2)$$

Then the cut off frequency for the circuit is 1/10 of the carrier frequency, so:

$$F_{Cut\text{-}off} = \frac{1}{10}\ x\ 20kHz = 2KHz \qquad (3.3)$$

So, to calculate the R load value that going to implement in circuit is calculate as below:

$$R = \frac{Vo2}{P} = \frac{(180/\sqrt{2})^2}{200} = 81\ \Omega \qquad (3.4)$$

Next, the L and C load are calculated by substitute the value from equation (3.2) until (3.4) as below:

$$C = \frac{1}{(2\Pi fcutoff)R\sqrt{2}} = \frac{1}{(2\Pi 2000)81\sqrt{2}} = 0.6947\mu F \qquad (3.5)$$

and

$$L = 2R^2C = 2(81)^2(0.6947\mu) = 9.1159mH \qquad (3.6)$$

Next, the sample time in the 'powergui' block always keep using 1µs for all simulation.

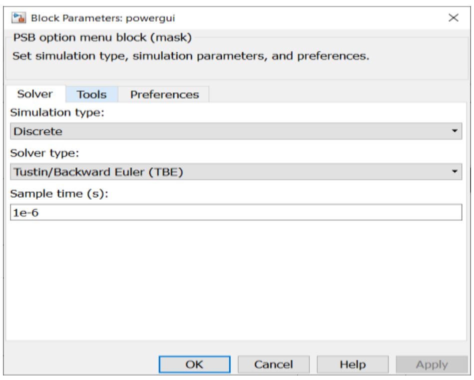

Figure 19 Sample Time in Powergui Block

3.5 Hybrid Pulse Wide Modulation Technique

In order to hybrid the PWM technique there is a few methods that has been applied which is by making the carrier waveform of the multilevel inverter narrow and wide. Meanwhile for the carrier frequency of all method is maintain at 20kHz and all RLC load value is same. The other components setting in the circuit also maintain unchanged. The hybrid PWM is built by performing the combination of two different type of conventional PWM such as PS PWM, PD PWM and so on. The circuit or modelling of the CHMI multilevel inverter is using the same as the conventional PWM CHMI multilevel inverter that has been construct before which is shown in Figure 18. Since the modelling is for five level multilevel inverter and the carrier signal is four signals because of equation number of levels minus one (m-1). So, during the hybrid the PWM it will be chosen and used two level of each PWM technique that going to be hybrid with each other. All the hybrid methods are being test and simulation with three differences switching technique which is low, high and variable (low and high) Carrier Frequency Bands (CFB).

3.5.1 Phase Shift – Phase Disposition (PS-PD) PWM

Figure 20 below shows the triangular carrier signal for low carrier frequency band switching technique of PS-PD PWM. On the other hand, Figure 21 shows the triangular carrier signal for high carrier frequency band switching technique and Figure 22 shows the triangular carrier signal for low carrier frequency band switching technique of PS-PD PWM.

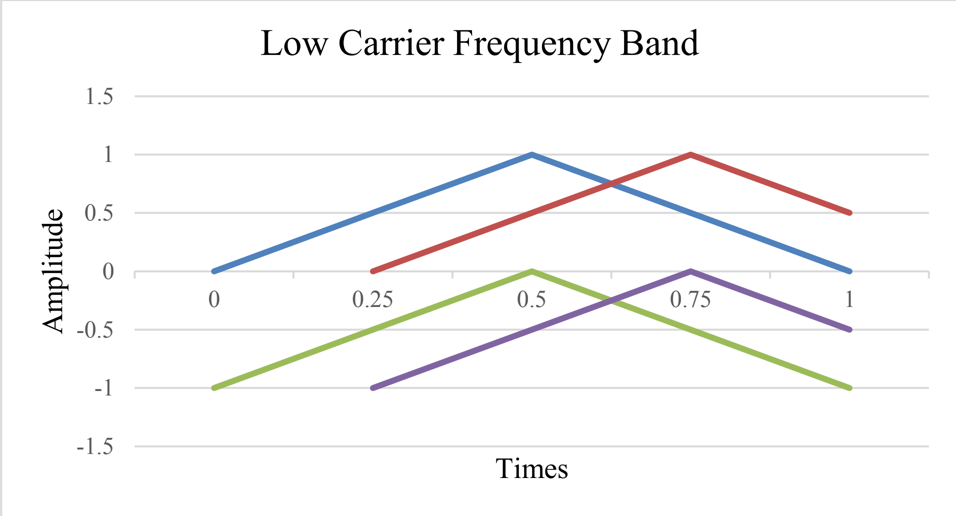

Figure 20 PS-PD PWM (Low Carrier Frequency Band)

For Low CFB PS-PD PWM, it constructs by the PD PWM carrier waveform that is shifted at two phases so at each phase has two carrier waveforms to perform the shifting role as shown in

Figure 20.

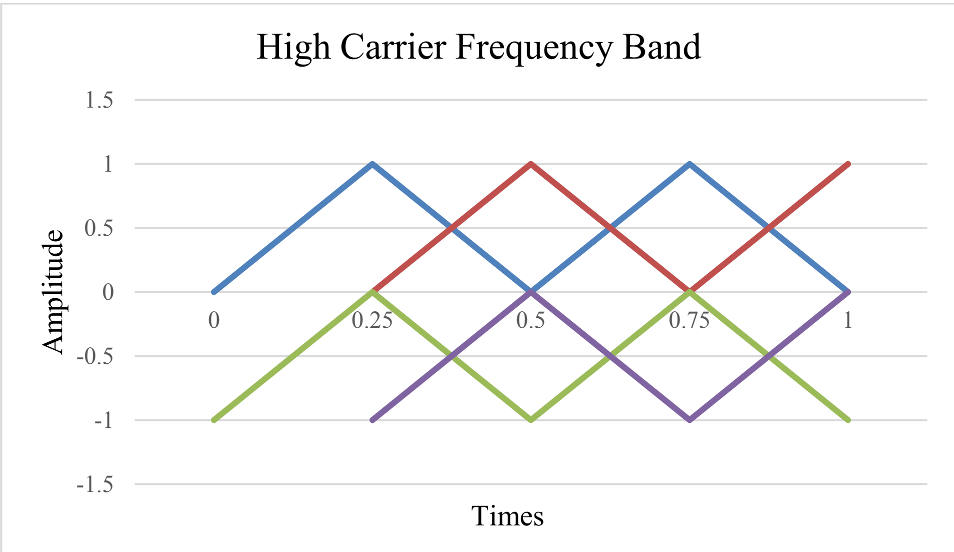

Figure 21 PS-PD PWM (High Carrier Frequency Band)

While for the High CFB PS-PD PWM is using the same concept as low CFB PS-PD PWM just difference at it is construct smaller or much narrow carrier waveform compare low CFB PS-PD PWM which for high CFB PS-PD PWM can complete two cycle of carrier waveform in one period but the low CFB PS-PD PWM only complete one cycle at one period.

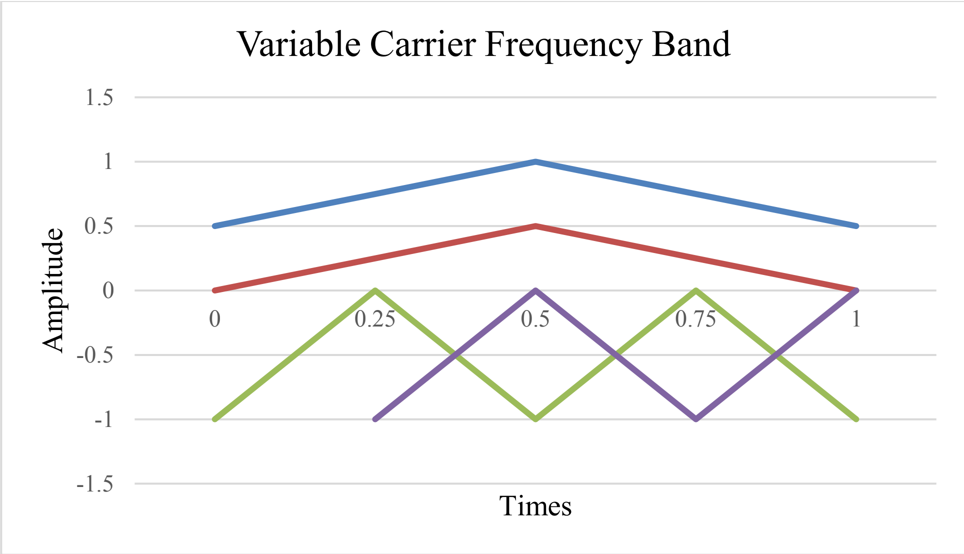

Figure 22 PS-PD PWM (Variable Carrier Frequency Band)

For variable CFB PS-PD PWM, it was construct by using two carrier waveforms of PD PWM at first phase and another two-carrier waveform of PS PWM for second phase. For first phase all carrier waveform is being set to be wider compare to the second phase.

3.5.2 Phase Shifted – Phase Opposition Disposition (PS-POD) PWM

For this hybrid PWM is by combine the phase shift PWM and phase opposition disposition PWM and it is the level shifting every two level of carrier signal of POD. This method is being test and simulation with three differences switching technique which is low, high and variable (low and high) carrier frequency bands.

Figure 23 below shows the triangular carrier signal for low carrier frequency band switching technique of PS-POD PWM. On the other hand, Figure 24 shows the triangular carrier signal for high carrier frequency band switching technique and Figure 25 shows the triangular carrier signal for low carrier frequency band switching technique of PS-POD PWM.

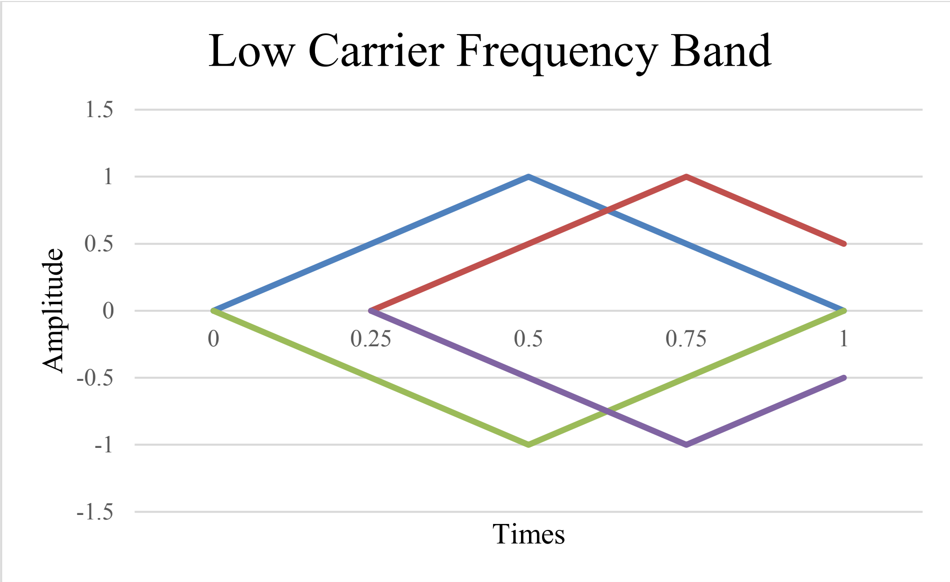

Figure 23 PS-POD PWM (Low Carrier Frequency Band)

For low CFB PS-POD PWM, it constructs by the POD PWM carrier waveform that is shifted at two phases so at each phase has two carrier waveforms.

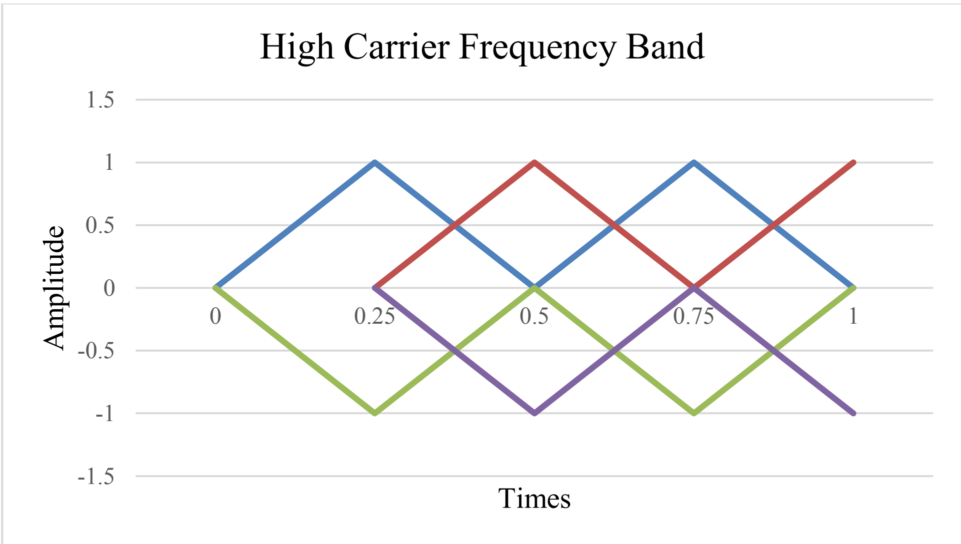

Figure 24 PS-POD PWM (High Carrier Frequency Band)

While for the High CFB PS-POD PWM is using the same concept as Low CFB PS-POD PWM just difference at it is construct smaller or much narrow carrier waveform compare low CFB PS-POD PWM which for high PS-POD PWM can complete two cycle of carrier waveform in one period but the high PS-POD PWM only complete one cycle at one period.

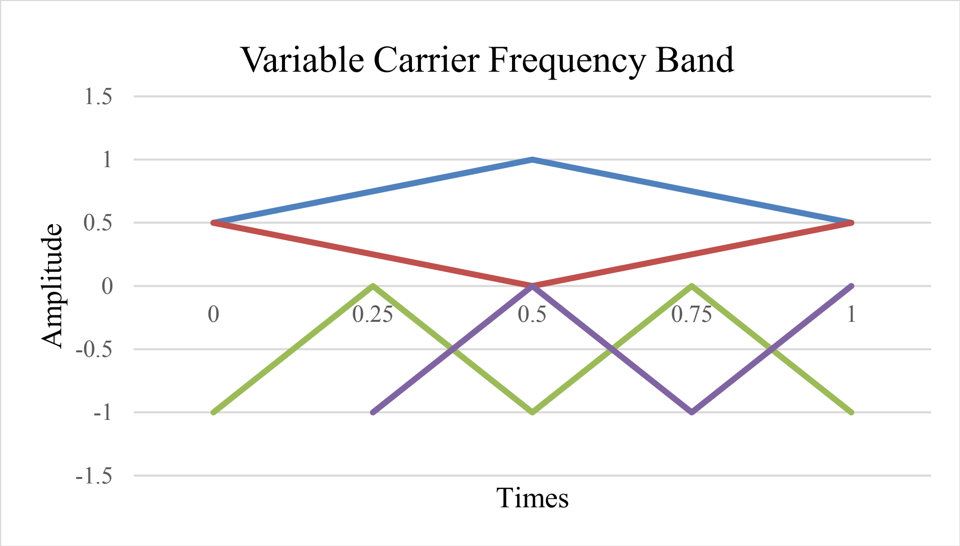

Figure 25 PS-POD PWM (Variable Carrier Frequency Band)

For variable CFB PS-POD PWM, it was construct by using two carrier waveforms of POD PWM at first phase and another two-carrier waveform of PS PWM for second phase. For first phase all carrier waveform is being set to be wider compare to the second phase.

3.5.3 Phase Shifted – Alternative Phase Opposition Disposition (PS-APOD) PWM

For this hybrid PWM is by combine the phase shift PWM and alternative phase opposition disposition PWM and it is the level shifting every two level of carrier signal of APOD. This method is being test and simulation with three differences switching technique which is low, high and variable (low and high) carrier frequency bands.

Figure 26 below shows the triangular carrier signal for low carrier frequency band switching technique of PS-APOD PWM. On the other hand, Figure 27 shows the triangular carrier signal for high carrier frequency band switching technique and Figure 28 shows the triangular carrier signal for low carrier frequency band switching technique of PS-APOD PWM.

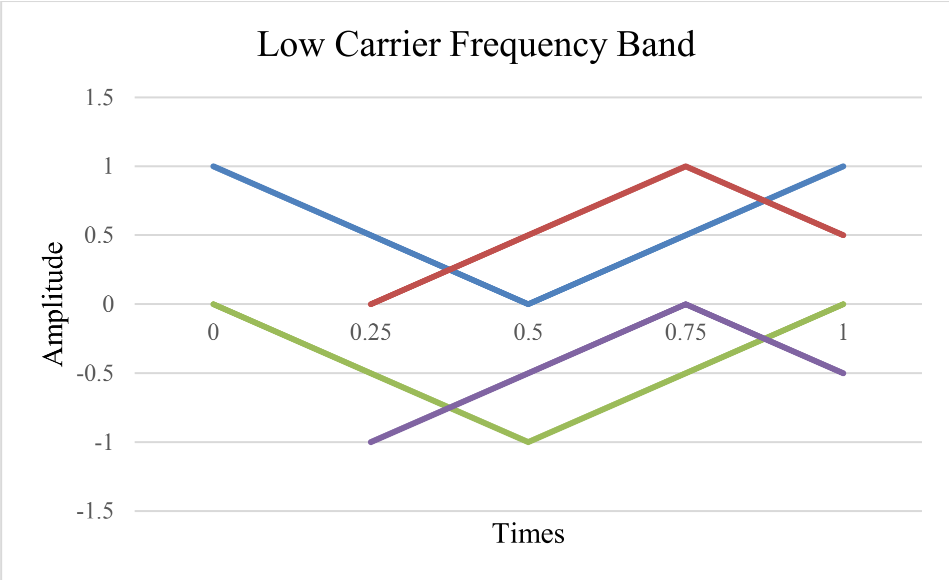

Figure 26 PS-APOD PWM (Low Carrier Frequency Band)

For low carrier frequency band, it was construct by setting the triangular carrier signal of APOD PWM complete one cycle in one time and the carrier signal also being shifted at odd level signal to the right and it made the carrier signal wider.

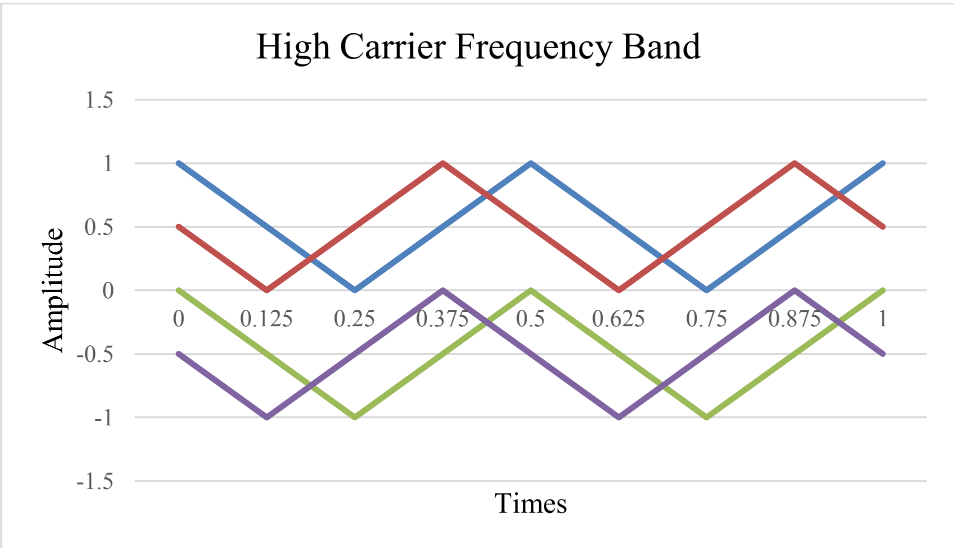

Figure 27 PS-APOD PWM (High Carrier Frequency Band)

For high carrier frequency band, it was construct by setting the triangular carrier signal APOD PWM complete two cycle in one time and the carrier signal also being shifted at odd level signal to the right and it made the carrier signal narrow.

