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Investigating the Harmonic Content of a PWM Inverter with Varying Modulation Index

Donald M. Sendima and Peter M. Makolo†

Department of Electrical Engineering, University of Dar es Salaam, P.O. Box 35131, TANZANIA

†Corresponding author: makolo.peter@gmail.com; ORCID: 0000-0002-3595-8468

ABSTRACT

Photovoltaic energy is a clean and endless vital renewable energy. In order to generate electricity from solar energy an inverter is required to transform the direct current into alternating current. Also, with the emerging of new ultra-high voltage direct current transmission technology, the rectification and inverters play a great role. Most three-phase two-level inverters draw harmonics that cause heat dissipation, waveform distortions hence affect the electrical loads. Knowing that Total Harmonic Distortion content of voltage source inverter is important and must be within the allowable range. Several schemes are suggested to mitigate the distortion in order to produce as much a sinusoidal output signal as would be possible. The most widely used control process of the semiconductor switches is Pulse Width Modulation technique. One of such schemes is using a Sinusoidal Pulse Width Modulation -based inverter which is usually used in inverters for industrial applications. In this paper, a study of the performance of the SPWM technique is presented for a three-phase H-bridge inverter and the simulation results obtained in MATLAB/Simulink demonstrate that the significantly investigation on the harmonics when varying the modulation index. These results confirm that the total harmonic distortion factor of the inverter output voltage decreases as the modulation index increases as a result, reduces the waveform distortion rate and suppresses the effects of harmonics. This is of great significance for the safe, stable, and efficient operation of the power system.

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INTRODUCTION

Power electronics is an advanced technology that involves the control and conversion of electrical power from its input into output form. The power electronics technology from the name itself deals with the transformation of conversion techniques with the help of electronic devices such as power semiconductor devices. Majorly, there are five types of power electronic circuits which are rectifiers, choppers, inverters, AC voltage controllers and cycloconverters. Each of the five types of power electronic converters carried different purpose. This paper deals with inverters, hence the methodology majorly consists of discussions about the stated subject (Buswig et al., 2019).

With the advancement of power electronics technology, the reliance on renewable energy systems grows. These renewable energy sources such as PV are mostly inverter-interfaced. Use of renewable energy resources for generation of electrical energy has gaining importance from last few decades (Bhattacharya & Samanta, 2024).

Among all types of renewable energy resources used for electricity generation, solar energy is gaining more attention. Solar energy generation module is larger in size as it has various components like rectifier, Power factor corrector and DC/AC or DC/DC converter for supplying load. In order to generate electricity from solar energy an inverter is required to transform the DC into AC voltage. In high power application areas three phase inverters are used to convert input DC voltage in an output AC voltage with variable frequency.

In MW range industrial applications use of three phase PWM inverters are gaining popularity. There are two types of PWM inverters which are voltage source PWM and current source PWM inverters depending on their energy storage components. Voltage source PWM inverters are having mature control strategies and it is being used in micro grid system, solar power and bidirectional energy storage systems (Bhattacharjee et al., 2018).

As the focus to reduce the harmonic produced by the inverter in the system, various studies have explored harmonic improvements though various techniques including the use of addition low pass filter circuit aids the achievement of smoother sine waveforms and a reduced THD value of 0.17%. There are various PWM techniques used in inverter model and among them SPWM technique is widely used because its circuit is simple and it has rugged controlling schemes. To reduce the harmonic content in output of VSI, a PWM technique which is sinusoidal pulse width modulation a low pass LC filter circuit is being introduced (Ji & Xu, 2025; Ismail et al., 2018).

Voltage source inverters are used in different applications, as adjustable speed ac motor drives, uninterruptible power supply (UPS) systems, emergency power supply systems, solar systems for generating ac electric power, frequency changers and others. The VSI is supplied from a stiff DC voltage source and generates a symmetric AC output voltage, in which both the magnitude and the frequency can be controlled. As the inverter output voltage contains significant harmonic contents hence proper output filtration has to be used to reduce the harmonic contents and hence, to improve the voltage waveform quality (Al-Adwan & Al Shiboul, 2020).

In this research, the proposed design used is the VSI type of inverter because it works with the complicated circuit and with the power semiconductor devices such as the IGBTs used in the research. The harmonic contents of the output voltage waveform of the SPWM inverter is a function of both the frequency of the triangular carrier signal and the modulation index (ma). In practice, the modulation index, is used to control the value of the output voltage of the SPWM inverter (Aihsan et al., 2020; Airin Rahman, 2017).

However, inverter plays a great role in electric drive system in industries. Electric drive is an industrial system which performs the conversion of electrical energy to mechanical energy or vice versa for running various processes like production plants, pumps, air compressors, music or image players, computer disc drives, robots etc. In most variable speed drives sinusoidal pulse width modulation voltage source inverters are used. Usually, machine design tools only consider the fundamental harmonic of the stator voltage when calculating the losses. These losses are caused by harmonics of the voltage and the current due to the PWM. Three phase squirrel cage induction motors are used for any motion control and automation. Then, SPWM based on firing of inverter provides the best constant V/F ratio control of a squirrel cage induction motor (Raghuwanshi et al., 2017).

The most widely used for voltage source inverters is Sinusoidal Pulse Width Modulation. Here a single phase Unipolar and Bipolar SPWM based H-bridge inverter are explored using MATLAB-Simulink to testify the result of different values of modulation index on the total THD. The best performance in the Bipolar inverter is given at ma =1.0 while that for Unipolar inverter is at ma = 0.9

(Aihsan et al., 2020; Bhattacharya & Samanta, 2024).

Modulation index (Ma) has significant impacts to harmonic content generation (unwanted frequency components generated) due to switching operation loss of PWM inverters. The harmonics generated can cause the equipment overheating such as transformers and energy losses which severely impact to equipment stress, power quality degradation, reducing efficient and equipment life span hence grid instability.

In this paper the performance of most prevalent modulation techniques which are SPWM, trapezoidal pulse width modulation (THPWM), sixty-degree pulse width modulation (SDPWM) and third harmonic trapezoidal pulse width modulation (THTRPWM) was analyzed and compared. A new modulation technique is proposed in this paper to reduce the THD and inverter power loss. The proposed technique shows promising performance in terms of inverter power loss and THD than that of the existing four techniques (Biswas et al., 2020; Mahbub & Hossain, 2021).

The main objective of this study is to analyze how the harmonic content of the output voltage changes as the modulation index is varied and this can be achieved by modelling and simulating a three-phase PWM inverters in MATLAB/Simulink, generate output voltage waveforms for different Ma values (0.5, 0.6, 0.8 and 1.0) and to perform FFT analysis to quantify THD and identify dominant harmonics at each Ma.

This study proposes an approach toward the modulization and improvement of the three-phase two-level, and multi-level PV inverter command, using space vector and sinusoidal control based on controlling the active and reactive current delivered into the grid indirectly with a resonant controller for a nonlinear load (NLL). The results of the simulations obtained by the new control methodology, SPWM and SVPWM show that its performance is better compared with the simple modulation (PWM) (Abdelhak et al., 2022).

This paper deals with the performance analysis of three phase induction motor drive fed by a SPWM voltage source inverter in terms of modulation index and frequency index. From the analysis we conclude that as the modulation index increased so decrease THD of line voltage and stator current. The fundamental voltage is increase for increase the modulation index. The line voltage, rotor speed and electromagnetic torque is also increase for increasing modulation index. Hence the author concluded that modulation index nearly to 1.0, ac drive performance is better (Sarker et al., 2020; Raghuwanshi et al., 2017).

CONCEPTUAL FRAMEWORK

Inverter in power electronics

Nowadays most of the appliances and machines work on AC power. In the absence of AC power, there should be some way to convert DC power to AC power. The device which can convert electrical energy of dc form into ac form is known as power inverter. They can come in different sizes and shapes and can vary from a high-power rating to a very low power rating. Also, they are different in efficiency, price and purpose. The DC and AC inverters are being widely used in ordinary household and industrial purpose to have an uninterruptable power supply. But nowadays inverters have become a very important part of renewable energy application as they are used to link a wind system or PV or other form of renewable energy to a power grid (Airin Rahman, 2017). The output voltage of the inverter is controlled by the internal control of the inverter itself and not by controlling the incoming DC output or outgoing ac output to control the output voltage. The Pulse Width Modulation (PWM) is the method for the internal control of an inverter in the power electronics as well as electric drives.

There are various types of PWM control techniques in the three-phase inverter which are SPWM, THIPWM and space vector pulse width modulation. Therefore, the SPWM technique is further discussed in this paper. The inverter is classified into two types which are voltage source inverter (VSI) and current source inverter (CSI). The classification can be identified based on the source or input to the inverter. The inverter is VSI if the source or input is DC voltage which controls the AC output voltage. For the CSI inverter, current is the input and controls the output current of PWM (Islam & Ayon, 2020).

In this research, the proposed design used is the three phase VSI type of inverter for the following reason. As can be compared to the CSI, VSI uses voltage as its input and the value is maintained constant. The current source for the input of CSI is constant but adjustable. The VSI type is used because it works with the complicated circuit and with the power semiconductor devices such as the IGBTs used in the research while for the CSI, it cannot be used because it only works for a simple circuit and cannot with-stand the reverse voltage. VSI has limited or zero impedance at the input terminals that cause the shape of the DC does not easily change while CSI has a high impedance that comes from the DC source current. Inverters are based on the production of the three types of different outputs which are the square wave inverter (Buswig et al., 2019; Bhattacharjee et al., 2018).

The proposed block diagram

This block diagram shows various electrical components as follows. The basic structure of SPWM generates sinusoidal pulse signals used to create a sinusoidal output by modulating the width of the pulses in a carrier waveform (typically a high-frequency triangle wave) with a sinusoidal reference signal. The DC supply represents the DC power source that provides the input energy for the system. This source could be a battery, rectified AC power, or another DC source. Whereas the inverter converts the DC supply into an AC output using the SPWM signals from the generator. The next block is low pass filter that smooths the high-frequency pulsed AC output from the inverter by attenuating the high-frequency components resulting to a cleaner AC output to be used by any three phase electrical loads such as three phase motors, transformers and many others as denoted in Figure 1 (Singh, 2020).

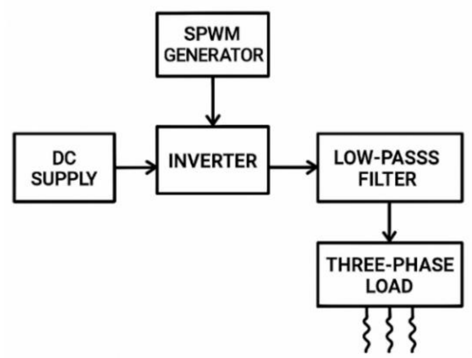

Figure 1: Basic Block diagram of SPWM.

In Figure 1, a fixed DC input voltage is given to the inverter and a controlled AC output voltage is obtained to be filtered by the low bass band filter then direct to the loads. The kind of loads discussed in this paper is three phase loads. This is the most popular method of controlling the output voltage and this method is termed as Pulse-Width Modulation Control (Kumar Pal & Singh, 2020).

Three phase inverters

Three phase inverters are devices to transform a constant DC input voltage to three phase of AC voltage. The circuit of the three-phase inverter is presented in Figure 2. Based on Figure 2, the circuit has six controlled switches which consist of upper controlled switches and lower controlled switches. The upper controlled switches are namely as S1, S3, and S5 while the lower controlled switched are namely as S2, S4, and S6. The three-phase inverter circuit has three branches and each of the branches is connected to one of the three phase voltages. Each of the branches has two controlled switches (Bhattacharjee et al., 2018).

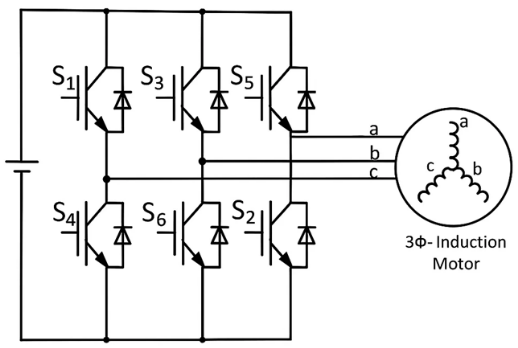

Figure 2: Circuit diagram of the three – phase full – bridge VSI circuit.