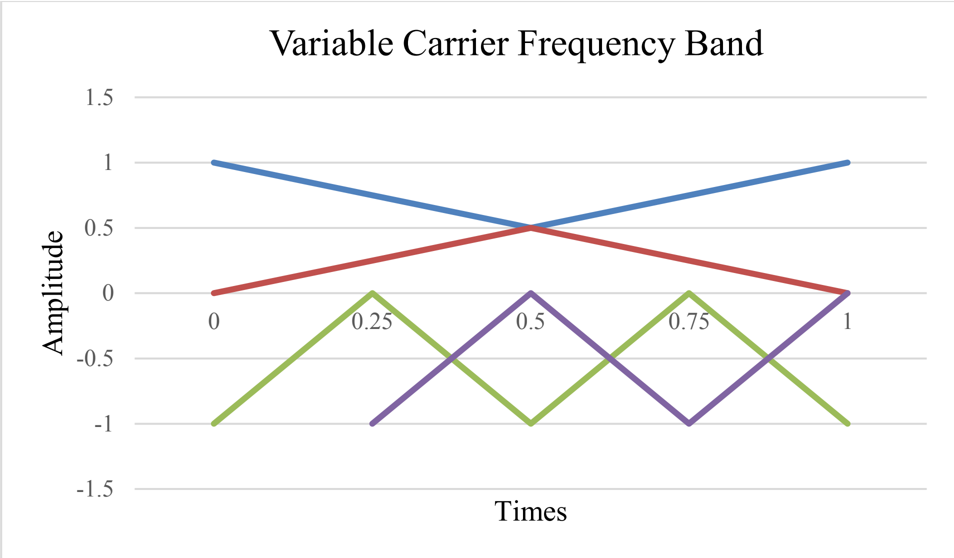

Figure 28 PS-APOD PWM (Variable Carrier Frequency Band)

For variable carrier frequency band, it was the combination of low and high carrier frequency band which for the first two level is APOD PWM carrier signal with low carrier frequency band and another two level of PS PWM carrier signal with high carrier frequency band.

3.5.4 Phase Disposition –Phase Opposition Disposition (PD-POD) PWM

For this hybrid PWM is by combine the phase disposition PWM and phase opposition disposition PWM. It was combined by insert first two level is PD PWM carrier signal and another two level are the POD PWM carrier signal. This method is being test and simulation with three differences switching technique which is low, high and variable (low and high) carrier frequency bands.

Figure 29 below shows the triangular carrier signal for low carrier frequency band switching technique of PD-POD PWM. On the other hand, Figure 30 shows the triangular carrier signal for high carrier frequency band switching technique and Figure 31 shows the triangular carrier signal for low carrier frequency band switching technique of PD-POD PWM.

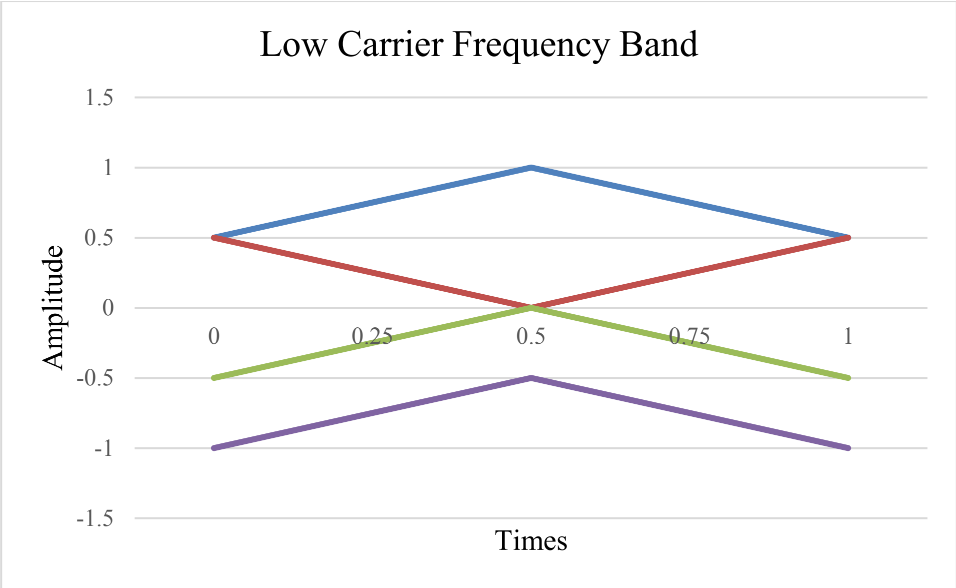

Figure 29 PD-POD PWM (Low Carrier Frequency Band)

For low carrier frequency band, it was construct by setting the triangular carrier signal of for both POD PWM and PD PWM to be complete one cycle in one and it made the carrier signal wider.

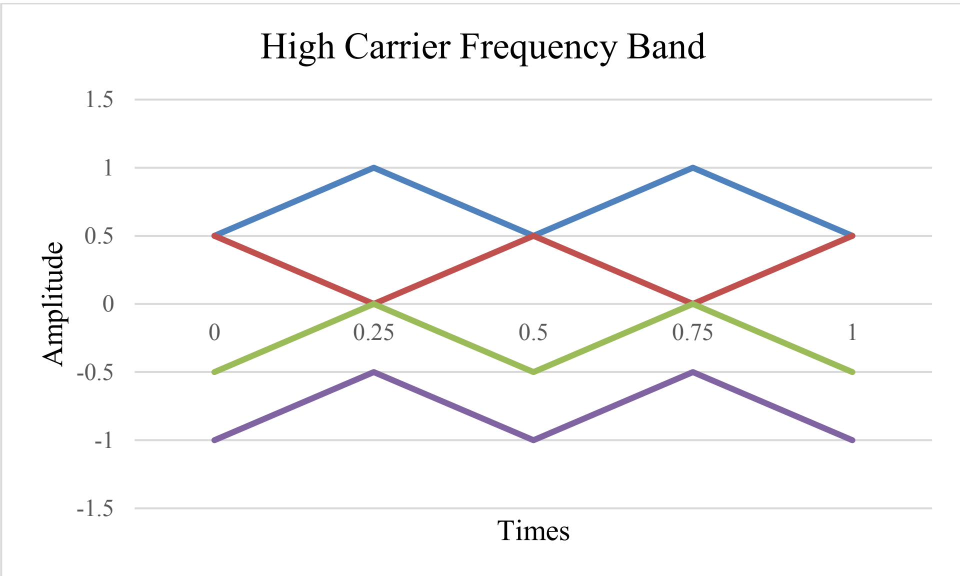

Figure 30 PD-POD PWM (High Carrier Frequency Band)

For high carrier frequency band, it was construct by setting the triangular carrier signal of for both POD PWM and PD PWM to be complete two cycle in one and it made the carrier signal narrow.

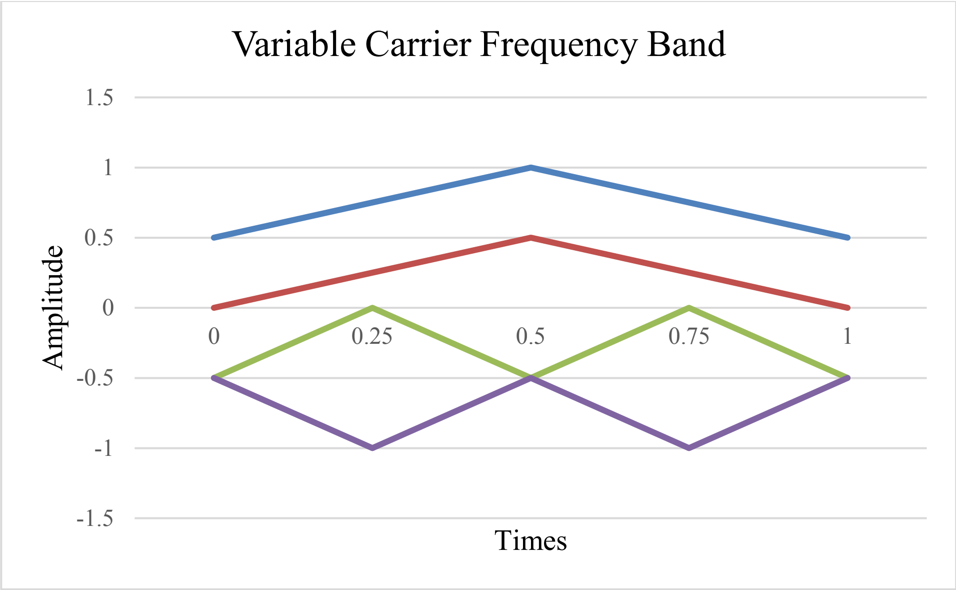

Figure 31 PD-POD PWM (Variable Carrier Frequency Band)

For variable carrier frequency band, it was the combination of low and high carrier frequency band which for the first two level is PD PWM carrier signal with low carrier frequency band and another two level of POD PWM carrier signal with high carrier frequency band.

3.5.5 Phase Disposition – Alternative Phase Opposition Disposition (PD-APOD) PWM

For this hybrid PWM is by combine the phase disposition PWM and alternative phase opposition disposition PWM. It was combined by insert first two level is PD PWM carrier signal and another two level are the APOD PWM carrier signal. This method is being test and simulation with three differences switching technique which is low, high and variable (low and high) carrier frequency bands.

Figure 32 below shows the triangular carrier signal for low carrier frequency band switching technique of PD-APOD PWM. On the other hand, Figure 33 shows the triangular carrier signal for high carrier frequency band switching technique and Figure 34 shows the triangular carrier signal for low carrier frequency band switching technique of PD-APOD PWM.

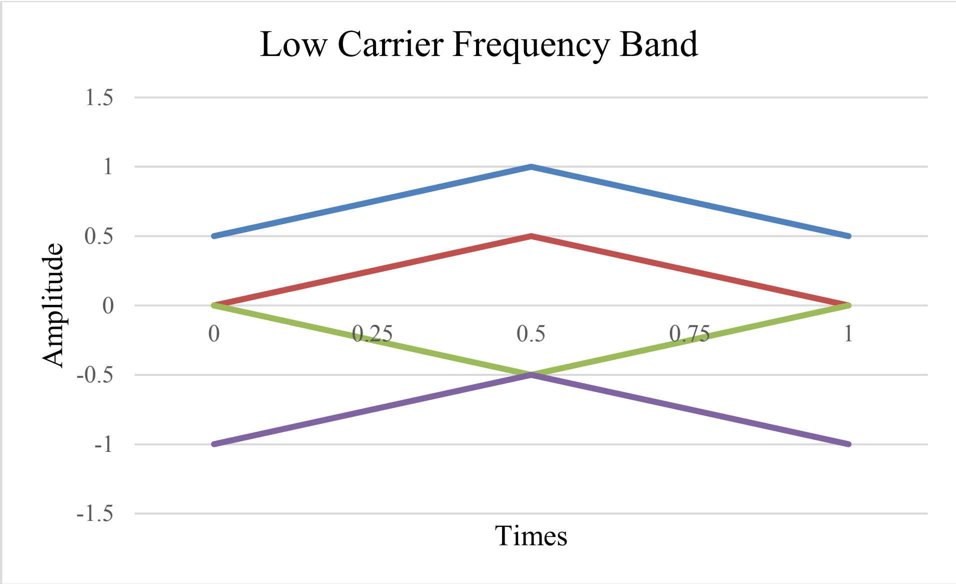

Figure 32 PD-APOD PWM (Low Carrier Frequency Band)

For low carrier frequency band, it was construct by setting the triangular carrier signal of for both PD PWM and APOD PWM to be complete one cycle in one and it made the carrier signal wider.

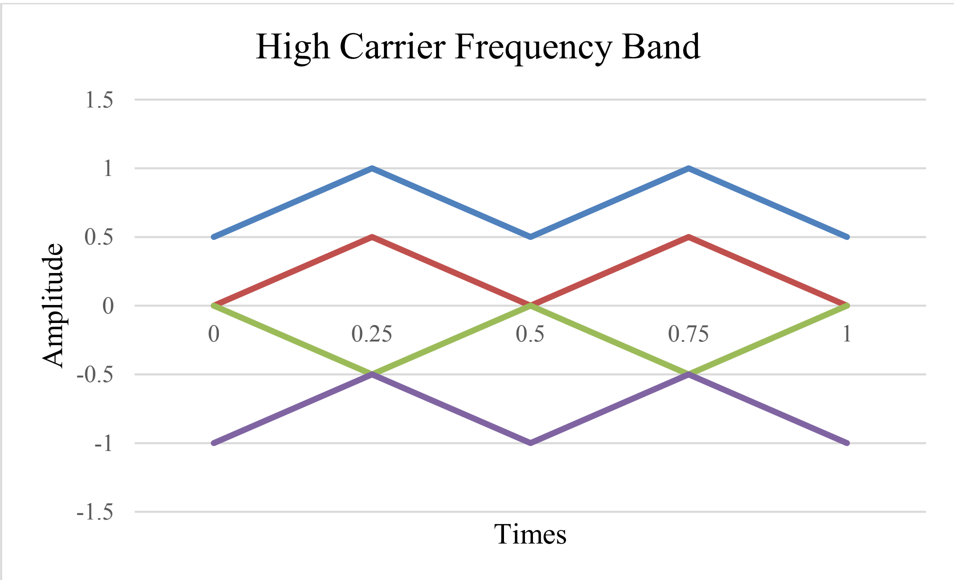

Figure 33 PD-APOD PWM (High Carrier Frequency Band)

For high carrier frequency band, it was construct by setting the triangular carrier signal of for both PD PWM and APOD PWM to be complete two cycle in one and it made the carrier signal narrow.

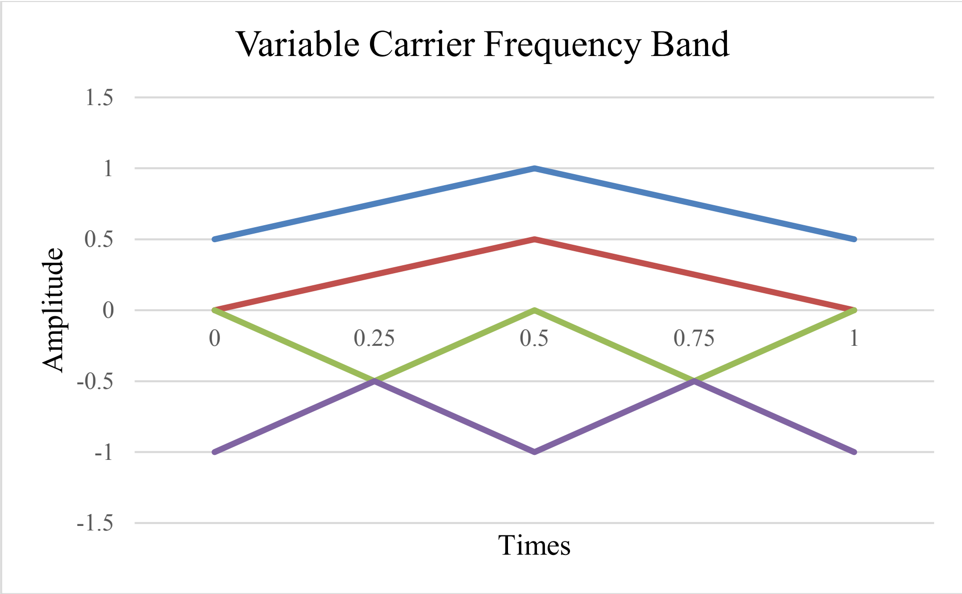

Figure 34 PD-APOD PWM (Variable Carrier Frequency Band)

For variable carrier frequency band, it was the combination of low and high carrier frequency band which for the first two level is PD PWM carrier signal with low carrier frequency band and another two level of APOD PWM carrier signal with high carrier frequency band.

3.5.6 Phase Opposition Disposition-Alternative Phase Opposition Disposition (POD-APOD) PWM

For this hybrid PWM is by combine the phase disposition PWM and alternative phase opposition disposition PWM. It was combined by insert first two level is POD PWM carrier signal and another two level are the APOD PWM carrier signal. This method is being test and simulation with three differences switching technique which is low, high and variable (low and high) carrier frequency bands.

Figure 35 below shows the triangular carrier signal for low carrier frequency band switching technique of POD-APOD PWM. On the other hand, Figure 36 shows the triangular carrier signal for high carrier frequency band switching technique and Figure 37 shows the triangular carrier signal for low carrier frequency band switching technique of POD-APOD PWM.

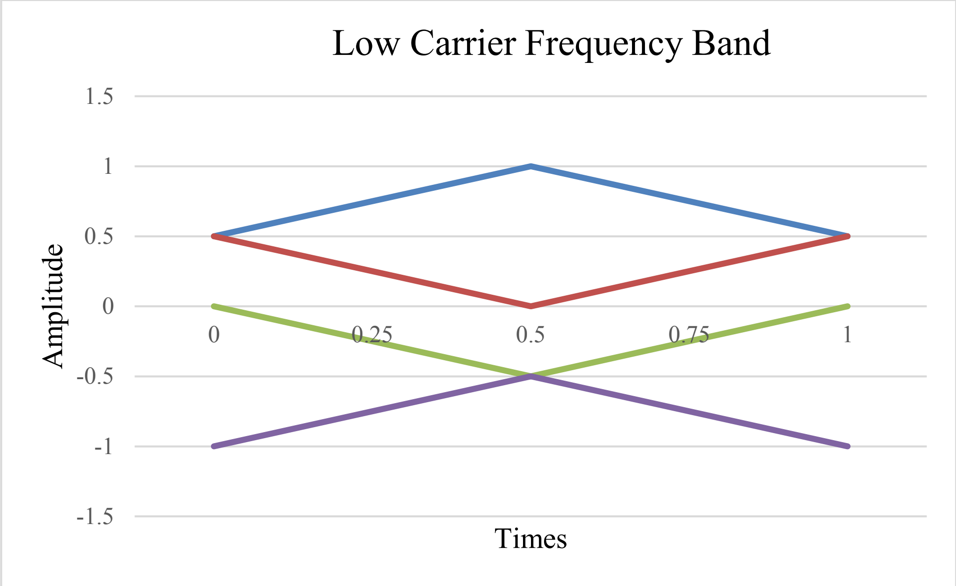

Figure 35 POD - APOD PWM (Low Carrier Frequency Band)

For low carrier frequency band, it was construct by setting the triangular carrier signal of for both POD PWM and APOD PWM to be complete one cycle in one and it made the carrier signal wider.