The first branch, A consists of switches S1 and S2. The second branch which is leg B, consist of switches S3 and S4 while switches S5 and S6 occupy the last branch, which is depicted as branch C. The circuit is divided into two halves. The positive half consists of switches S1, S3 and S5 and the negative half consist of the switch-es S2, S4 and S6. As can be seen in Figure 2, the S1, S3, and S5 will conduct during the positive half cycle of three phase output voltage whereas S2, S4, and S6 will conduct during the negative half cycle of three phase output voltage. The switch used in the main inverter circuit is the IGBT (Bhattacharjee et al., 2018).

Total Harmonic Distortion

One of the causal disturbances of the less optimum current and the resulting voltage, is the THD which is a symptom of sinusoidal wave formation arising from the multiplication of integers with its fundamental frequency. THD is an important index that is widely used to determine the quality of electrical power in transmission and distribution systems (Bushra et al., 2024).

The total harmonic distortion is the sum of each of the harmonics amplitudes and expressed as a percentage of the fundamental frequency. Harmonic is a quantity having a frequency that is integral multiples of the fundamental frequency. The standard for the value of THD has been established to be below 5%. The index is used to measure the deviation of periodic waveforms containing harmonics of perfect sine waves. THD analysis is important to measure the quality of output current and voltage of the inverter (Mahbub & Hossain, 2021; Buswig et al., 2019).

Sinusoidal pulse width modulation technique

Inverter outputs can be controlled by exercising pulse width modulation techniques or PWM within the inverter. PWM method is implemented in inverter by adjustment of ON and OFF periods of inverter IGBTs. Among all other PWM techniques SPWM technique is preferable and will be discussed in this paper. In this method the pulse amplitude remains constant while the duty cycles are different for each period of time. By modulating the width of pulses, inverter output voltage can control and reduction of THD can be done. The pulse signal generation in SPWM technique is being done by comparing the sinusoidal reference signal with triangular carrier signal of cut off frequency fc. The switching devices will be ON whenever the reference sinusoidal signals become greater than the carrier triangular wave (Yumi et al., 2024).

The line side fundamental component frequencies and magnitudes can be varied by varying modulation signal frequency and magnitude. Here in three phase voltage source inverter three sine waves are needed as a reference signal and they are phase shifted by 120° with the desired output voltage frequency is taken (Bhattacharjee *et al.*, 2018; Mousa & Rabih, 2021). The signals are compared to a carrier signal with very high frequency. Sinusoidal PWM has its basis in modulation theory of communication engineering.

In this modulation method a real time comparison of sinusoidal AC reference V_{ref} with a high frequency carrier V_c which is triangular in nature is done in order determine the switching instants. Following rule can be used to determine the switching instants for each pole, if $V_{ref} > V_c$, top switch of a specific phase is turned on and if $V_{ref} < V_c$, bottom switch of a specific phase is turned on. The carrier signal is compared with the three-phase sinusoidal reference signal and thus the gate pulse for switching is generated. The peak amplitude of reference sinusoidal signal determines the modulation index (Mattoo & Bhat, 2023; Ezzidin Hassan Elmabrouk Aboadla, 2016).

Advantages of using SPWM techniques in VSI: -

i. The method of implementation and controlling is easy
ii. Linear operation in controlling outputs
iii. Lesser dissipation of power
iv. No degradation of device as there is no ageing or temperature variation related effects
v. Digital microprocessor compatible
vi. Switching losses are lower
vii. DC power can be utilized more effectively by getting higher output voltage with the same DC input
viii. Lower order harmonics reduction in output voltage and current of the VSI

Filter circuit design

In power electronics, a filter, as presented in Figure 3, is a circuit designed to remove unwanted frequency components from electrical signals, ensuring a clean and stable output. Filters are essential for remove high-frequency switching noise (e.g., from PWM inverters), Smooth Waveforms by convert pulsating DC (from rectifiers) into steady DC and reduce EMI by minimize electromagnetic interference affecting other devices (Vijay Shankar, 2019).

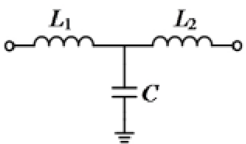

Figure 3: Filter circuit diagram.

In three phase VSI model for reduction of higher order harmonics its needed to design LCL filter circuit where L is the inductance and C is the capacitance. As by using SPWM technique the lower order harmonics can be reduced so, LCL filter should be designed as low pass filter for reduction of higher order harmonics and economic. The inductor used in the filter circuit should have current rating greater than or equal to maximum value of inverter output current. The inductor used can be of small value for reduction of ripples in output (Bhattacharjee et al., 2018; Bhattacharya & Samanta, 2024).

The function of the filter is to smoothen the waveform of the output parameter which in this case is the voltage. It also helps in eliminating higher order harmonics. The selection of inductor and capacitor values conforms to the premise that the inductor current rating should not be less than the upper limit of the inverter output current in the circuit.

These findings not only provide a new perspective for the design and optimization of three-phase inverters but also hold theoretical and practical significance for advancing new energy technology. Through this study, we hope to provide valuable reference for engineers and researchers in the field of power electronics, promoting the development of more efficient and reliable inverter technology (Buswig et al., 2019).

METHODOLOGY

This section describes the simulation software used is MATLAB/Simulink as well as FFT toolbox analyzer. The parameters chosen for the SPWM modeling circuit components are as tabulated in the Table 1.

Table 1: Three-phase full-bridge VSI with SPWM components description

Component	Specification
DC source voltage	Amplitude– 400Vdc
IGBT	Ideal
Three phase Load	Star connected with a neutral point, L – 1mH and C - 1μF
Sinusoidal reference voltage signals	Phase shift – 120 degrees
Triangular carrier waveform	1 kHz
Switching logic comparator blocks	Generate gate pulses for switches by comparing the reference and carrier signals

Measurement Blocks	Voltage and current across the load
Simulation time	0.1s (5 cycles)
Scope blocks	To visualize the reference and carrier waveforms, the switching signals, the line-to-neutral voltages, the line-to-line voltages, and the load currents.
Modulation index (Ma)	Ma – 0.5, 0.6 0.8 and 1

Simulation Model

A Simulink model of a three-phase full-bridge VSI using Sinusoidal Pulse Width Modulation (SPWM) shown in Figure 4 is created in MATLAB- Simulink. By simulating the model, the behavior of three phase voltages and currents on various modulation index and their impact to THD are observed and discussed.

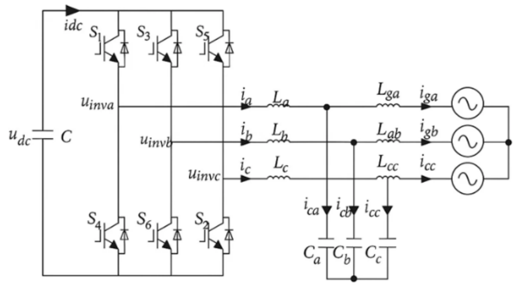

Figure 4: A Simulink model of a three-phase full-bridge VSI with three phase loads.

The data used in the model of this research are shown in Table 2.

Table 2: Data used in the model

Parameter	Value
System frequency	$f = 50\ Hz$
DC input voltage	$Vdc = 400\ V$
Inductance	$L = 0.001\ H$
Capacitance	$C = 16\mu\ F$
Modulation index	Ma =0.5, 0.6, 0.8, 1.0.
Simulation time	$T = 0.1\ s$
Conduction mode	120 degrees
Carrier peak amplitude	1

RESULTS AND DISCUSSION

The circuit in Figure 4 was simulated for a sufficient duration of 5 cycles (0.1 s) of the input waveforms and its behavior was studied. The results below are the observed three sinusoidal reference waveforms and the triangular carrier waveform, switching signals for all six switches, the output voltages and current waveforms across the load over the five cycles of the output waveforms. In this section each waveform is going to be plotted below. Figure 5 shows the three sinusoidal reference waveforms and triangular carrier wave form at the same scope.

Figure 6 clearly shows the switching signals for the inverter switches 1 and 4. This is the first group of switches in the three-phase inverter circuit. Figure 7 clearly shows the switching signals for the inverter switches 3 and 6. Figure 8 clearly shows the switching signals for the inverter switches 5 and 2.

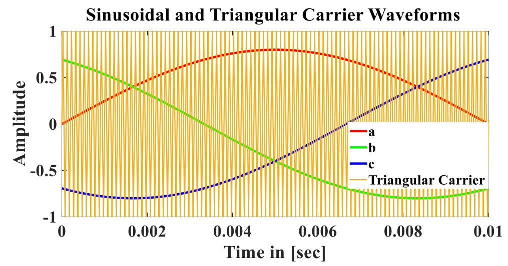

Figure 5: Three sinusoidal reference waveforms and triangular carrier waveform.

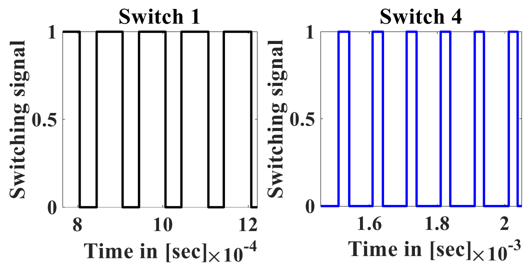

Figure 6: Switching signals for the inverter switches 1 and 4.

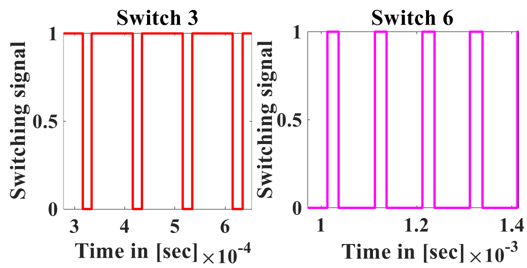

Figure 7: Switching signals for the inverter switches 3 and 6.

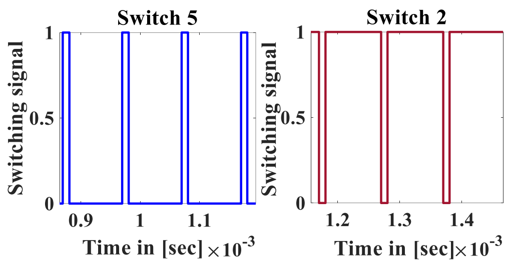

Figure 8: Switching signals for the inverter switches 5 and 2.

Waveform's Parameters

Therefore, from the model above, we can clearly observe the three-phase output line-to-neutral voltage waveforms as seen in Figure 9. Figure 10 clearly describes the three-phase output line to line waveforms behaviour. Figure 11 clearly shows the three-phase load current waveforms behaviour.

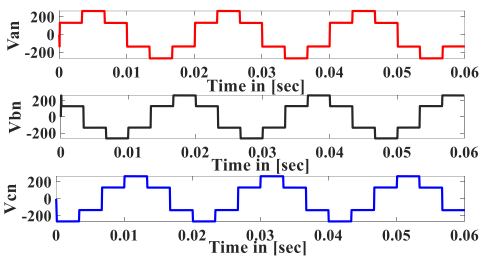

Figure 9: Three-phase output line-to-neutral voltage waveforms.

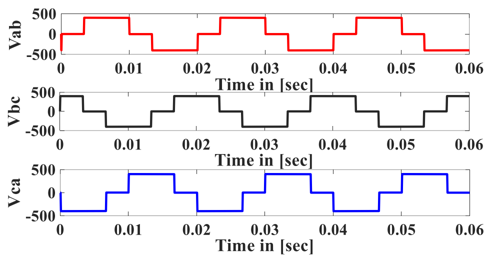

Figure 10: Three-phase output line-to-line voltage waveforms.

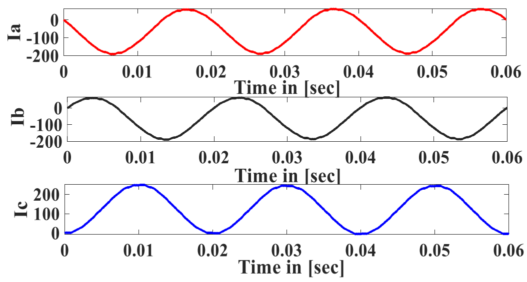

Figure 11: Three-phase load current waveforms.