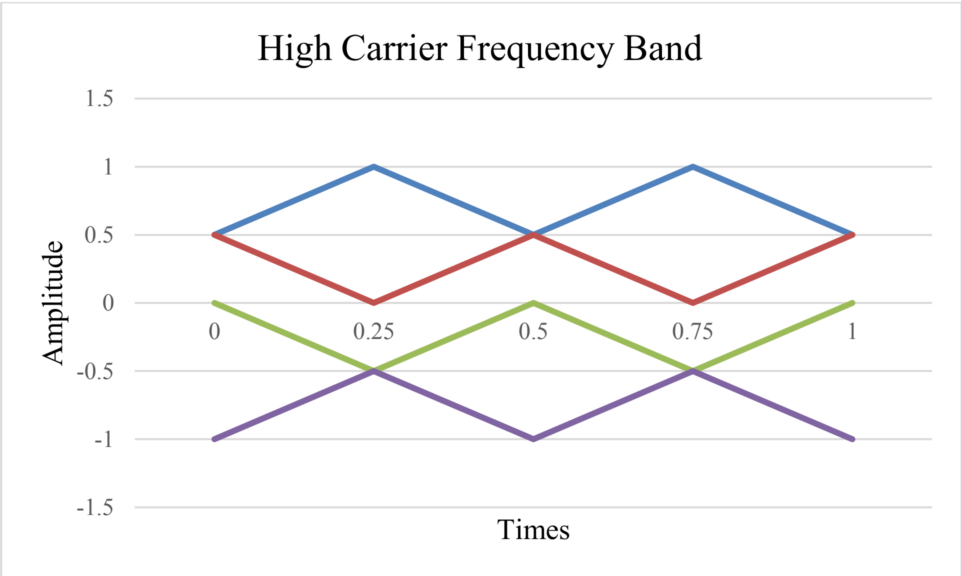

Figure 36 POD-APOD PWM (High Carrier Frequency Band)

For high carrier frequency band, it was construct by setting the triangular carrier signal of for both POD PWM and APOD PWM to be complete two cycle in one and it made the carrier signal narrow.

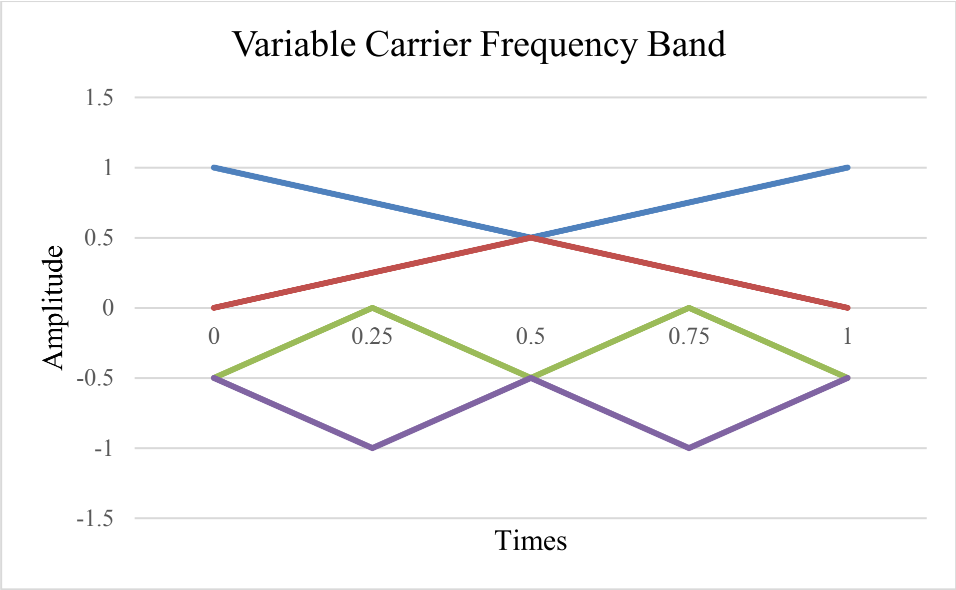

Figure 37 POD-APOD PWM (Variable Carrier Frequency Band)

For variable carrier frequency band, it was the combination of low and high carrier frequency band which for the first two level is APOD PWM carrier signal with low carrier frequency band and another two level of POD PWM carrier signal with high carrier frequency band.

3.6 Conventional Phase Disposition (PD) PWM

In phase disposition PWM is in the same phase for all carriers signal that placed above zero-reference line and below the zero-reference line. Since in this research work it being used to perform the comparison of THD value so it also being develop in three switching technique that same in the hybrid PWM technique which is low, high and variable carrier frequency band.

Figure 38 below shows the triangular carrier signal for low carrier frequency band switching technique of PD PWM. On the other hand, Figure 39 shows the triangular carrier signal for high carrier frequency band switching technique and Figure 40 shows the triangular carrier signal for low carrier frequency band switching technique of PD PWM.

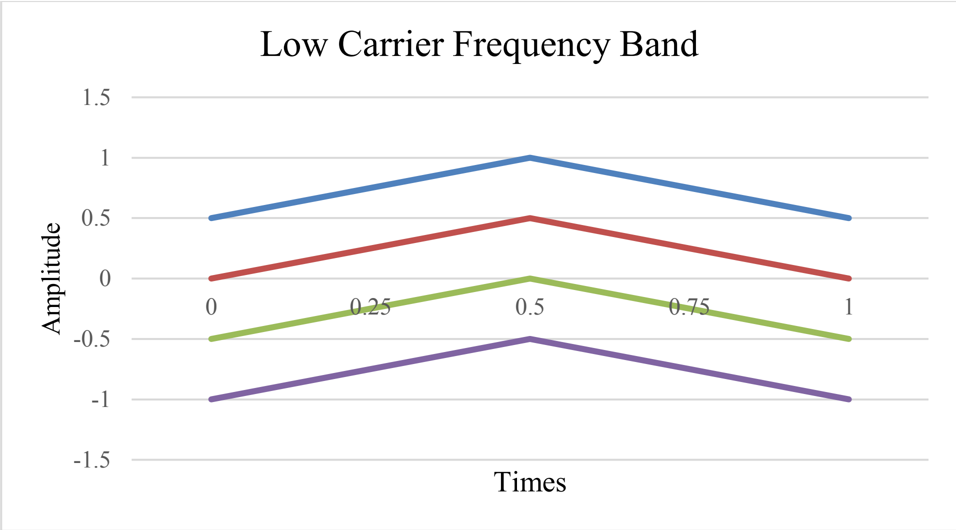

Figure 38 PD PWM (Low Carrier Frequency Band)

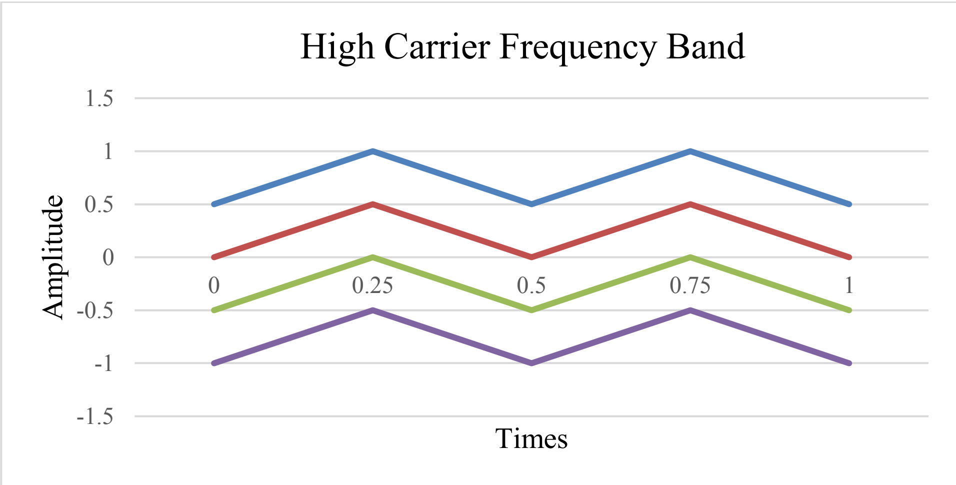

Figure 39 PD PWM (High Carrier Frequency Band)

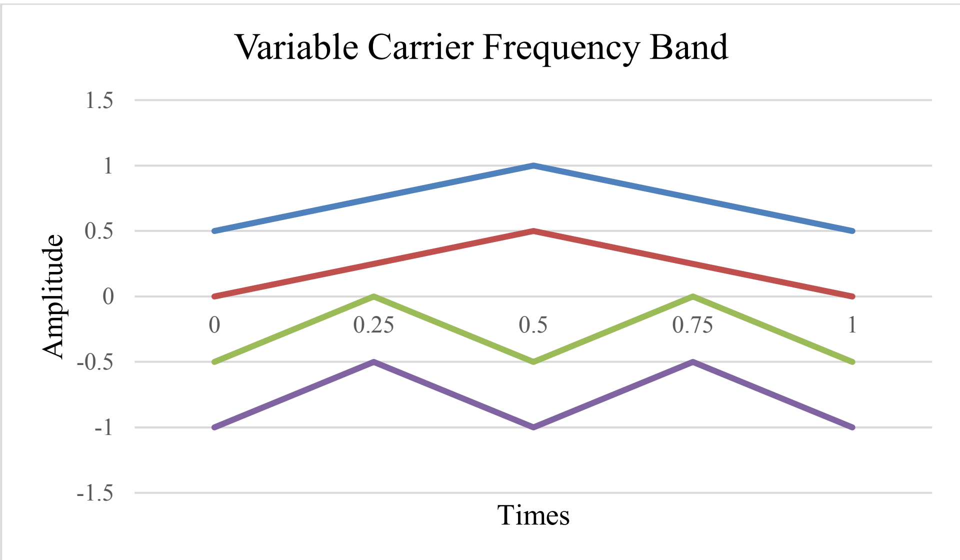

Figure 40 PD PWM (Variable Carrier Frequency Band)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The simulation block for all PWM method is same as in Figure 18 just the different at its carrier signal. The number of carrier signal was determined as below:

$$m - 1 = 5 - 1 = 4 \text{ carrier signal} \qquad (3.\ 7)$$

where the m is the number of levels for the multilevel inverter. So, from the calculation there will be four carrier signals to be used for the multilevel inverter and one reference signal. Then the carrier signal was being create by using the one sequence block for one carrier signal and each of them will be edited in tab Figure 41 below:

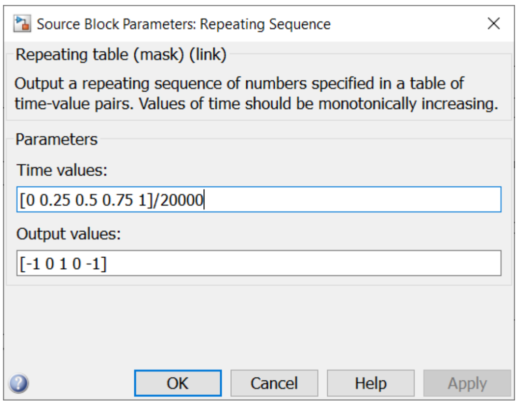

Figure 41 Repeating Sequence Block

4.2 Phase Disposition PWM Multilevel Inverter

Figure 42 below shows the input waveform of PD PWM generated by MATLAB SIMULINK simulation.

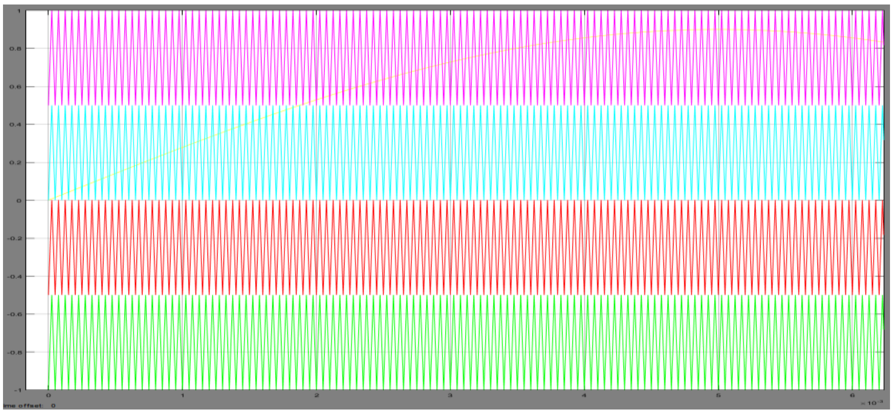

Figure 42 Input Waveform of PD PWM

4.2.1 PD PWM Low Carrier Frequency Band (LCFB)

Figure 43 shows the output five level waveform and Figure 44 shows the output voltage and current waveform of Low Carrier Frequency Band PD PWM. Besides, Figure 45 shows the generated THD value by the Low Carrier Frequency Band PD PWM.

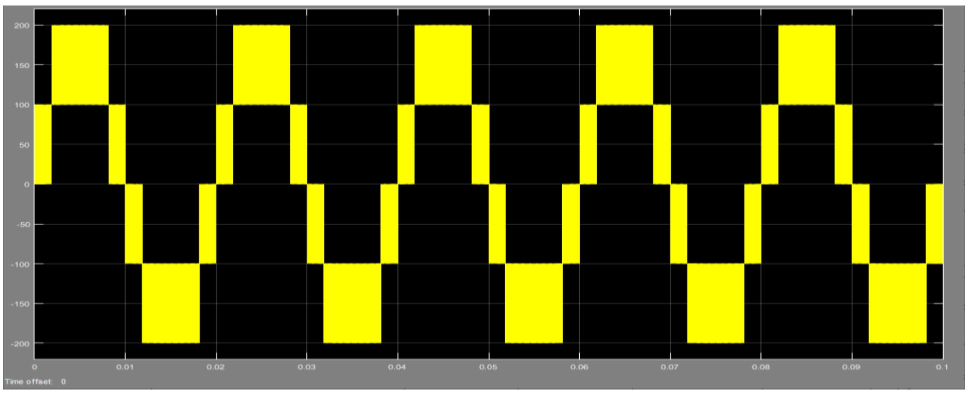

Figure 43 Output 5-Level Waveform PD PWM (Low Carrier Frequency Band)

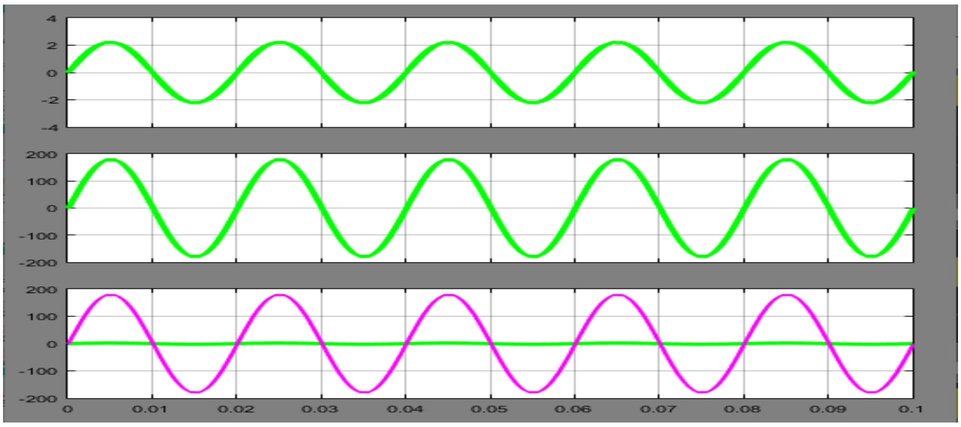

Figure 44 Output Voltage and Current Waveform PD PWM (Low Carrier Frequency Band)

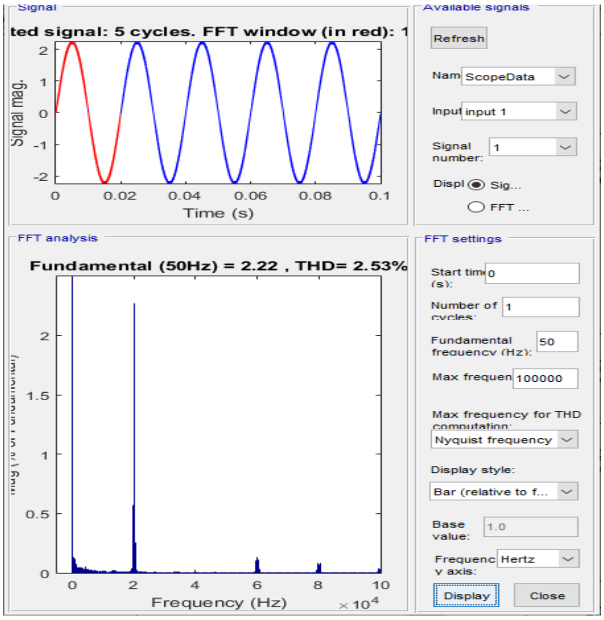

Figure 45 Harmonic Distortion by PD PWM (Low Carrier Frequency Band)

4.2.2 PD PWM High Carrier Frequency Band (HCFB)

Figure 46Figure 43 shows the output five level waveform and Figure 47 shows the output voltage and current waveform of High Carrier Frequency Band PD PWM. Besides, Figure 48 shows the generated THD value by the High Carrier Frequency Band PD PWM.