Numerical Analysis and Reporting

The theoretical value of RMS output voltage was obtained from the formulae in (1) and Ma used was 1;

$$V_{rms} = \frac{\sqrt{3} \times \text{ma} \times V_{dc}}{\sqrt{2}} \quad (1)$$

$$= \frac{\sqrt{3} \times 1 \times 100\text{V}}{\sqrt{2}} = 122.47V$$

From the simulation, the recorded value of RMS output is 168.3V and calculated was 122.47V. From the simulation results, a number of observations were made, Table 3 summarizes some of the observed parameters and gives a comparison with their theoretical expected values.

Table 3: Observed and theoretical parameters

Parameter	Observed value	Theoretical value
RMS output voltage	168.3V	122.47V

Therefore, in a balanced three-phase system, the line-to-line voltages (V_{ab}, V_{bc} and V_{ca}) must be phase-shifted by 120° relative to each other and must follow a specific relationship with the line-to-neutral (phase) voltages (V_{an}, V_{bn} and V_{cn}). The relation between the line-to-line voltage and the line to ground voltage in (2) is based on the output RMS voltage which is taken from the measurement scope in the Simulink, the relation between them is given by (2).

$$V_{LG} = \frac{V_{LL}}{\sqrt{3}} \quad (2)$$

V_{LG} is line to ground voltage and $V_{LL}$is line to line voltage.

Simulations

By using the same simulation set up, we perform harmonic analysis on one of the line-to-line output voltage waveforms V_{LL} by FFT Analysis tool in Simulink.

Harmonic analysis using FFT

For FFT analysis, 5 cycles were analyzed from 0 to 10000 Hz maximum frequency under 50 Hz fundamental frequency and Figure 12 shows the magnitude spectra of output voltage. The circuit in Figure 4 was simulated again for a sufficient duration of 5 cycles (0.1 s) using the same simulation setup and its behavior was studied.

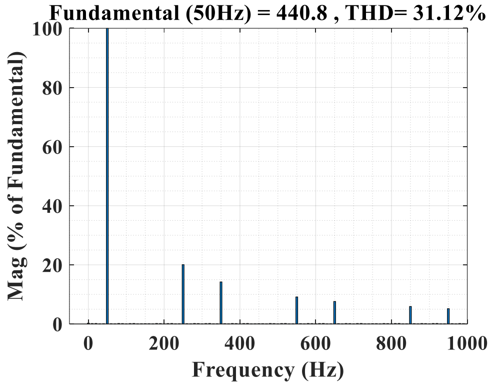

Figure 12: Magnitude spectrum of the line-to-line output voltage.

Harmonics Contribution of Dominant Harmonics

From Figure 12, the desired signal is at 50Hz with 100% of fundamental and the dominant harmonics are shown in Table 4.

Table 4: Fundamental component and the dominant harmonics

Frequency (Hz)	% contribution	Relation with fundamental frequency	
250	20.07	250/50 = 5	Odd
350	14.23	350/50 = 7	Odd
550	9.14	550/50 = 11	Odd
650	7.62	650/50 = 13	Odd
850	5.93	850/50 = 17	Odd
950	5.18	950/50 = 19	Odd

After FFT computation the following points were observed

The SPWM and square wave outputs differ significantly in their harmonic characteristics, primarily due to their switching strategies. A square wave is generated by abruptly switching between two voltage levels (e.g., +V and -V) at the fundamental frequency (e.g., 50Hz). This creates sharp voltage transitions and a waveform rich in low-frequency odd-order harmonics (3rd, 5th, 7th, etc.) with amplitudes decaying as $1n$, where n is the harmonic order. For example, a 50 Hz square wave has a 3rd harmonic at 150 Hz (33% amplitude of the fundamental) and a 5th harmonic at 250 Hz (20% amplitude). These low-frequency harmonics result in high Total Harmonic Distortion (THD > 40%) causing issues like motor heating, torque pulsations, and electromagnetic interference (EMI). Filtering these harmonics is challenging as they lie close to the fundamental frequency which require bulky and expensive passive components.

In contrast, SPWM uses a high-frequency carrier signal (e.g., triangular wave at 1–10 kHz) modulated by a sinusoidal reference. From Figure 12, the fundamental frequency is 50 Hz (desired sinusoidal output frequency) and is 100% of the output signal. The dominant harmonics are 5th harmonics (250Hz with 20.07%) and 7th harmonics (350Hz with 14.23%). The other harmonic signals have a small contribution compared to the mentioned dominant harmonics. Since the harmonics are odd integrals of the fundamental frequency, the odd harmonics are the dominant harmonics of the expected AC output signal.

Furthermore, the THD of the simulated signal is 31.12%. According to the IEEE standard 519, when the THD of the signal is greater than 5% means the signal is poor. Also, the performance of the circuit can be improved by connecting a filtering capacitor (or an LCL filter) in parallel with the load.

SPWM also requires more complex control circuitry to generate the modulated pulses and manage feedback whereas square waves are simpler and cheaper to implement but suffer from severe EMI due to their sharp edges and low-frequency harmonic content. For the resistive inductive load, its output voltage without filtering inductor is the same as that of the resistive load without filtering.

Modulation Index Variation

The modulation index (Ma) is a fundamental control parameter in PWM techniques (like SPWM) that determines the output voltage magnitude, waveform quality and harmonic performance of inverters. It is the ratio of peak magnitudes of the modulating waveform and the carrier waveform. The essence of varying modulation index is output voltage control, harmonic performance and system efficiency while keeping the output frequency and switching frequency constant. In this experiment the five different values of the ma have been used (0.5, 0.6 0.8 and 1).

Test Case 1: For modulation index 0.5

The sine wave was set 0.5 amplitude as the triangular carrier with a peak amplitude of 1 and the RMS voltage observed was 125.1 V.

Harmonic analysis using FFT

For FFT analysis, 5 cycles were analyzed from 0 to 1000 Hz maximum frequency under 50 Hz fundamental frequency. Thus, the harmonic analysis was performed on the modulation index of 0.5 and Figure 13 shows the magnitude spectra of output voltage.

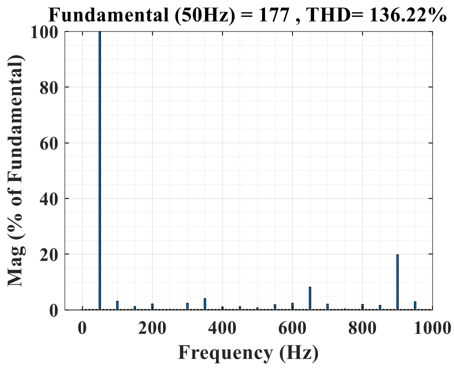

Figure 13: Magnitude spectrum of the line-to-line output voltage as a function of modulation index 0.5

From Figure 13, the Total Harmonic Distortion (THD) is 136.22% which is too high. This is because of small modulation index selected (0.5). Also, the magnitude spectra, dominant harmonics is 900Hz (19.85% harmonics contribution). But this value was obtained when the maximum frequency was 1000Hz.

Test Case 2: For modulation index 0.6

From the Simulink model above in Figure 4, the sine wave was set 0.6 amplitude as the triangular carrier with a peak amplitude of 1 and the RMS voltage observed was 136.7 V.

Harmonic analysis using FFT

For FFT analysis, 5 cycles were analysed from 0 to 1000 Hz maximum frequency under 50 Hz fundamental frequency. Thus, the harmonic analysis was performed on the modulation index of 0.6 and Figure 14 shows the magnitude spectra of output voltage.

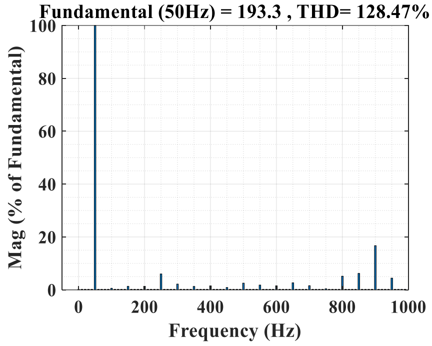

Figure 14: Magnitude spectrum of the line-to-line output voltage as a function of modulation index 0.6.

From Figure 14, the Total Harmonic Distortion (THD) is 128.4% which is smaller compare with THD when modulation index is 0.5. Also, the magnitude spectra, dominant harmonics is 900 Hz (16.71% harmonics contribution). But this value was obtained when the maximum frequency was 1000Hz. Therefore, by analyzing the THD using 0.6 modulation index, it shows the great improvement in minimizing the distortion compare to 0.5.

Test Case 3: For modulation index 0.8

The sine wave was set 0.8 amplitude as the triangular carrier with a peak amplitude of 1 and the RMS output voltage observed was 185.8 V.

Harmonic analysis using FFT

For FFT analysis, 5 cycles were analyzed from 0 to 1000 Hz maximum frequency under 50 Hz fundamental frequency. Thus, the harmonic analysis was performed on the modulation index of 0.8, Figure 15 shows the magnitude spectra of output voltage. From Figure 15, the Total Harmonic Distortion (THD) is 97.7% which is smaller compare with THD when modulation index is 0.6. Also, the magnitude spectra, dominant harmonics is 900 Hz (23.91% harmonics contribution). But this value was obtained when the maximum frequency was 1000Hz.

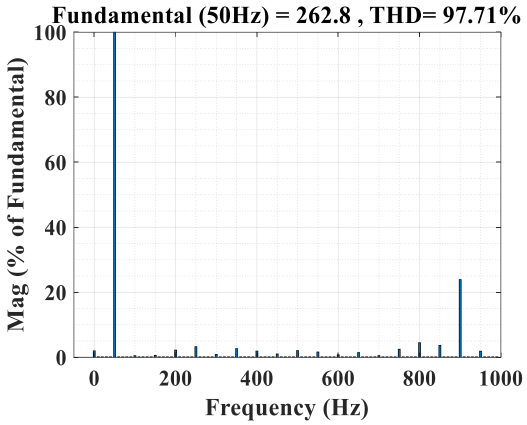

Figure 15: Magnitude spectrum of the line-to-line output voltage as a function of modulation index 0.8.

Test Case 4: For modulation index 1

The sine wave was set 1 amplitude in the model as the triangular carrier with a peak amplitude of 1, the RMS output voltage observed was 236 V from the Scope of the simulation.

Harmonic analysis using FFT

For FFT analysis, 5 cycles were analyzed from 0 to 1000 Hz maximum frequency under 50 Hz fundamental frequency. Thus, the harmonic analysis was performed on the modulation index of 1 and Figure 16 shows the magnitude spectra of output voltage.

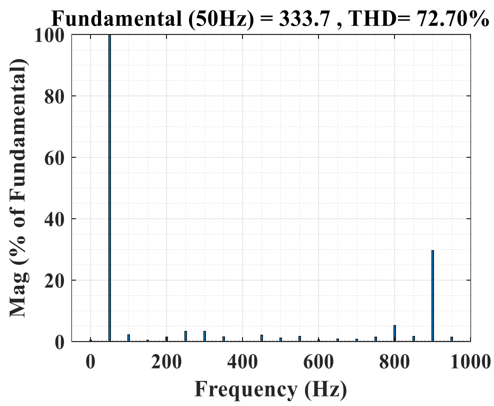

Figure 16: Magnitude spectrum of the line-to-line output voltage as a function of modulation index 1.

From Figure 16, the THD is 72.69% which is smaller compare with THD when modulation index is 0.8. Also, the magnitude spectra, dominant harmonics is 900 Hz (29.64% harmonics contribution). But this value was obtained when the maximum frequency was 1000Hz as a switching frequency.

Table 5 shows clearly the relationship between modulation index, THD and RMS Voltage. It shows the relationship when modulation index increases versus the content of THD as well as the RMS voltage.

Table 5: THD obtained at selected modulation index values

Modulation index	Total harmonic distortion%	RMS Voltage (V)
0.5	136.22	125.1
0.6	128.47	136.7
0.8	97.70	185.8
1.0	71.69	236

The analysis has been carried under modulation range and showing the effect the modulation index. From Table , we conclude that as the modulation index increased so decrease THD of line voltage. Also, the fundamental RMS voltage is increased for increase the modulation index. Therefore, we conclude that at modulation index as approaching nearly to 1.0, the inverter performance becomes better.

Also, from the analysis we conclude that as the frequency modulation index increased so decrease THD of line voltage. The fundamental voltage is increase for increase the frequency modulation index. The line voltage increases for increasing frequency variation.