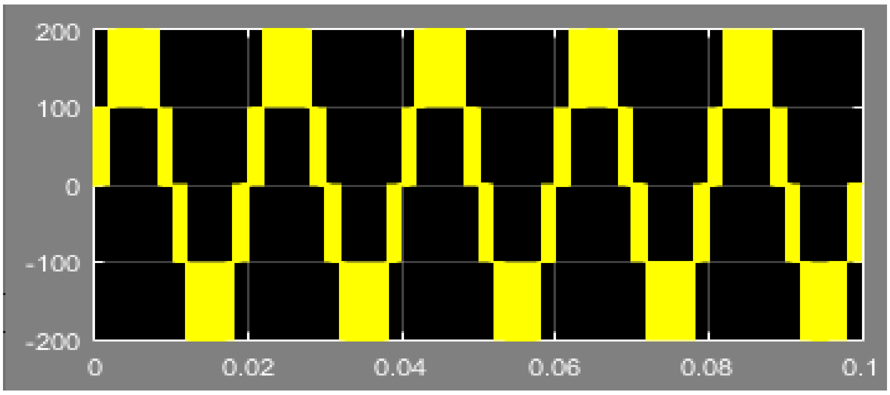

Figure 46 Output 5-Level Waveform PD PWM (High Carrier Frequency Band)

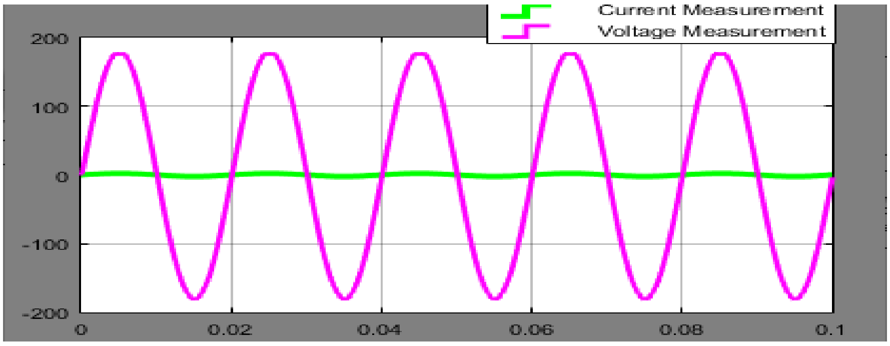

Figure 47 Output Voltage and Current Waveform PD PWM (High Carrier Frequency Band)

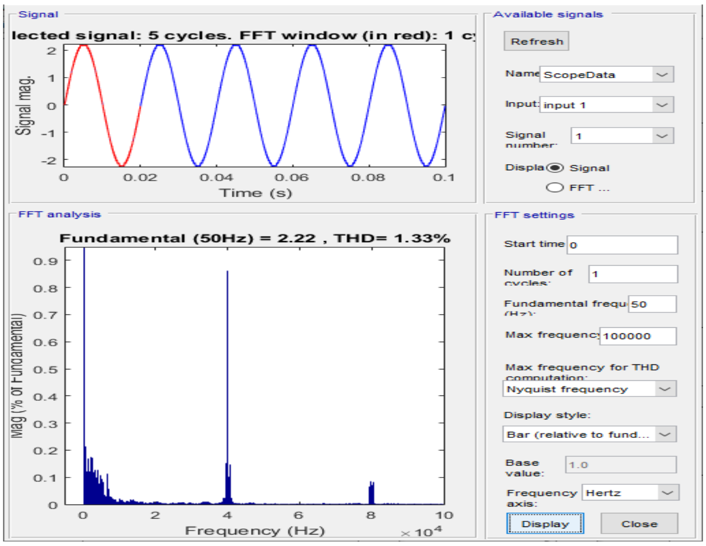

Figure 48 Harmonic Distortion by PD PWM (High Carrier Frequency Band)

4.2.3 PD PWM Variable Carrier Frequency Band (VCFB)

Figure 49 shows the output five level waveform and Figure 50 shows the output voltage and current waveform of Variable Carrier Frequency Band PD PWM. Besides, Figure 51 shows the generated THD value by the Variable Carrier Frequency Band PD PWM.

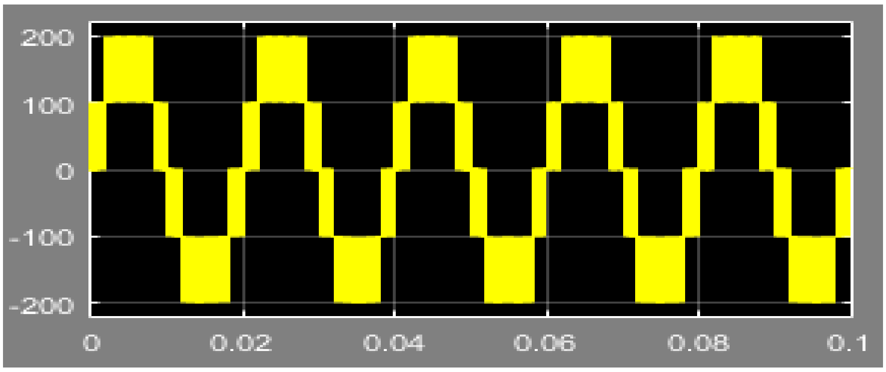

Figure 49 Output 5-Level Waveform PD PWM (Variable Carrier Frequency Band)

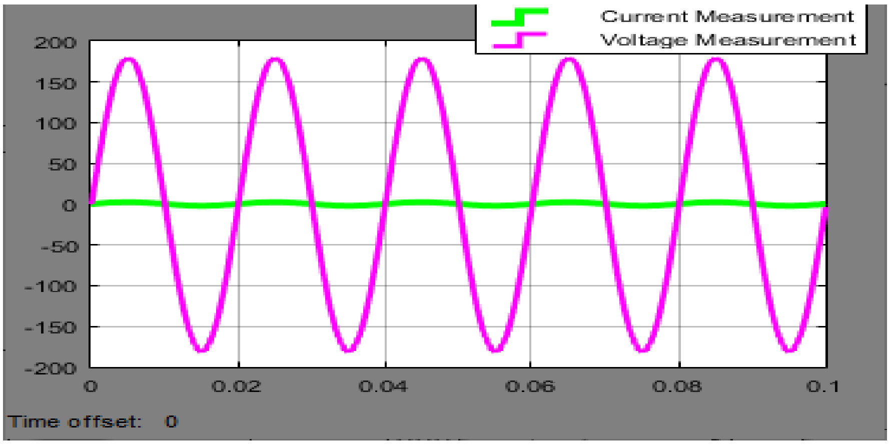

Figure 50 Output Voltage and Current Waveform PD PWM (Variable Carrier Frequency Band)

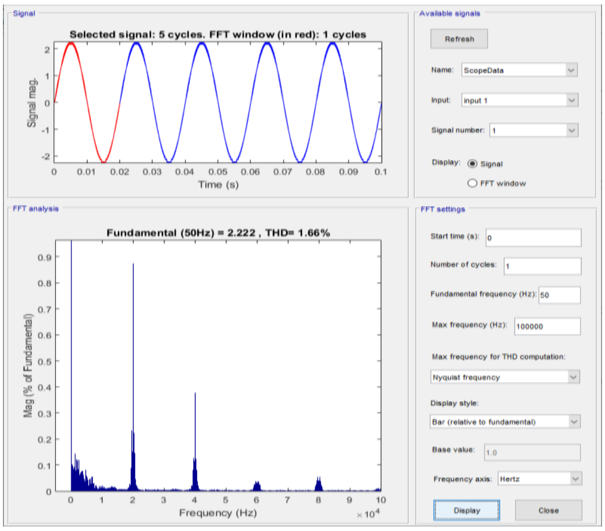

Figure 51 Harmonic Distortion by PD PWM (Variable Carrier Frequency Band)

Table 5 Generated THD (%) by PD PWM

Switching Techniques (PD PWM)	Harmonic Distortion, THD Value (%)
Low Carrier Frequency Band	2.00
High Carrier Frequency Band	1.33
Variable Carrier Frequency Band	1.66

Table 5 shows all the THD value generated by PD PWM for three switching technique. The reference signal and the four carrier signals are in the same phase and below the zero-reference line too which can been observe in Figure 42. The output five level is determined at front of the load and the generated output voltage and current for whole circuit is determined after the load is applied. From the output current, the THD is being determined which is 2.00% for low carrier frequency band, 1.33% for high carrier frequency band and 1.66% for variable carrier frequency band of harmonic is being generated by this PD PWM multilevel inverter. Overall, the output voltage is 180V for all the three switching techniques of PD PWM.

4.3 Hybrid Pulse Wide Modulation Technique

4.3.1 Phase Shift – Phase Disposition (PS-PD) PWM

4.3.1.1 PS-PD PWM Low Carrier Frequency Band (LCFB)

Figure 52 shows the output five level waveform and Figure 53 shows the output voltage and current waveform of Low Carrier Frequency Band PS-PD PWM. Besides, Figure 54 shows the generated THD value by the Low Carrier Frequency Band PS-PD PWM.

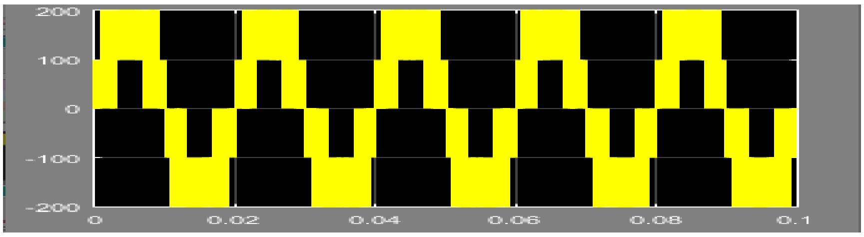

Figure 52 Output 5-Level Waveform PS-PD PWM (Low Carrier Frequency Band)

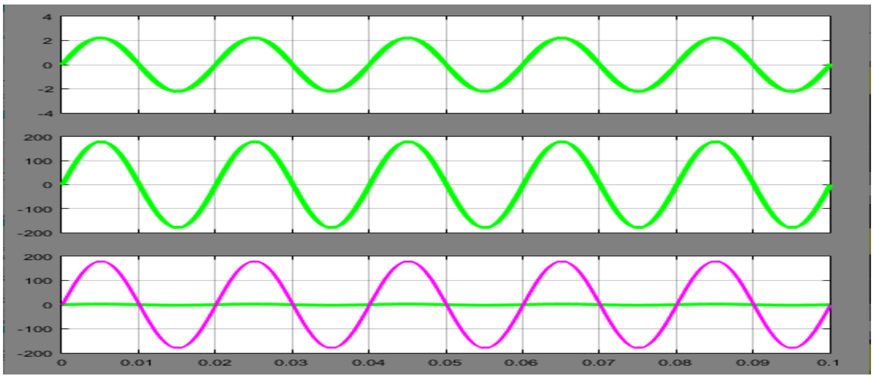

Figure 53 Output Current and Voltage Waveform PS-PD PWM (Low Carrier Frequency Band)

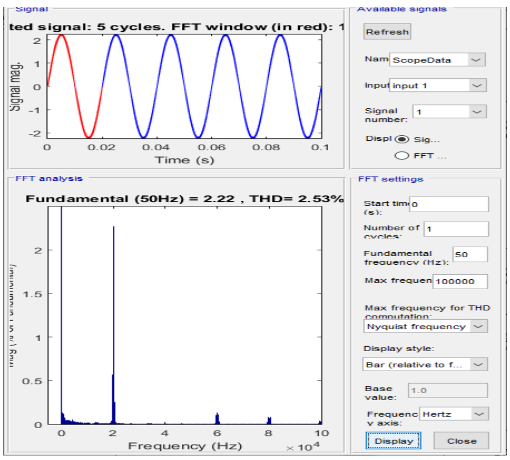

Figure 54 Harmonic Distortion by PS-PD PWM (Low Carrier Frequency Band)

4.3.1.2 PS-PD PWM High Carrier Frequency Band (HCFB)

Figure 55 shows the output five level waveform and Figure 56 shows the output voltage and current waveform of High Carrier Frequency Band PS-PD PWM. Besides, Figure 57 shows the generated THD value by the High Carrier Frequency Band PS-PD PWM.

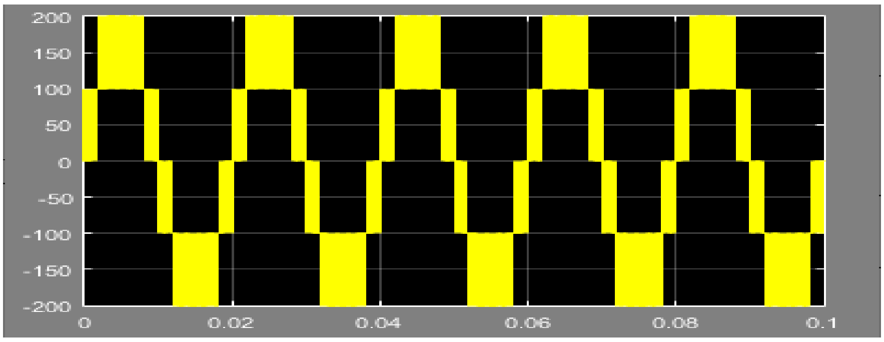

Figure 55 Output 5-Level Waveform PS-PD PWM (High Carrier Frequency Band)

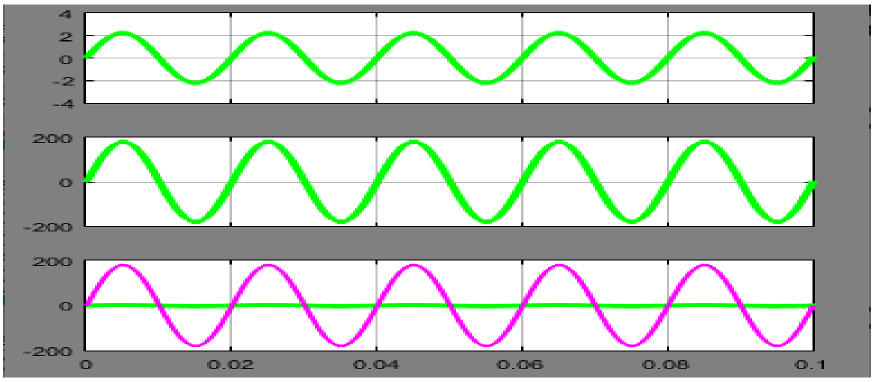

Figure 56 Output Current and Voltage Waveform PS-PD PWM (High Carrier Frequency Band)

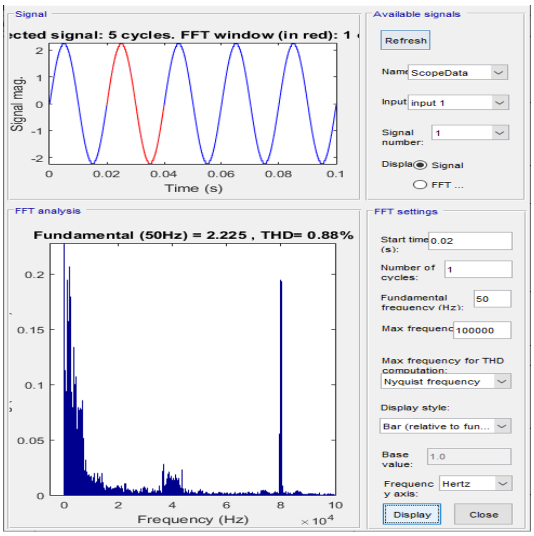

Figure 57 Harmonic Distortion by PS-PD PWM (High Carrier Frequency Band)

4.3.1.3 PS-PD PWM Variable Carrier Frequency Band (VCFB)

Figure 58 shows the output five level waveform and Figure 59 shows the output voltage and current waveform of Low Carrier Frequency Band PS-PD PWM. Besides, Figure 60 shows the generated THD value by the Low Carrier Frequency Band PS-PD PWM.

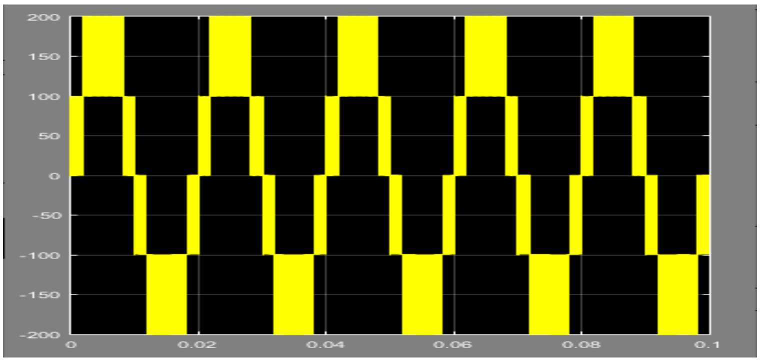

Figure 58 Output 5-Level Waveform PS-PD PWM (Variable Carrier Frequency Band)

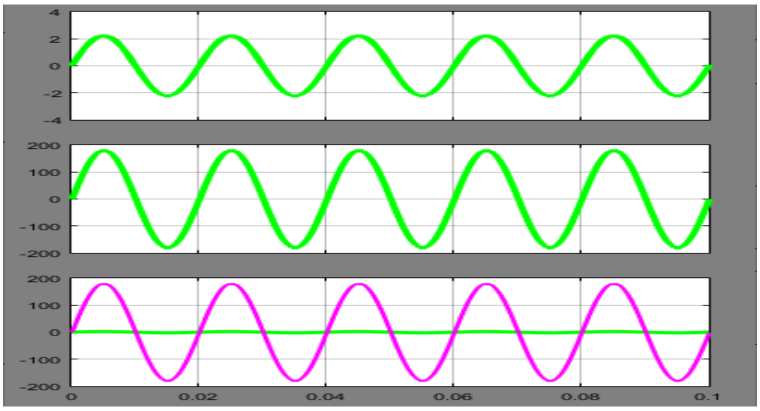

Figure 59 Output Current and Voltage Waveform PS-PD PWM (Variable Carrier Frequency Band)

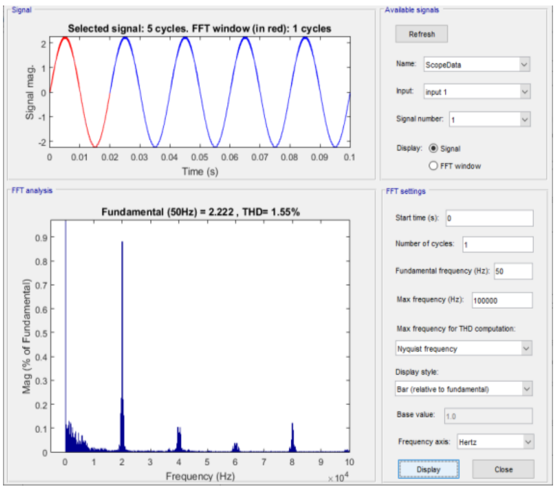

Figure 60 Harmonic Distortion by PS-PD PWM (Variable Carrier Frequency Band)

Table 6 Generated THD by PS-PD PWM

Switching Techniques (PS-PD PWM)	Harmonic Distortion, THD Value (%)
Low Carrier Frequency Band	2.53
High Carrier Frequency Band	0.88
Variable Carrier Frequency Band	1.55

From the Table 6 above shows the generated THD value by PS-PD PWM which the highest THD is 2.53% by low carrier frequency band and the lowest THD is 0.88% by the high carrier frequency band. For the output voltage is all around 178V which is almost 180V.

4.3.2 Phase Shift – Phase Opposition Disposition (PS-POD) PWM

4.3.2.1 PS-POD PWM Low Carrier Frequency Band (LCFB)

Figure 61 shows the output five level waveform and Figure 62 shows the output voltage and current waveform of Low Carrier Frequency Band PS-POD PWM. Besides, Figure 63 shows the generated THD value by the Low Carrier Frequency Band PS-POD PWM.

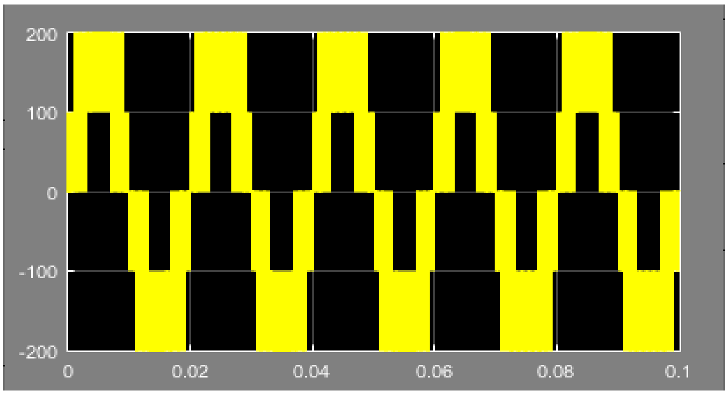

Figure 61 Output 5-Level Waveform PS-POD PWM (Low Carrier Frequency Band)

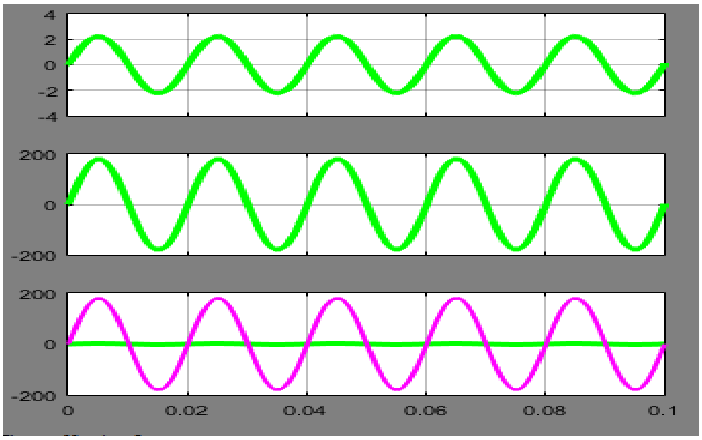

Figure 62 Output Current and Voltage Waveform PS-POD PWM (Low Carrier Frequency Band)

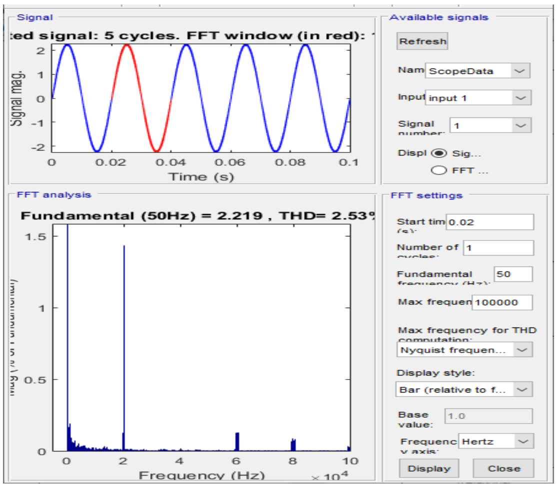

Figure 63 Harmonic Distortion by PS-POD PWM (Low Carrier Frequency Band)

4.3.2.2 PS-POD PWM High Carrier Frequency Band (HCFB)

Figure 64 shows the output five level waveform and Figure 65 shows the output voltage and current waveform of High Carrier Frequency Band PS-POD PWM. Besides, Figure 66 shows the generated THD value by the High Carrier Frequency Band PS-POD PWM.

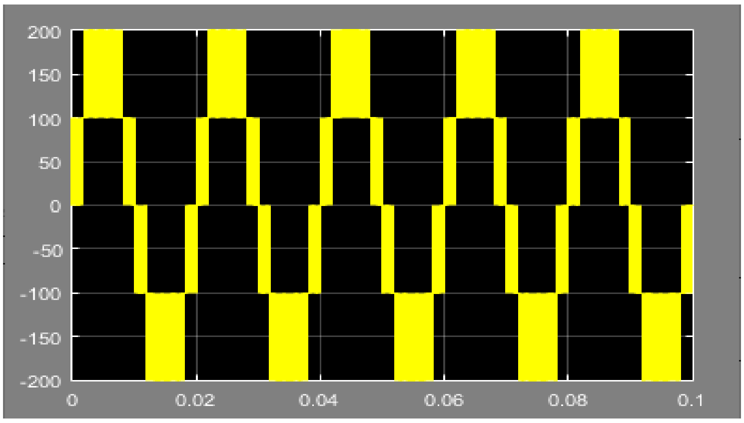

Figure 64 Output 5-Level Waveform PS-POD PWM (High Carrier Frequency Band)

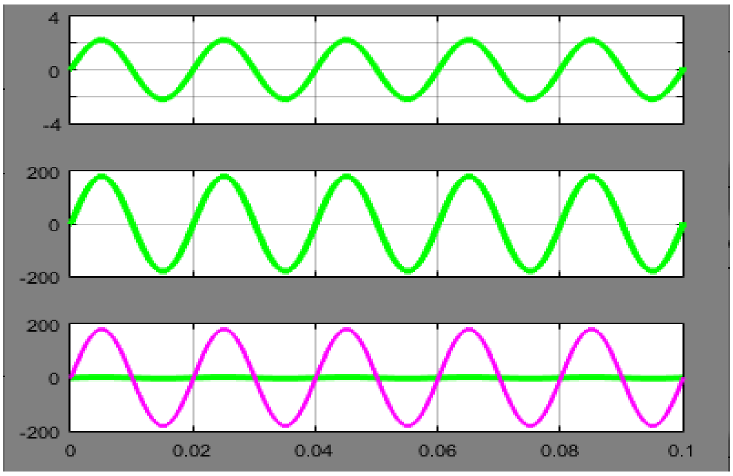

Figure 65 Output Current and Voltage Waveform PS-POD PWM (High Carrier Frequency Band)

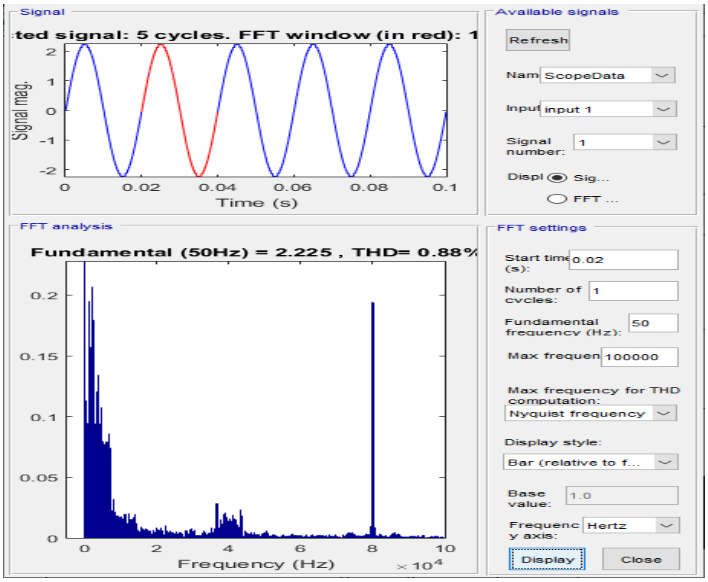

Figure 66 Harmonic Distortion by PS-POD PWM (High Carrier Frequency Band)

4.3.2.3 PS-POD PWM Variable Carrier Frequency Band (VCFB)

Figure 67 shows the output five level waveform and Figure 68 shows the output voltage and current waveform of Variable Carrier Frequency Band PS-POD PWM. Besides, Figure 69 shows the generated THD value by the Variable Carrier Frequency Band PS-POD PWM.

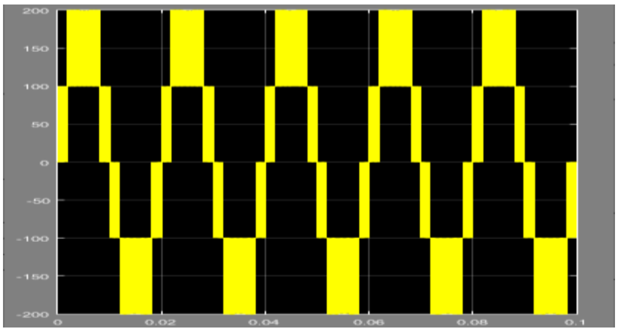

Figure 67 Output 5-Level Waveform PS-POD PWM (Variable Carrier Frequency Band)

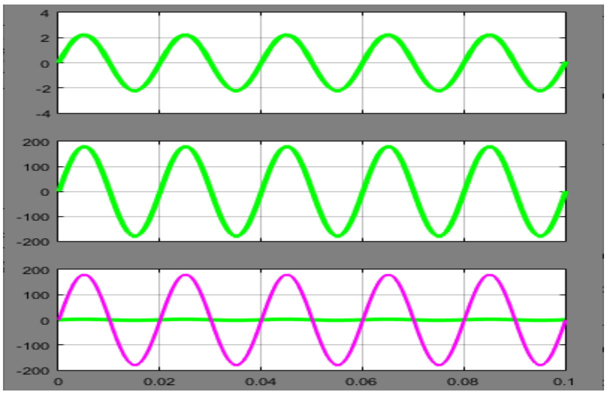

Figure 68 Output Current and Voltage Waveform PS-POD PWM (Variable Carrier Frequency Band)

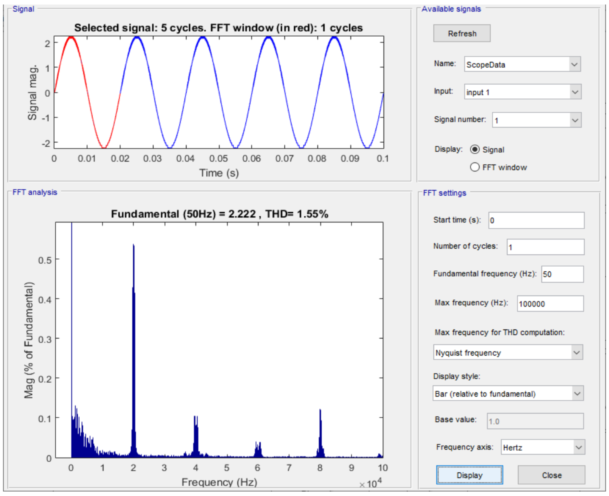

Figure 69 Harmonic Distortion by PS-POD PWM (Variable Carrier Frequency Band)

Table 7 Generated THD by PS-POD PWM

Switching Techniques (PD PWM)	Harmonic Distortion, THD Value (%)
Low Carrier Frequency Band	2.53
High Carrier Frequency Band	0.88
Variable Carrier Frequency Band	1.55

From the Table 7 above shows that the generated THD value by PS-POD PWM is same with the THD generated by PS-PD PWM which the highest THD is 2.53% by low carrier frequency band and the lowest THD is 0.88% by the high carrier frequency band. For the output voltage is all around 178V which is almost 180V.

4.3.3 Phase Shift – Alternative Phase Opposition Disposition (PS-APOD) PWM

4.3.3.1 PS-APOD PWM Low Carrier Frequency Band (LCFB)

Figure 70 shows the output five level waveform and Figure 71 shows the output voltage and current waveform of Low Carrier Frequency Band PS-APOD PWM. Besides, Figure 72 shows the generated THD value by the Low Carrier Frequency Band PS-APOD PWM.

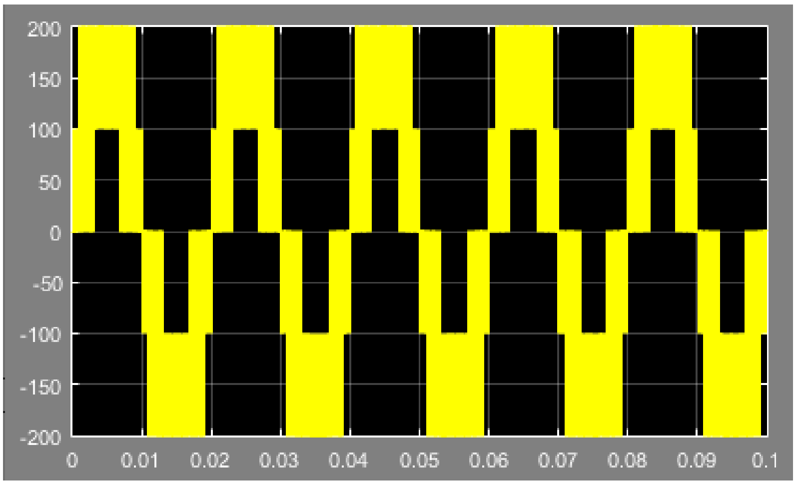

Figure 70 Output 5-Level Waveform PS-APOD PWM (Low Carrier Frequency Band)

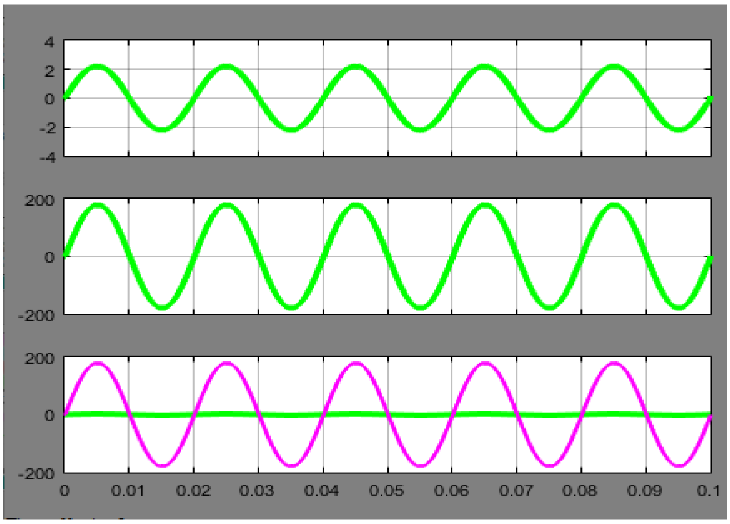

Figure 71 Output Current and Voltage Waveform PS-APOD PWM (Low Carrier Frequency Band)

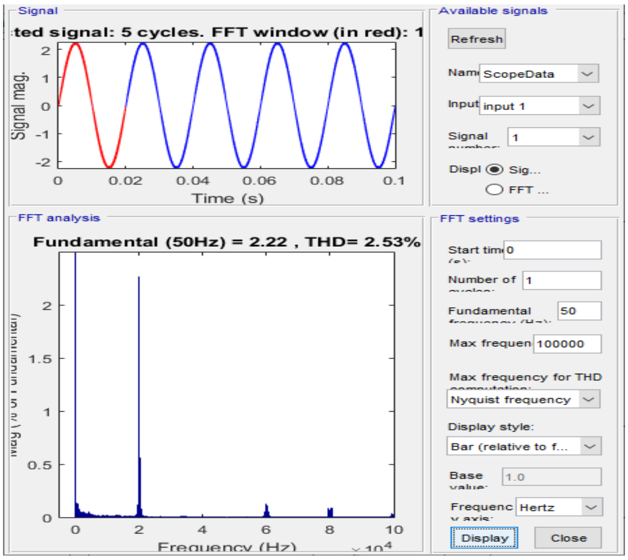

Figure 72 Harmonic Distortion by PS-APOD PWM (Low Carrier Frequency Band)

4.3.3.2 PS-APOD PWM High Carrier Frequency Band (HCFB)

Figure 73 shows the output five level waveform and Figure 74 shows the output voltage and current waveform of High Carrier Frequency Band PS-APOD PWM. Besides, Figure 75 shows the generated THD value by the High Carrier Frequency Band PS-APOD PWM.

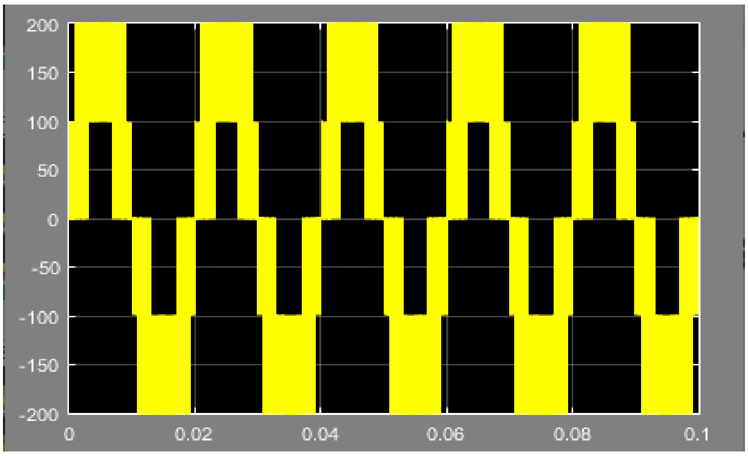

Figure 73 Output 5-Level Waveform PS-APOD PWM (High Carrier Frequency Band)

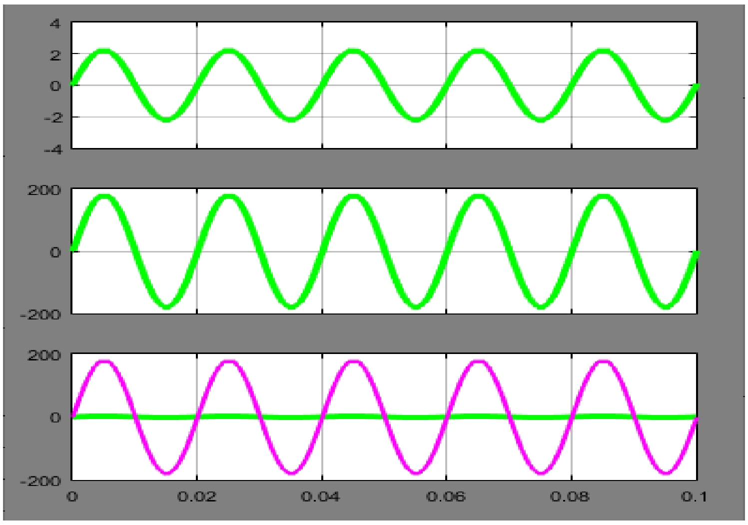

Figure 74 Output Current and Voltage Waveform PS-APOD PWM (High Carrier Frequency Band)

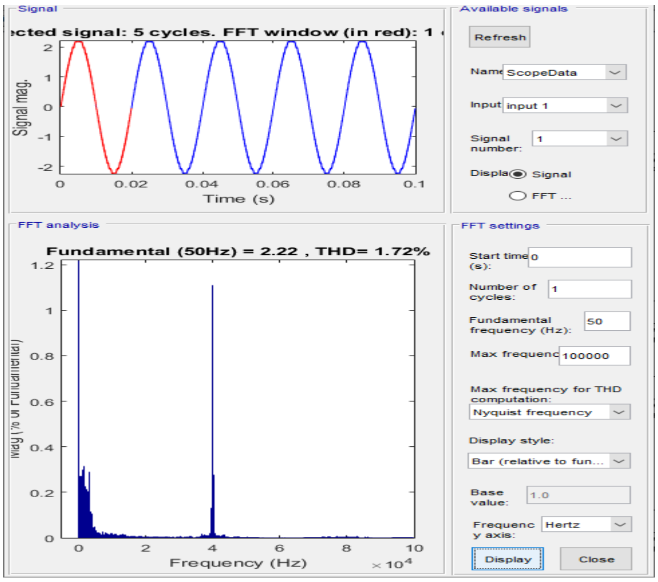

Figure 75 Harmonic Distortion by PS-APOD PWM (High Carrier Frequency Band)

4.3.3.3 PS-APOD PWM Variable Carrier Frequency Band (VCFB)

Figure 76 shows the output five level waveform and Figure 77 shows the output voltage and current waveform of Variable Carrier Frequency Band PS-APOD PWM. Besides, Figure 78 shows the generated THD value by the Variable Carrier Frequency Band PS-APOD PWM.