Frequency Variation

By setting the modulation index to a fixed value of 0.8, then simulating the three-phase VSI for at least different output frequencies which are 100Hz, 150Hz and 200Hz while keeping the switching frequency constant (10KHz).

Case 1: When the frequency is 100 Hz and switching frequency is 10KHz

After the FFT analysis the observed voltage was 311.4 V. Figure 17 shows the plot for the harmonic spectra for the output line to line voltage. The result in Figure 17 shows that THD is somehow large in the frequency of 100Hz which also states RMS the voltage effect.

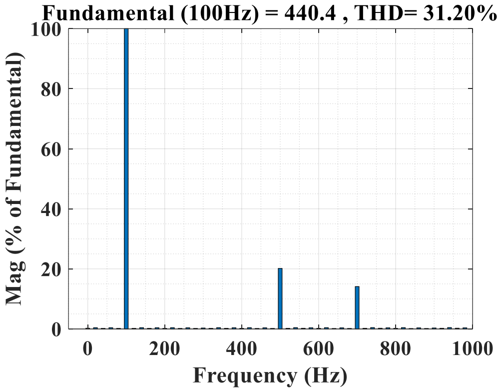

Figure 17: The magnitude spectra for the line-to-line voltage at frequency 100 Hz.

Case 2: When the frequency is 150 Hz and switching frequency is 10KHz

After the FFT analysis the observed voltage was 311.6V. Figure 18 shows the plot for the harmonic spectra for the output line to line voltage.

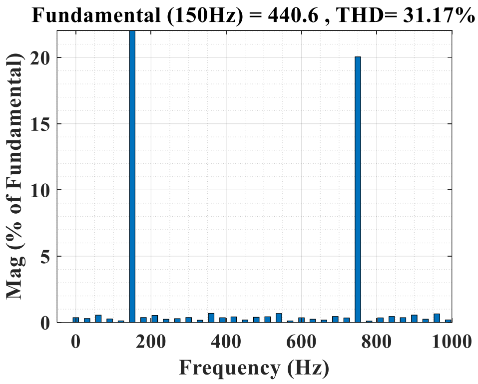

Figure 18: The magnitude spectra for the line-to-line voltage at frequency 150 Hz.

Case 3: When the frequency is 200 Hz and switching frequency is 10KHz

After the FFT analysis the observed voltage was 312.2V. Figure 19 shows the plot for the harmonic spectra for the output line to line voltage.

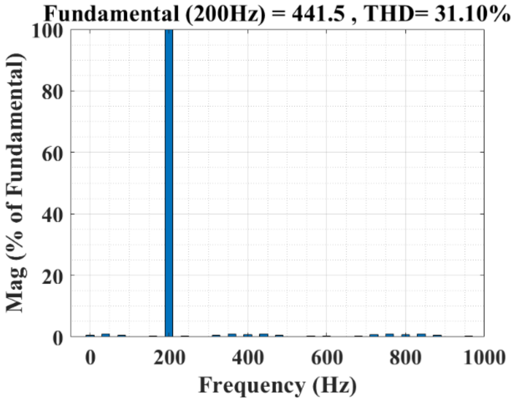

Figure 19: The magnitude spectra for the line-to-line voltage at frequency 200 Hz.

Table 6 shows the comparison of the data collected after the FFT analysis which shows the output RMS voltage, different values of frequency, total harmonic distortions, the dc component and the dominant harmonics observed.

Table 6: The results from the FFT analyzer at different output frequency

Frequency (Hz)	RMS voltage (V)	Total harmonic distortion THD (%)
100	311.4	31.20
150	311.6	31.17
200	312.2	31.10

From the tabulated data in Table 6 a system shows that the THD values were around 31% across output frequencies of 100 Hz, 150 Hz and 200 Hz whereby there is a gradual increase in the fundamental RMS voltage as the frequency increases by considering Ma = 0.8 and constant switching frequency of 10 KHz. At 100 Hz, the THD is 31.20% with a fundamental voltage of 311.4V. At 150 Hz, the THD drops marginally to 31.17% and the voltage rises to 311.6V and at 200 Hz, the THD drops marginally to 31.10% and the voltage rises to 312.2V. This clearly shows that when frequency increases the harmonics tend to decrease while the RMS output voltage increases. Such harmonics can lead to issues like motor overheating, electromagnetic interference (EMI), and inefficiencies in transformers or inductive loads.

Performance Comparison of SPWM with Other Common PWM Techniques

All these PWM techniques are used to turn on or turn off the switches of three phase inverter through gate pulses. The variation of performances is analyzed by measuring THD for every PWM technique. The lower THD indicates better performance of inverter. SPWM is one of the most widely used modulation techniques in inverters due to its simplicity and effectiveness. Below are the key advantages of SPWM compared to other PWM methods include: -

SPWM uses a simple comparison between a sinusoidal reference wave and a high-frequency triangular carrier wave to generate switching pulses makes easier to implement in microcontroller, DSPs reducing development time and cost while other techniques like SVPWM and THIPWM require more complex calculations and vector transformations. SPWM produces a nearly sinusoidal output with lower THD than others normal used PWM method which makes it superior in better performance. SPWM offers lower Switching losses a fixed switching frequency, leading to predictable and manageable losses while SVPWM and THIPWM require more frequent switching and increasing losses. Also, SPWM has better compatibility with passive filters since it generates well - defined harmonic clusters around the switching frequency that makes easier to filter out high-frequency noise using LC filters.

CONCLUSION

This research presented goal of development and modelling of three phase inverters using SPWM in the MATLAB Simulink software and hardware part are achieved. The SPWM control technique is built in the MATLAB Simulink which control the switches in the three-phase inverter in the software and produced satisfactory result. The three-phase SPWM inverter with an added filter succeeded in generating a clean or smooth and sinusoidal output voltage having lower harmonics. Hence, the proposed SPWM control technique met the approved standard THD requirements for improved performance of equipment and power quality. In the future, the analysis and comparison of the THD using different SPWM control technique can be done using the power analyzer to measure the harmonic. This will be useful in the improvement of the performance of nonlinear loads.

REFERENCES

Abdelhak, L., Anas, B., Jamal, B., & Mostafa, E. O. (2022). Optimized control of three-phase inverters to minimize total harmonic distortion in a grid-connected photovoltaic system. *International Journal of Power Electronics and Drive Systems*, ***13***(4), 2255–2268. doi:10.11591/ijpeds.v13.i4.pp2255-2268.