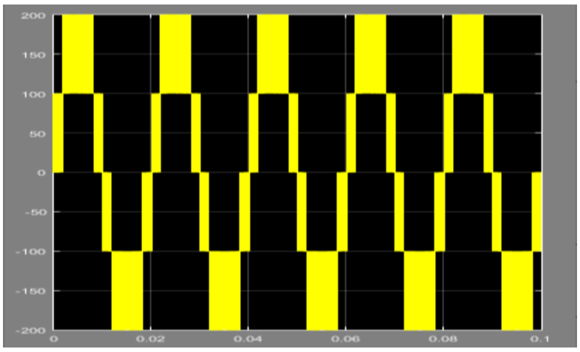

Figure 76 Output 5-Level Waveform PS-APOD PWM (Variable Carrier Frequency Band)

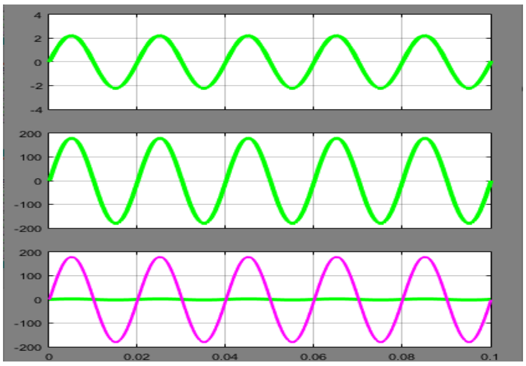

Figure 77 Output Current and Voltage Waveform PS-APOD PWM (Variable Carrier Frequency Band)

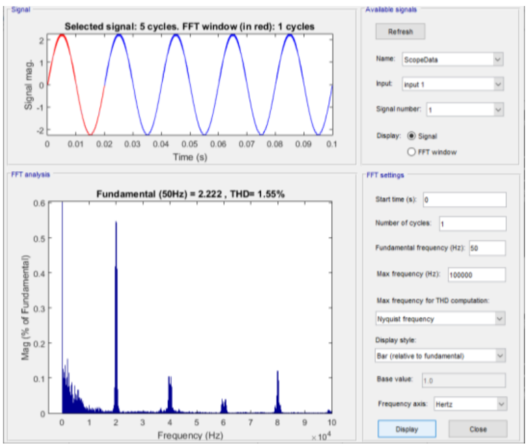

Figure 78 Harmonic Distortion by PS-APOD PWM (Variable Carrier Frequency Band)

Table 8 Generated THD by PS-APOD PWM

Switching Techniques (PD PWM)	Harmonic Distortion, THD Value (%)
Low Carrier Frequency Band	2.53
High Carrier Frequency Band	1.72
Variable Carrier Frequency Band	1.55

From the Table 8 above shows that the generated THD value by PS-APOD PWM which the highest THD is 2.53% by low carrier frequency band and the lowest THD is 1.55% by the variable carrier frequency band. For the output voltage is 176V for high carrier frequency band and 178V for other two switching techniques which is almost 180V.

4.3.4 Phase Disposition - Phase Opposition Disposition (PD-POD) PWM

4.3.4.1 PD-POD PWM Low Carrier Frequency Band (LCFB)

Figure 79 shows the output five level waveform and Figure 80 shows the output voltage and current waveform of Low Carrier Frequency Band PD-POD PWM. Besides, Figure 81 shows the generated THD value by the Low Carrier Frequency Band PD-POD PWM.

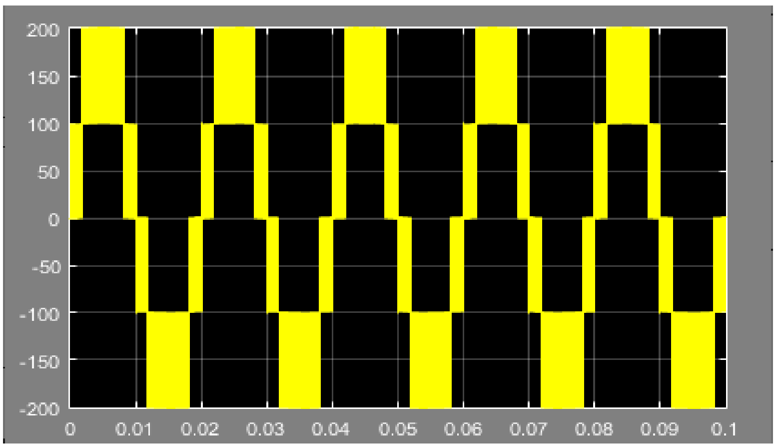

Figure 79 Output 5-Level Waveform PD-POD PWM (Low Carrier Frequency Band)

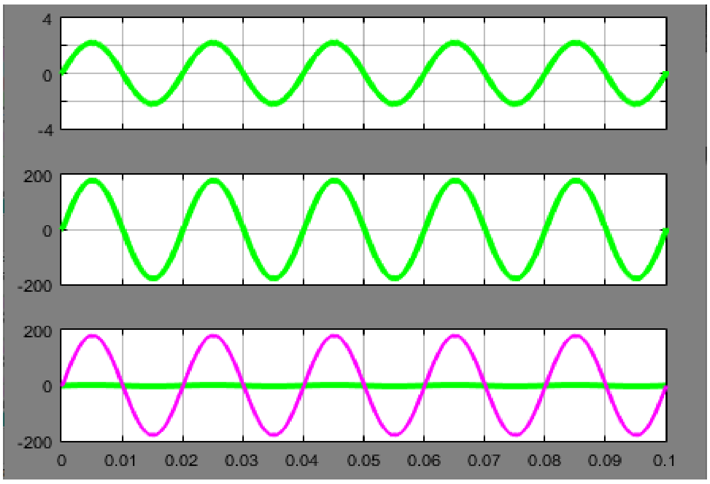

Figure 80 Output Current and Voltage Waveform PD-POD PWM (Low Carrier Frequency Band)

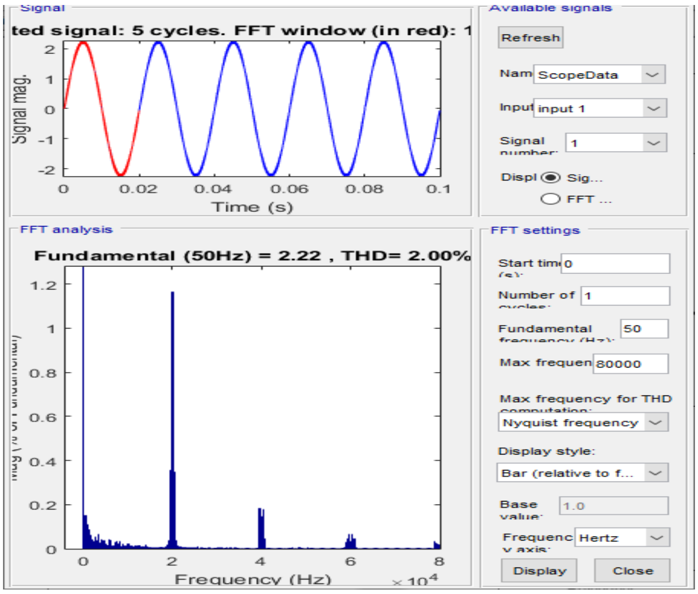

Figure 81 Harmonic Distortion by PD-POD PWM (Low Carrier Frequency Band)

4.3.4.2 PD-POD PWM High Carrier Frequency Band (HCFB)

Figure 82 shows the output five level waveform and Figure 83 shows the output voltage and current waveform of High Carrier Frequency Band PD-POD PWM. Besides, Figure 84 shows the generated THD value by the High Carrier Frequency Band PD-POD PWM.

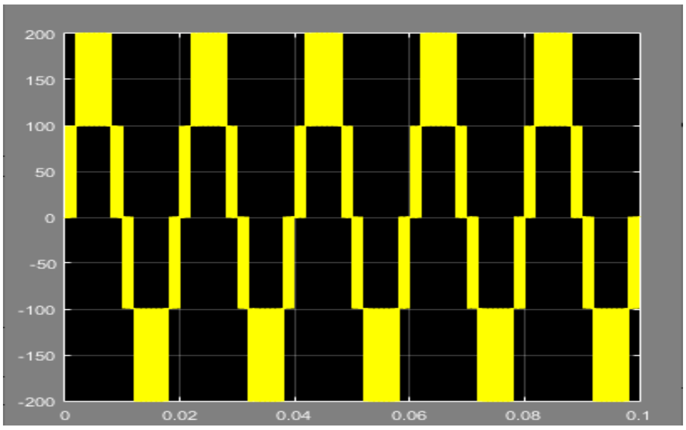

Figure 82 Output 5-Level Waveform PD-POD PWM (High Carrier Frequency Band)

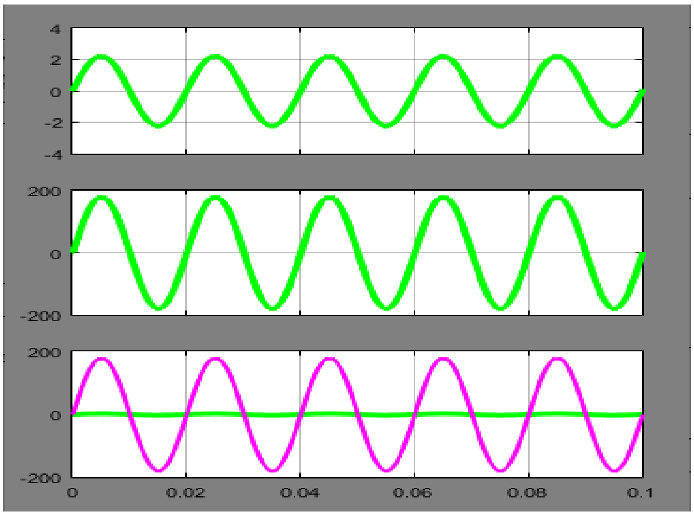

Figure 83 Output Current and Voltage Waveform PD-POD PWM (High Carrier Frequency Band)

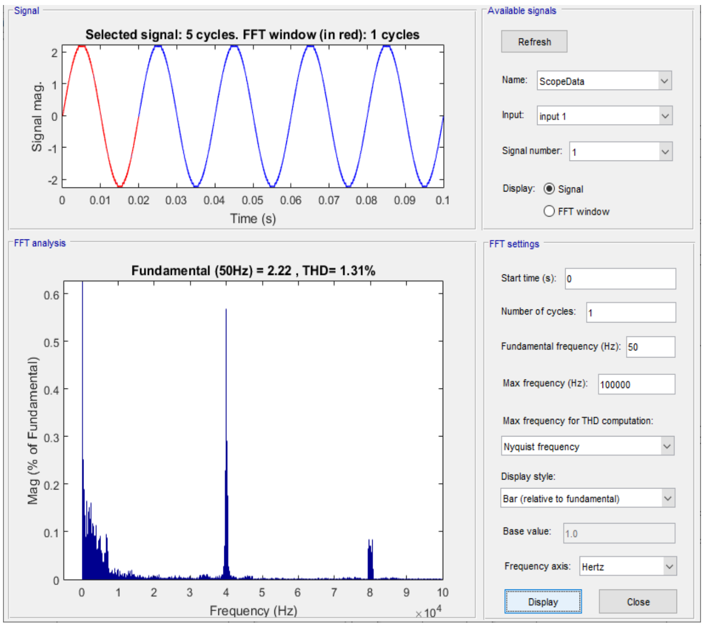

Figure 84 Harmonic Distortion by PD-POD PWM (High Carrier Frequency Band)

4.3.4.3 PD-POD PWM Variable Carrier Frequency Band (VCFB)

Figure 85 shows the output five level waveform and Figure 86 shows the output voltage and current waveform of Variable Carrier Frequency Band PD-POD PWM. Besides, Figure 87 shows the generated THD value by the Variable Carrier Frequency Band PD-POD PWM.

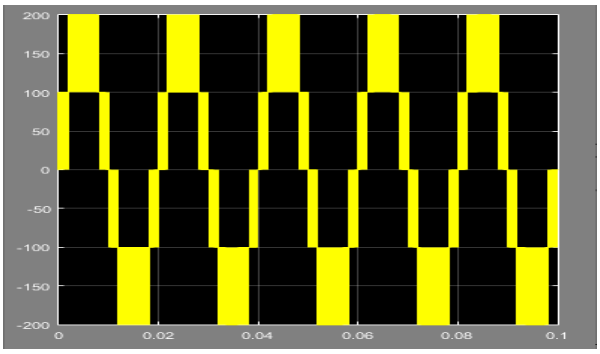

Figure 85 Output 5-Level Waveform PD-POD PWM (Variable Carrier Frequency Band)

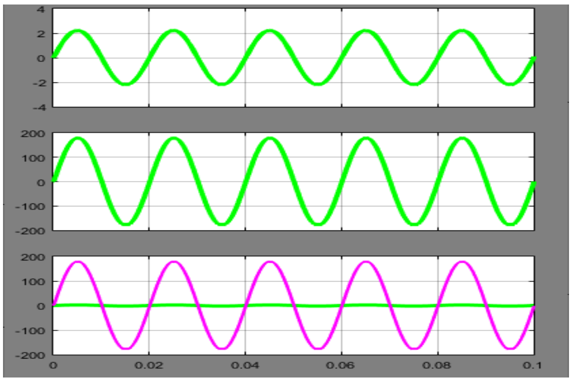

Figure 86 Output Current and Voltage Waveform PD-POD PWM (Variable Carrier Frequency Band)

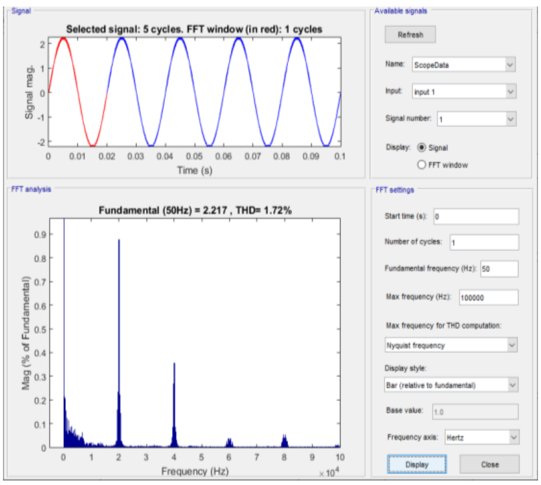

Figure 87 Harmonic Distortion by PD-POD PWM (Variable Carrier Frequency Band)

Table 9 Generated THD by PD-POD PWM

Switching Techniques (PD PWM)	Harmonic Distortion, THD Value (%)
Low Carrier Frequency Band	2.00
High Carrier Frequency Band	1.31
Variable Carrier Frequency Band	1.72

From the Table 9 above shows that the generated THD value by PD-POD PWM which the highest THD is 2.00% by low carrier frequency band and the lowest THD is 1.31% by the high carrier frequency band. For the output voltage is 178V which is almost 180V.

4.3.5 Phase Disposition - Alternative Phase Opposition Disposition (PD-APOD) PWM

4.3.5.1 PD-APOD PWM Low Carrier Frequency Band (LCFB)

Figure 88 shows the output five level waveform and Figure 89Figure 86 shows the output voltage and current waveform of Low Carrier Frequency Band PD-APOD PWM. Besides, Figure 90 shows the generated THD value by the Low Carrier Frequency Band PD-APOD PWM.

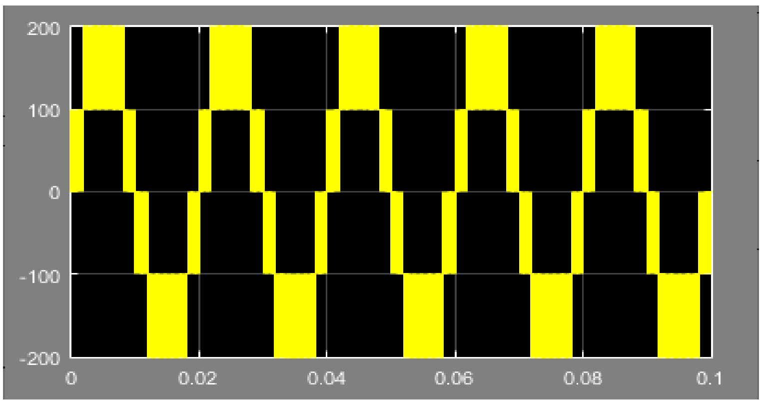

Figure 88 Output 5-Level Waveform PD-APOD PWM (Low Carrier Frequency Band)

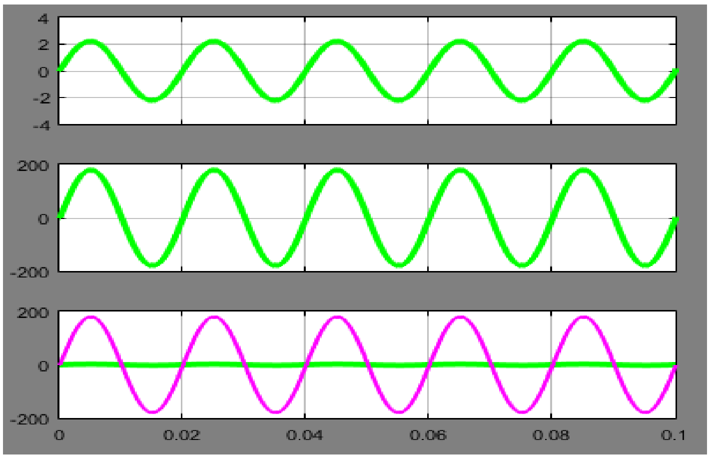

Figure 89 Output Current and Voltage Waveform PD-APOD PWM (Low Carrier Frequency Band)

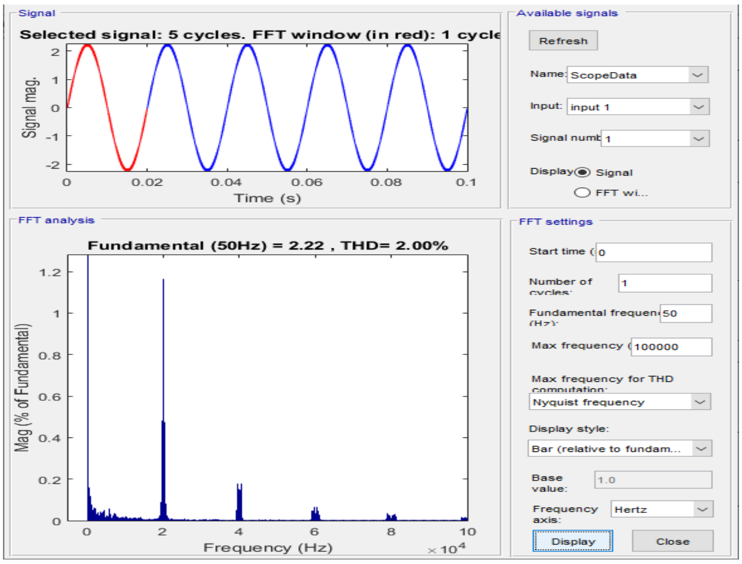

Figure 90 Harmonic Distortion by PD-APOD PWM (Low Carrier Frequency Band)

4.3.5.2 PD-APOD PWM High Carrier Frequency Band (HCFB)

Figure 91 shows the output five level waveform and Figure 92 shows the output voltage and current waveform of High Carrier Frequency Band PD-POD PWM. Besides, Figure 93 shows the generated THD value by the High Carrier Frequency Band PD-POD PWM.

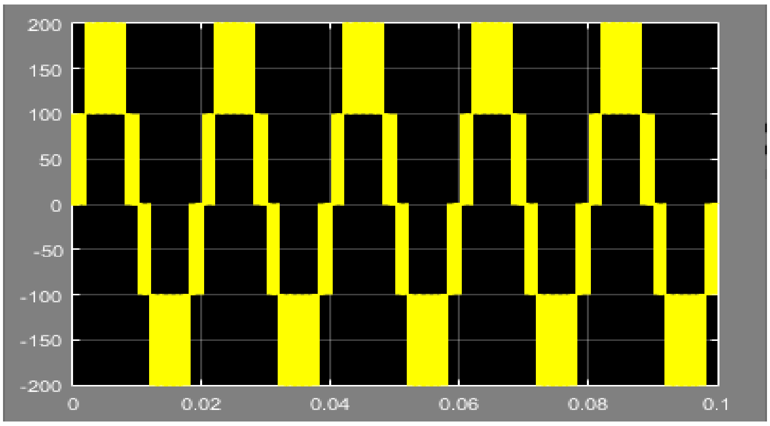

Figure 91 Output 5-Level Waveform PD-APOD PWM (High Carrier Frequency Band)

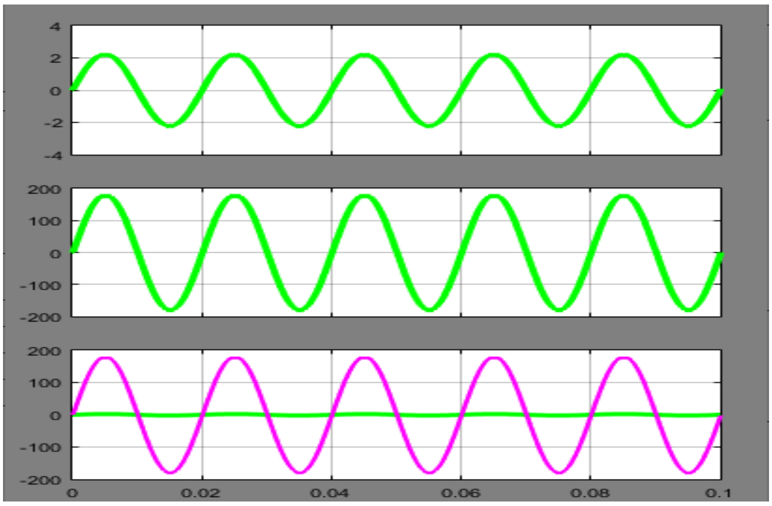

Figure 92 Output Current and Voltage Waveform PD-APOD PWM (High Carrier Frequency Band)

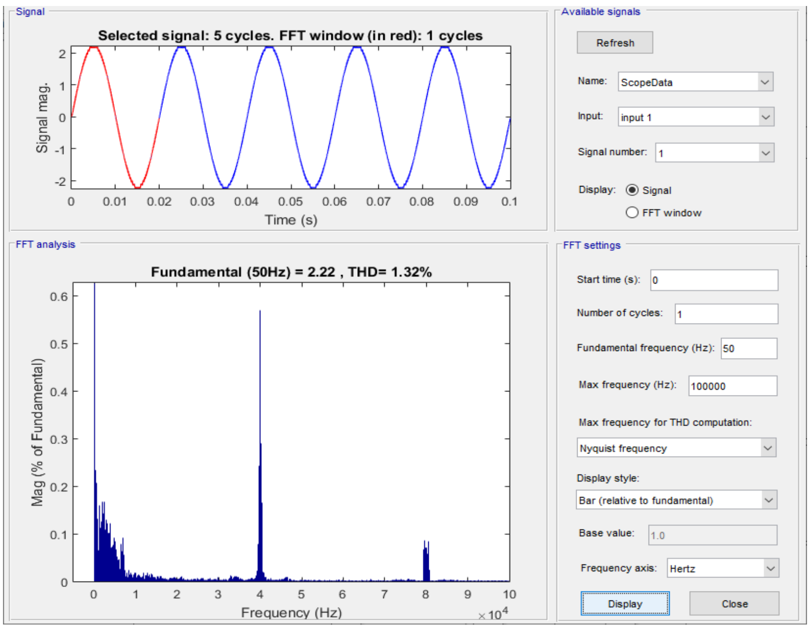

Figure 93 Harmonic Distortion by PD-APOD PWM (High Carrier Frequency Band)

4.3.5.3 PD-APOD PWM Variable Carrier Frequency Band (VCFB)

Figure 94 shows the output five level waveform and Figure 95 shows the output voltage and current waveform of Variable Carrier Frequency Band PD-POD PWM. Besides, Figure 96 shows the generated THD value by the Variable Carrier Frequency Band PD-POD PWM.

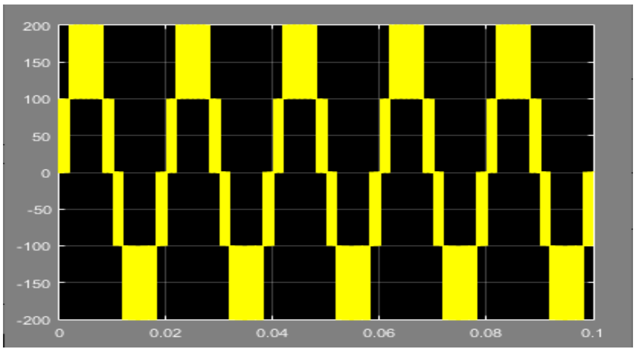

Figure 94 Output 5-Level Waveform PD-APOD PWM (Variable Carrier Frequency Band)

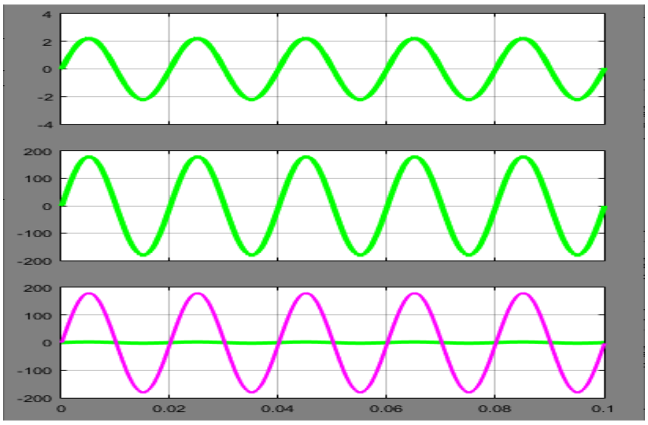

Figure 95 Output Current and Voltage Waveform PD-APOD PWM (Variable Carrier Frequency Band)

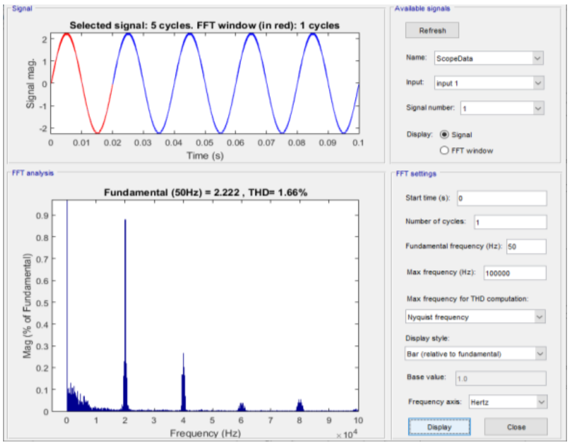

Figure 96 Harmonic Distortion by PD-APOD PWM (Variable Carrier Frequency Band)

Table 10 Generated THD by PD-APOD PWM

Switching Techniques (PD PWM)	Harmonic Distortion, THD Value (%)
Low Carrier Frequency Band	2.00
High Carrier Frequency Band	1.32
Variable Carrier Frequency Band	1.66

From the Table 10 above shows that the generated THD value by PD-POD PWM which the highest THD is 2.00% by low carrier frequency band and the lowest THD is 1.32% by the high carrier frequency band. For the output voltage is 178V which is almost 180V.

4.3.6 Phase Opposition Disposition - Alternative Phase Opposition Disposition (POD-APOD) PWM

4.3.6.1 POD-APOD PWM Low Carrier Frequency Band (LCFB)

Figure 97 shows the output five level waveform and Figure 98 shows the output voltage and current waveform of Low Carrier Frequency Band POD-APOD PWM. Besides, Figure 99 shows the generated THD value by the Low Carrier Frequency Band POD-APOD PWM.

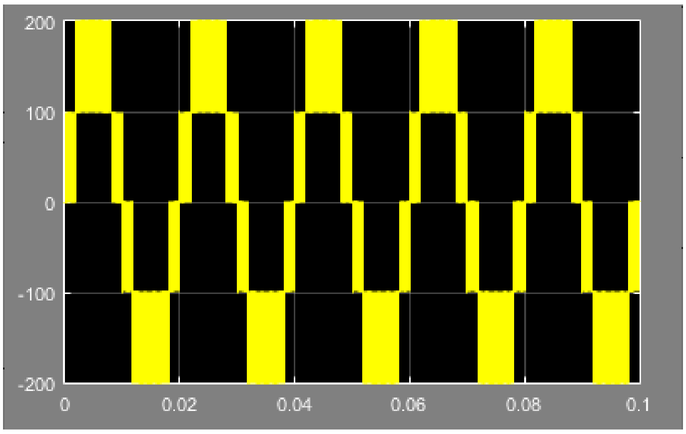

Figure 97 Output 5-Level Waveform POD-APOD PWM (Low Carrier Frequency Band)

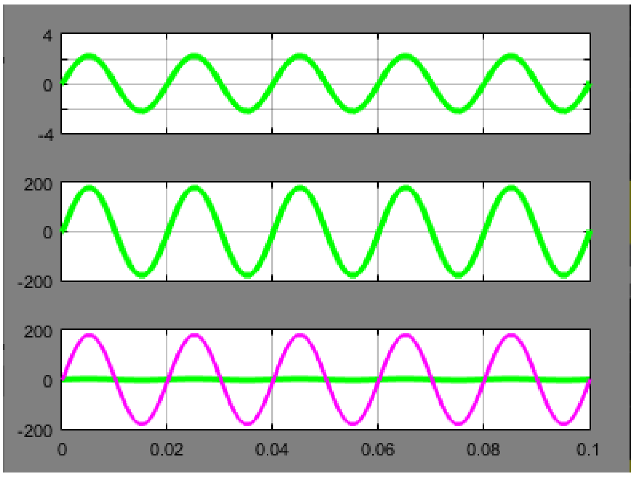

Figure 98 Output Current and Voltage Waveform POD-APOD PWM (Low Carrier Frequency Band)

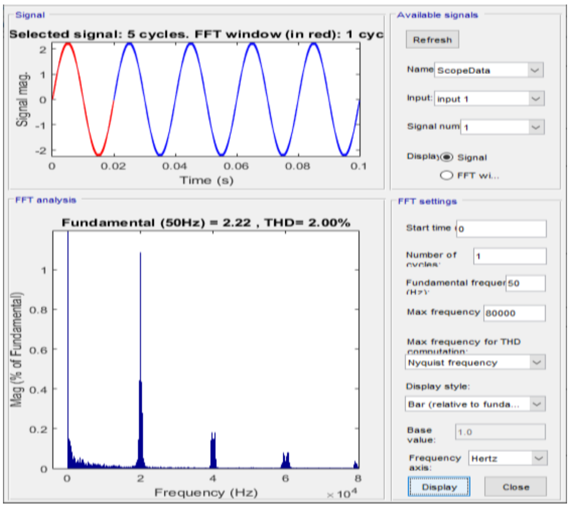

Figure 99 Harmonic Distortion by POD-APOD PWM (Low Carrier Frequency Band)

4.3.6.2 POD-APOD PWM High Carrier Frequency Band (HCFB)

Figure 100 shows the output five level waveform and Figure 101 shows the output voltage and current waveform of High Carrier Frequency Band POD-APOD PWM. Besides, Figure 102 shows the generated THD value by the High Carrier Frequency Band POD-APOD PWM.

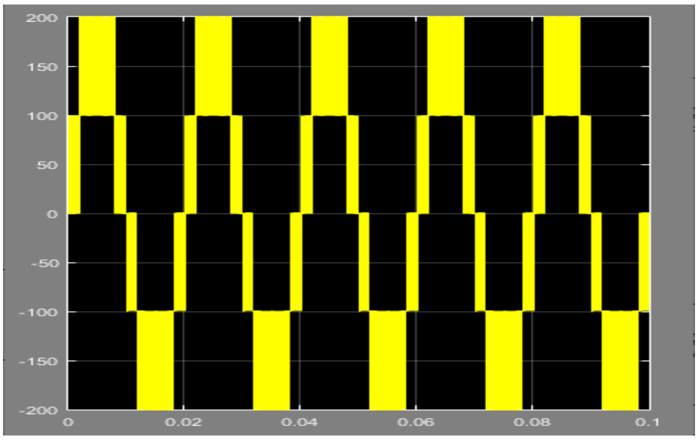

Figure 100 Output 5-Level Waveform POD-APOD PWM (High Carrier Frequency Band)

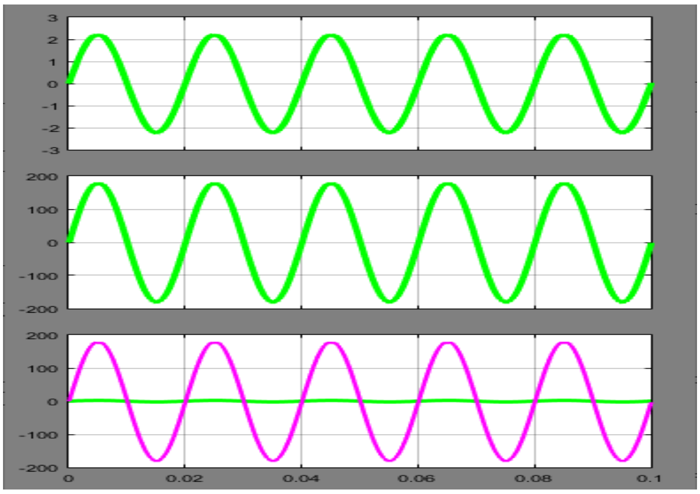

Figure 101 Output Current and Voltage Waveform POD-APOD PWM (High Carrier Frequency Band)

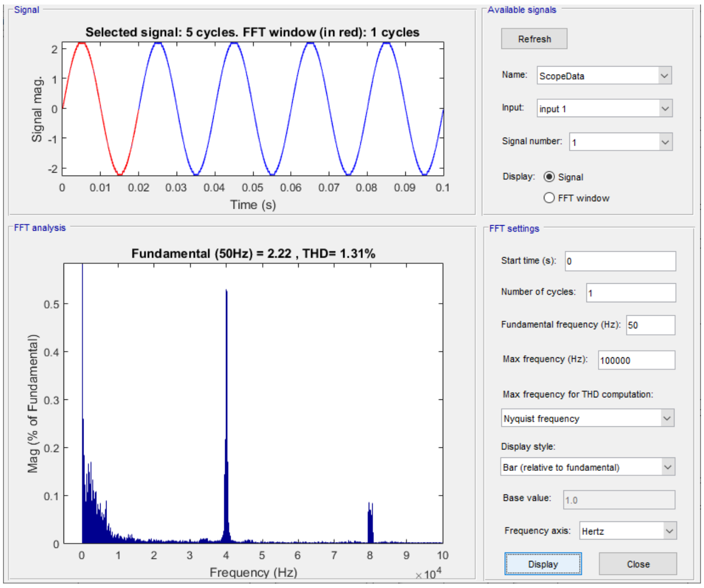

Figure 102 Harmonic Distortion by POD-APOD PWM (High Carrier Frequency Band)

4.3.6.3 POD-APOD PWM Variable Carrier Frequency Band (VCFB)

Figure 103 shows the output five level waveform and Figure 104 shows the output voltage and current waveform of Variable Carrier Frequency Band POD-APOD PWM. Besides, Figure 105 shows the generated THD value by the Variable Carrier Frequency Band POD-APOD PWM.

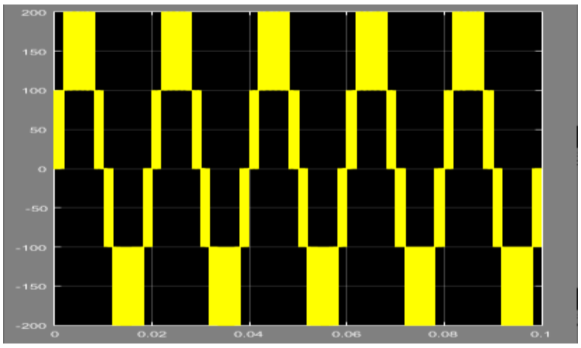

Figure 103 Output 5-Level Waveform POD-APOD PWM (Variable Carrier Frequency Band)

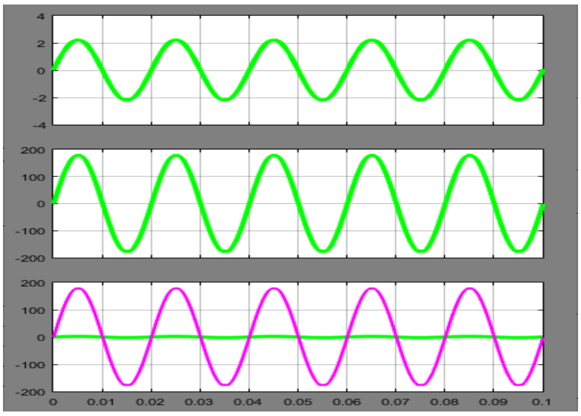

Figure 104 Output Current and Voltage Waveform POD-APOD PWM (Variable Carrier Frequency Band)

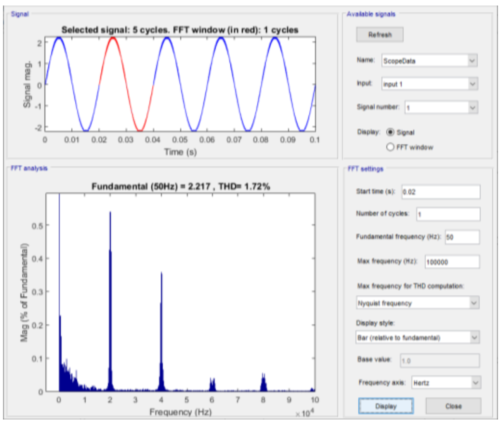

Figure 105 Harmonic Distortion by POD-APOD PWM (Variable Carrier Frequency Band)

Table 11 Generated THD by POD-APOD PWM

Switching Techniques (PD PWM)	Harmonic Distortion, THD Value (%)
Low Carrier Frequency Band	2.00
High Carrier Frequency Band	1.31
Variable Carrier Frequency Band	1.72

From the Table 11 above shows that the generated THD value by POD-APOD PWM which the highest THD is 2.00% by low carrier frequency band and the lowest THD is 1.31% by the high carrier frequency band. For the output voltage is 178V which is almost 180V.