Aihsan, M. Z., Yusof, A. M., Ahmad, N. I., Saifizi, M., Habibah, H. M., Rahman, D. H. A., & Mustafa, W. A. (2020). Performance Analysis of Unipolar SPWM Inverter: Resistive load and Inductive load. *IOP Conference Series: Materials Science and Engineering*, ***932***(1). doi:10.1088/1757-899X/932/1/012074.

Rahman, A., Rahman, M. M., & Islam, M. R. (2017, December). Performance analysis of Three Phase Inverters with different types of PWM techniques. 2017 *2nd International Conference on Electrical & Electronic Engineering (ICEEE)* (pp. 1-4). IEEE. doi: 10.1109/CEEE.2017.8412864.

Al-Adwan, I. M., & Al Shiboul, Y. A. (2020). Effect of the Modulation Index and the Carrier Frequency on the Output Vol Tage Waveform of the Spwm Voltage Source Inverter. *Proceedings of the 17th International Multi-Conference on Systems, Signals and Devices, SSD 2020*, 960–968. doi:10.1109/SSD49366.2020.9364104.

Bhattacharjee, T., Jamil, M., & Jana, A. (2018, March). Design of SPWM based three phase inverter model. *2018 Technologies for Smart-City Energy Security and Power (ICSESP)* (pp. 1-6). IEEE. doi:10.1109/ICSESP.2018.8376696.

Bhattacharya, S., & Samanta, S. (2024). Comparative Analysis of Various Sinusoidal

Pulse Width Modulation Techniques. *2024 3rd International Conference on Power, Control and Computing Technologies, ICPC2T 2024*, 200–205. doi:10.1109/ICPC2T60072.2024.10474983.

Biswas, S. P., Anower, M. S., Sheikh, M. R. I., Islam, M. R., Kouzani, A. Z., & Parvez Mahmud, M. A. (2020, October 16). A New Modulation Technique to Improve the Performance of Three Phase Inverters. *2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, ASEMD 2020*. doi:/10.1109/ASEMD49065.2020.9276295.

Bushra, E., Zeb, K., Ahmad, I., & Khalid, M. (2024). A comprehensive review on recent trends and future prospects of PWM techniques for harmonic suppression in renewable energies-based power converters. *Results in Engineering, 22*. doi:10.1016/j.rineng.2024.102213.

Buswig, Yonis. M., Albalawi, H., Julai, N. bin, Othman, A.-K. bin H., Affam, A., & Qay, O. (2019). Development and Modelling of Three Phase Inverter for Harmonic Improvement using Sinusoidal Pulse Width Modulation (SPWM) Control Technique. *International Journal of Recent Technology and Engineering (IJRTE)*, ***8***(4), 1897–1902. doi:10.35940/ijrte.C4624.118419.

Aboadla, E. H. E., Khan, S., Habaebi, M. H., Gunawan, T., Hamidah, B. A., & Yaacob, M. B. (2016, January). Effect of modulation index of pulse width modulation inverter on Total Harmonic Distortion for Sinusoidal. *2016 International Conference on Intelligent Systems Engineering (ICISE)* (pp. 192-196). IEEE. doi:10.1109/INTELSE.2016.7475119.

Islam, M. T., & Ayon, S. I. (2020, December 19). Performance Analysis of Three-Phase Inverter for Minimizing Total Harmonic Distortion Using Space Vector Pulse Width Modulation Technique. *ICCIT 2020 - 23rd International Conference on Computer and Information Technology, Proceedings*. doi:10.1109/ICCIT51783.2020.9392687.

Ismail, N., Permadi, A., Risdiyanto, A., Susanto, B., & Ramdhani, M. A. (2018). The Effect of Amplitude Modulation Index and Frequency Modulation Index on Total Harmonic Distortion in 1-Phase Inverter. *IOP Conference Series: Materials Science and Engineering*, ***288***(1). doi:10.1088/1757-899X/288/1/012107.

Ji, Y., & Xu, Y. (2025). Analysis of Three-Phase Inverter SPWM Modulation Strategy. *Proceedings of 2024 International Symposium on Integrated Circuit Design and Integrated Systems, ICDIS 2024*, 447–455. doi:10.1145/3702191.3708490.

Pal, V. K., & Singh, S. (2020). Design of Sinusoidal Pulse Width Modulation 3 Phase Bridge Inverter. *International Research Journal of Engineering and Technology (IRJET)* e-ISSN, 2395-0056.

Mahbub, M., & Hossain, M. A. (2021). Design, Simulation and Comparison of Three-phase Symmetrical Hybrid Sinusoidal PWM fed Inverter with Different PWM Techniques. *International Conference on Robotics, Electrical and Signal Processing Techniques*, 1–5. doi:10.1109/ICREST51555.2021.9331086.

Mattoo, B. A., & Bhat, A. H. (2022, July). Comparative analysis of various PWM techniques for voltage source inverter. In *2022 1st International Conference on Sustainable Technology for Power and Energy Systems (STPES)* (pp. 1-6). IEEE. doi:10.1109/stpes54845.2022.10006650.

Raghuwanshi, S. S., Khare, V., & Gupta, K. (2017, August). Analysis of SPWM VSI fed AC drive using different modulation index. *2017 International Conference on Information, Communication, Instrumentation and Control (ICICIC)* (pp. 1-6). IEEE. doi:10.1109/ICOMICON.2017.8279070.

Sarker, R., Datta, A., & Debnath, S. (2020). FPGA-based variable modulation-indexed-SPWM generator architecture for constant-output-voltage inverter applications. *Microprocessors and Microsystems, 77*. doi:10.1016/j.micpro.2020.103123.

Shankar, V., Kumar, A., & Tiwari, A. N. (2019, September). Performance analysis of three phase voltage source inverter using PWM and SPWM techniques. *2019 International Conference on Computing, Power and Communication Technologies (GUCON)* (pp. 759-763). IEEE.

Yumi, K. M., Ilham, S. M., Yusof, A. M., Kimpol, N., & Habibah, H. M. (2024). A studies on variation modulation index towards SPWM unipolar inverter. *AIP Conference Proceedings*, ***2750***(1). doi:10.1063/5.0151365.