Table 12 Generated THD Value by Hybrid PWM

Switching Techniques / Hybrid PWM	LOWCARRIER FREQUENCY BAND THD (%)	HIGH CARRIER FREQUENCY BAND THD (%)	VARIABLE CARRIER FREQUENCY BAND THD (%)
PS-PD PWM	2.53	0.88	1.55
PS-POD PWM	2.53	0.88	1.55
PS-APOD PWM	2.53	1.72	1.55
PD-POD PWM	2	1.31	1.72
PD-APOD PWM	2	1.32	1.66
POD-APOD	2	1.31	1.72
PD PWM	2	1.33	1.66

From the Table 12 above, the comparison of THD value between each methods of Hybrid PWM is being analyse and the Hybrid PWM techniques are compared with the PD PWM to extract out or choose the best one to be used for the multilevel inverter. To show the better comparison between the techniques, each methods of Hybrid PWM has being simulated in three switching technique that is Low Carrier Frequency Band, High Carrier Frequency Band and Variable Carrier Frequency Band. Overall, in this research work the generated THD value is all smaller than Malaysia Standard Limit of 5% maximum and should not higher than 5% otherwise it will be disqualified to be used for the power system.

Figure 106 below shows the low carrier frequency band comparison and Figure 107 shows the high carrier frequency band comparison between six type of Hybrid PWM. On the other hand, Figure 108 shows the variable carrier frequency band comparison between six type of Hybrid PWM and Figure 109 shows the comparison of three switching technique for all developed Hybrid PWM.

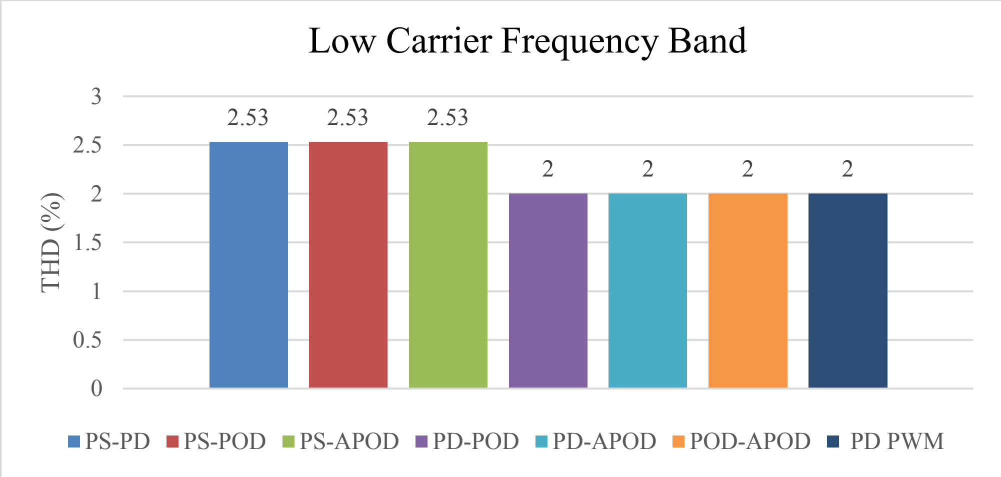

Figure 106 Low Carrier Frequency Band Comparison

From Figure 106 above shows that the highest THD value the being generated is 2.53% and the lowest is 2.00%. From this switching technique there are no the best method to be recommended since the lowest THD is same with the PD PWM which 2.00%.

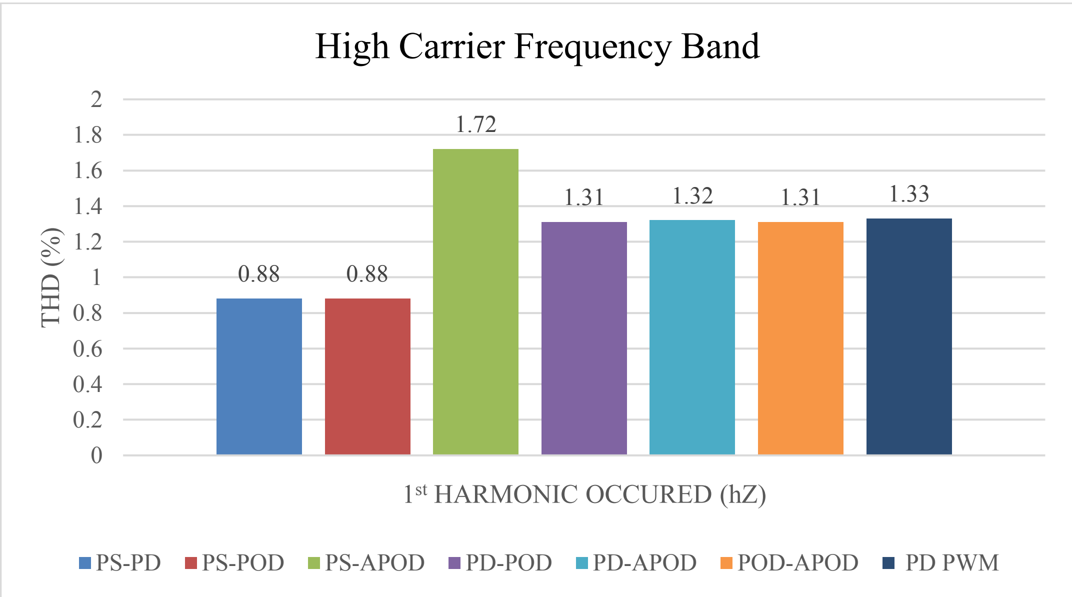

Figure 107 High Carrier Frequency Band Comparison

From Figure 107 above shows that the highest THD value the being generated is 1.72% and the lowest is 0.88%. From this switching technique there are two the best methods that is PS-PD PWM and PS-POD to be recommended since it THD value is only 0.88% by compare to PD PWM THD which is 1.33%. Besides, there also have another three methods is recommended that is PD-POD PWM, PD-APOD and POD-APOD PWM which it only generated 1.32% and 1.31% of THD.

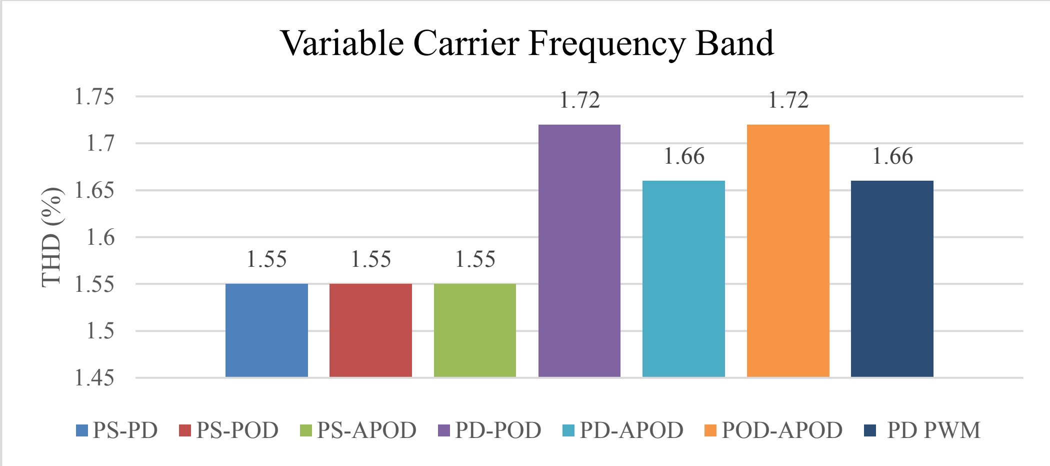

Figure 108 Variable Carrier Frequency Band Comparison

From Figure 108 above shows that the highest THD value the being generated is 1.72% and the lowest is 1.55%. From this switching technique there are three the best methods to be used that is PS-PD PWM, PS-POD PWM and PS-APOD PWM to be recommended since it THD value is only 1.55% by compare to PD PWM THD which is 1.66%.

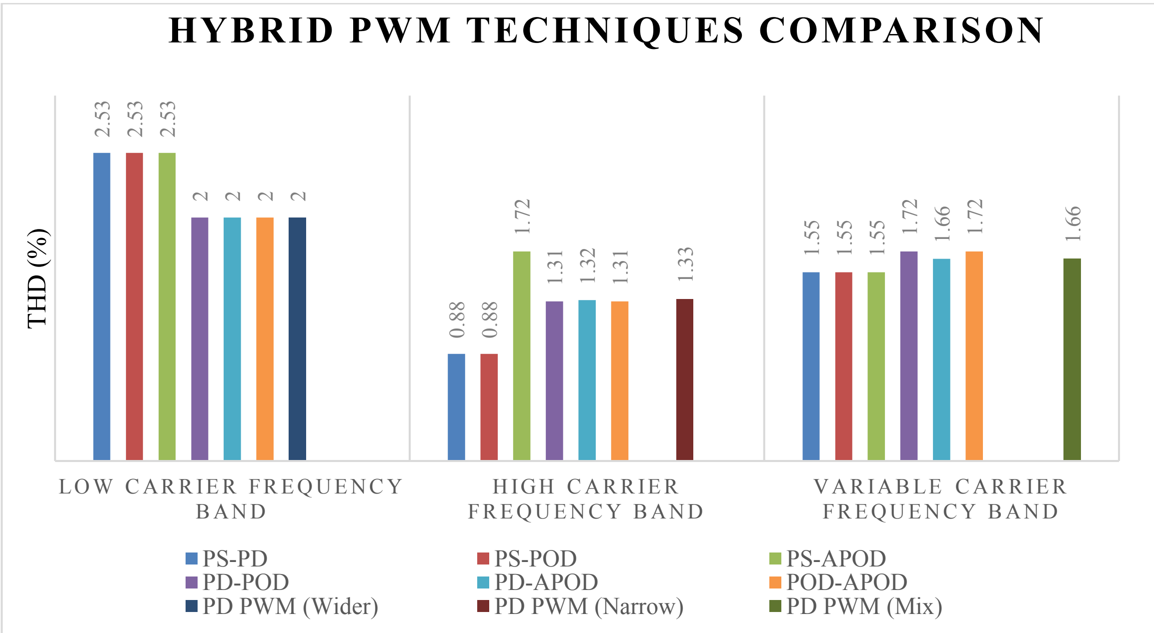

Figure 109 Hybrid PWM Techniques Comparison

From this research work, all generated THD value is below 5% which all actually can be used in the power system since the THD value for Hybrid PWM is compared to the PD PWM so the best from different methods and switching techniques can be identify clearly.

By compared three switching techniques, the most better switching techniques is the High Carrier Frequency Band follow by Variable Carrier Frequency Band and Low Carrier Frequency Band. Since the High Carrier Frequency Band is the better among the three switching techniques, almost all method is the best method to use since it all generated THD is less than the THD generated by the PD PWM except for the PS-APOD PWM. Table 13 below is showing all the recommended Hybrid PWM to be used in the power system after compared with PD PWM.

Table 13 Recommended Hybrid PWM

SWITCHING TECHNIQUE	HYBRID PWM TECHNIQUE	THD (%)
HIGH CARRIER FREQUENCY BAND	PS-PD PWM	0.88
	PS-POD PWM	0.88
	PD-POD PWM	1.31
	PD-APOD PWM	1.32
	POD-APOD PWM	1.31
VARIABLE CARRIER FREQUENCY BAND	PS-PD PWM	1.55
	PS-POD PWM	1.55
	PS-APOD PWM	1.55

CHAPTER 5

CONCLUSION

5.1 Introduction

In this chapter, the conclusion for the overall analysis that has been conducted will be elaborated.

5.2 Conclusion

The objectives of the analysis have been achieved which are to simulate and analyse the performance of multiple Hybrid PWM technique and compare it with the conventional phase disposition PWM technique in terms of the harmonic percentage. The analysis has been done by using the MATLAB SIMULINK to model the Cascaded H-Bridge Multilevel Inverter that fixed for whole research work that the multiple Hybrid PWM technique applied to perform the switching in the system to generate more better output. To complete this research work, all the parameters are fixed such as the 20kHz carrier frequency, RLC load value and modulation index. All the work and analysis were obtained by the Simulink simulation which analyse the total harmonic distortion for six methods of Hybrid PWM technique that consists PS-PD PWM, PS-PODPWM, PS-APOD PWM, PD-POD PWM, PD-APOD PWM and POD-APODPWM. Other than that, three switching technique also used to perform the analysis which is Low Carrier Frequency Band, High Carrier Frequency Band and Variable Carrier Frequency Band. Overall, all the developed Hybrid PWM methods is within the Malaysia Standard THD limit 5% so means that all the developed methods can be applied in the power system. Based on the comparison of three switching technique with generated Hybrid PWM THD and PD PWM THD, the switching technique of High Carrier Frequency Band showing the lowest THD that is 0.88%, 1.31% and 1.32% by PS-PD PWM, PS-POD PWM, PD-POD PWM, PD-APOD PWM and POD-APOD PWM than PD PWM THD that is 1.33%. Since the High Carrier Frequency Band switching technique is showing the best result, so it can be concluded that more cycles to be completed in one time, the smaller the generated THD value. By using this technique and methods, the output was improved without affecting the other parameters in the model just by changing the carrier frequency band. So, by choosing this method, it will indirectly save the cost of development.

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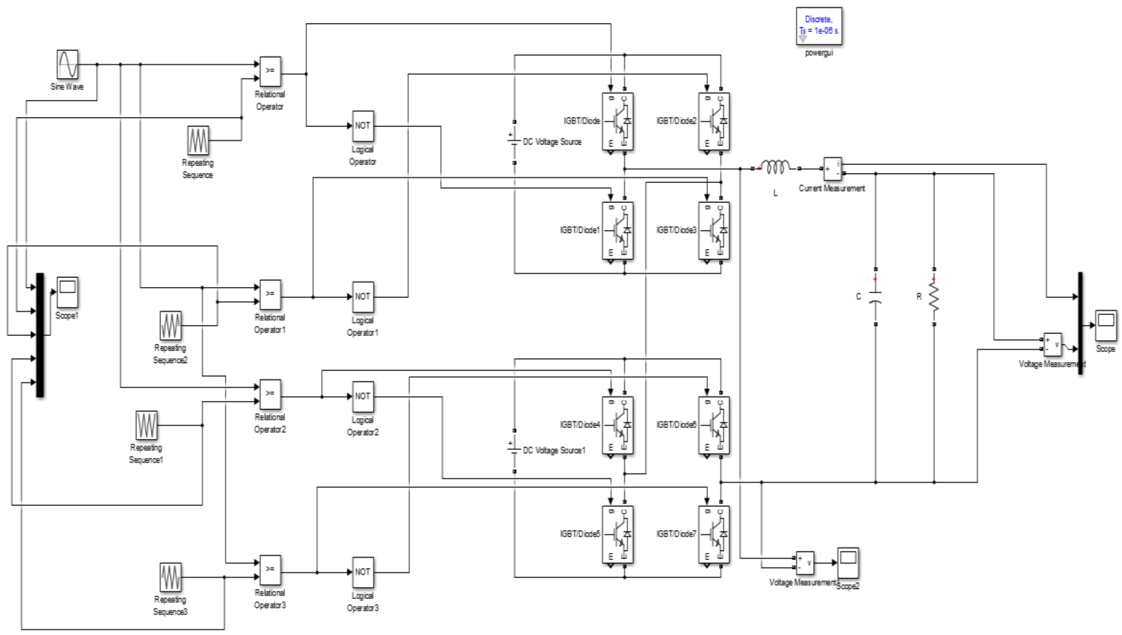
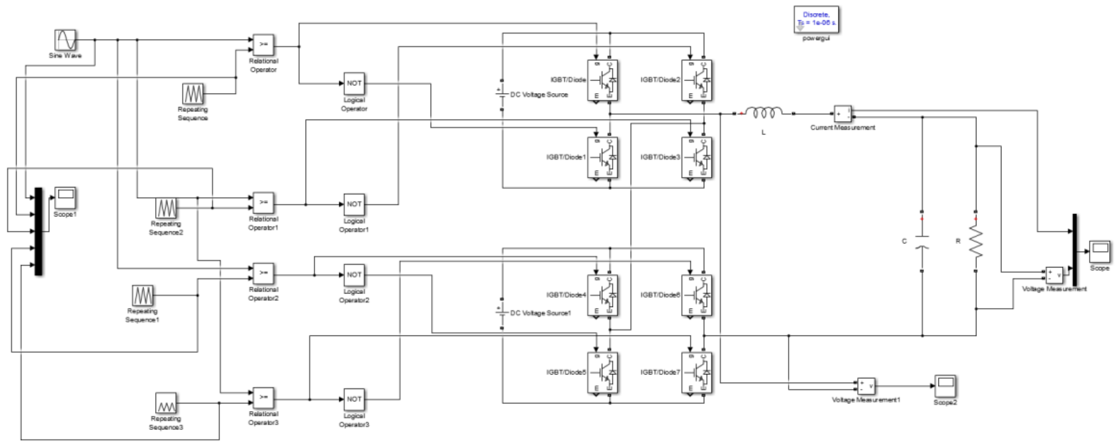
APPENDIX A
CIRCUIT FOR ALL METHODS

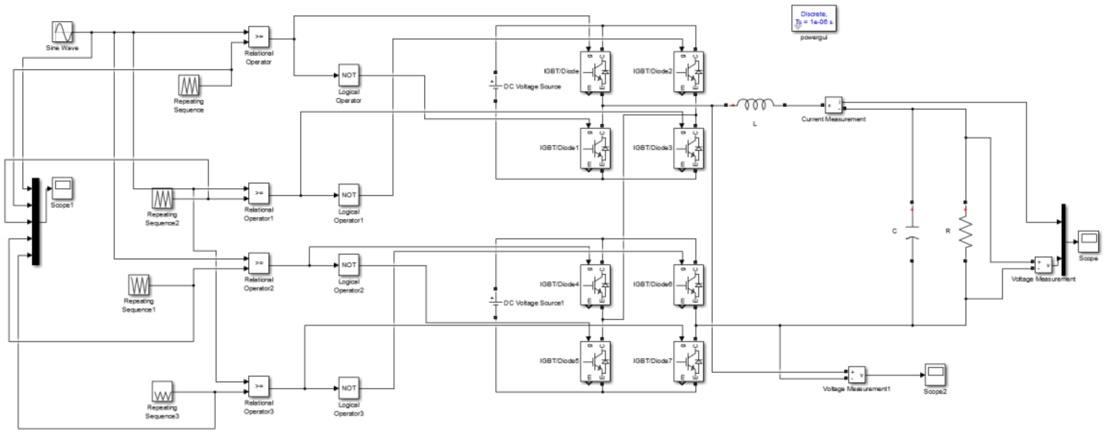
Phase Shift PWM Multilevel inverter:



PHASE DISPOSITION PWM MULTILEVEL INVERTER:



PHASE 0PPOSITION DISPOSITION PWM MULTILEVEL INVERTER:



ALTERNATIVE PHASE OPPOSITION DISPOSITION PWM MULTILEVEL INVERTER: