Development and Modelling of Three Phase Inverter for Harmonic Improvement using Sinusoidal Pulse Width Modulation (SPWM) Control Technique

Yonis. M. Buswig, Azuka Affam, Hani Albalawi, Norhuzaimin bin Julai, Al-Khalid bin Hj Othman, and Ohirul Qays

Abstract: ***This paper describes the design of a 400 V, three-phase voltage source inverter system using Sinusoidal Pulse Width Modulation (SPWM) control technique. Pulse Width Modulation (PWM) is an internal control technique for inverters. The Sinusoidal Pulse Width Modulation (SPWM) technique is the type of PWM used in this work. The aim is to reduce the harmonic produced by the inverter. Current standards require that total harmonic distortion (THD) be minimal. A three-phase SPWM signal is implemented in order to create an output voltage which is closer to a true sine wave and reduce harmonics. The development and model were implemented using MATLAB Simulink soft-ware and hardware parameters. The addition of a low pass filter circuit aids the achievement of smoother sine waveforms and a reduced THD value of 0.17%. The proposed concept has been validated through experimentally on a laboratory prototype by using DSP TMS320F28335 real-time digital control. The experimental outcomes emphasize the authenticity of the suggested technique in reducing harmonics, which can be promising to power quality improvement.***

Index Terms - Harmonic Improvement; Power Quality Improvement; Sinusoidal Pulse Width Modulation (SPWM); Total Harmonic Distortion (THD); Three-phase Inverter Systems.

I. 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.

Inverters are widely used in the world to convert direct current to alternating current having variable amplitude and variable frequency. 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. Pulse Width Modulation (PWM) is the method for the internal control of an inverter [1]. There are various types of PWM control techniques in the three phase inverter such as sinusoidal pulse width modulation (SPWM), third-harmonic injection PWM (THIPWM) and space vector pulse width modulation (SVPWM) [2-3]. 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 by 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.

In this research, the proposed design used the 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 research deals with the three phase inverter where the power semiconductor devices are used. Therefore, 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 [4].

Inverters are based on the production of the three types of different outputs which are the square wave inverter, the modified sine wave inverter and a pure sine wave inverter.

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Yonis. M. Buswig, Department of Electrical and Electronic Engineering, Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

Hani Albalawi, Department of Electrical Engineering, University of Tabuk, Saudi Arabia

Norhuzaimin bin Julai, Department of Electrical and Electronic Engineering, Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

Al-Khalid bin Hj Othman, Department of Electrical and Electronic Engineering, Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

Azuka Affam, Department of Electrical and Electronic Engineering, Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

Ohirul Qay Department of Electrical and Electronic Engineering, Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

The square wave inverter is the simplest type of inverter which generates a symmetrical square wave and almost the same as pure sine wave except that it is not smooth. It converts a constant DC signal to a phase shifting AC signal. Square wave inverter consists of negative and positive level. It has been reported in [5-7] that although the cost of the square wave is less expensive, it exhibits high harmonics as a disadvantage. Thus, it is not suitable to use for the electronic devices or the inductive loads. Therefore, it is not efficient for the running appliances because the power consumption by the square wave type inverter is high.

A modified sine wave inverter is more complicated than a simple square wave inverter. It generates a square like wave output. It is almost similar to the square wave inverter output except that it has an addition for the level which is zero level or volts. Before it switches to the positive or negative level, it has to stop at the zero level. Hence, the sequence is positive-zero-negative and repeats between the three levels. The modified sine wave has some draw-back that is similar to the square wave inverter. Several studies [5], [8-9] have identified that the modified sine wave require a simple hardware structure but it contains high distortion that comes from the harmonics. This results in low efficiency and poor power quality due to the power loss. Besides that, this type of inverter causes extra heat and produce a hissing or audible noise for the running ac motor [5].

A pure sine wave inverter transforms DC supply into a nearly sinusoidal waveform. [5], [8], [10] described the pure sine wave inverter as expensive due to the complex structure or design, how-ever, it has the lowest level of harmonic distortion and EMI com-pared to the others. Furthermore, it has high efficiency because it consumes less power and less heat generation. Thus, this causes a very clean supply and reduces noise that is suitable for working with motors, electronic system and sensitive equipment in addition to working with the PWM technique.

Total harmonic distortion (THD) is the sum of each of the harmonics amplitudes and expressed as a percentage of the fundamental frequency [11]. Harmonic is a quantity having a frequency that is integral multiples of the fundamental frequency [11].

The standard for the value of THD has been established in [12]. This allows the permissible THD value to be below 5%. Attempts have been made in several research to improve three phase inverter harmonics using the SPWM. In [13], a modification of the SPWM technique succeeded in reducing the THD value to 1.65% via simulation. An improvement of 0.88% is achieved in [14]. However, the THD values obtained in both cases can be further reduce with a better technique. Also, the elimination of harmonics demonstrated during simulation was not verified experimentally.

In this paper, a modified SPWM technique is proposed to further eliminate higher order harmonics and obtain a THD value which bests the previous works. Examination of the technique is based on the THD value and the output voltage waveform. Results of simulation and experimental verification indicate a reduction in harmonics and low production cost.

Subsequent sections of this paper follow in this manner. The methodology in Section 2 justifies the sequential steps taken in the work as related to the simulation, inverter design, filter design and experimental verification. The simulation and experimental waveform with THD results are presented and discussed in Section 3. Section 4 is a comparison of previous research work and benchmarks after which conclusions are drawn in Section 5.

II. MATERIALS AND METHODS

The research block diagram design is presented in Figure 1. The project design consists of two parts which are the software part and hardware part. The input of the project is the control technique which is the SPWM where it is implemented in the MATLAB Simulink. The programming code in the MATLAB Simulink of the SPWM is sent and implemented to the Digital Signal Processors (DSP) microcontroller. The SPWM signals are sent to the gate driver and then sent to the three phase inverter print-ed circuit board (PCB). The three phase inverter is connected to the load which is the three phase load

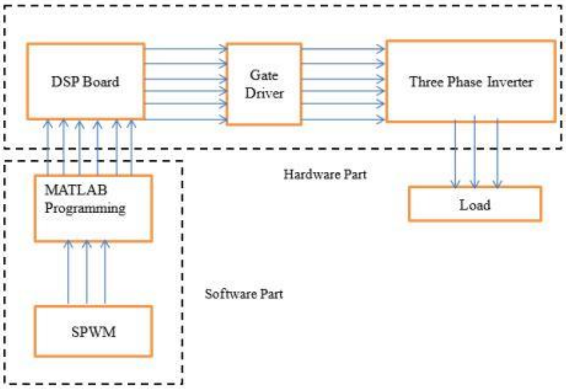

Fig. 1: Research block diagram

A. Three Phase Inverter

Three phase inverter is a device to transform a constant DC input voltage to three phase of AC voltage. The circuit of the three phase inverter as designed with the Proteus software is presented in Figure 2. Three single-phase inverters have been connected in parallel to obtain a three phase output in [15].

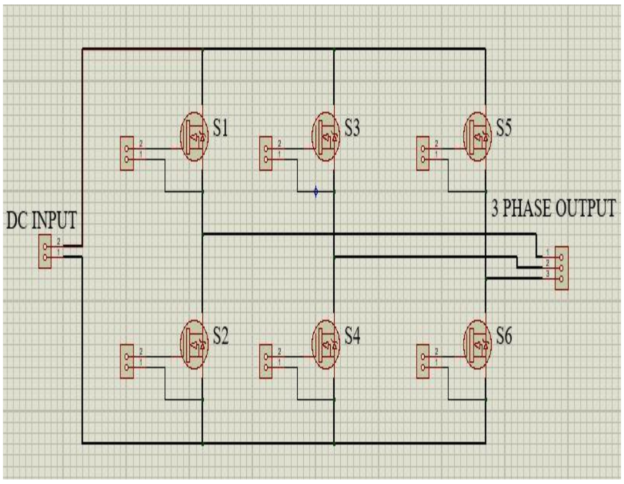

Fig. 2: Three phase inverter circuit

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. 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. The IGBT boasts of preferred qualities over the power MOSFET which are not limited to, high forward and reverse voltage blocking capacity, relatively fast switching speed, low driving power and easy control.

B. Simulation of Proposed SPWM Control Technique

The SPWM control technique is implemented using the MATLAB Simulink software and is sent to the digital signal processor to generate the modulated pulses. The modulated pulses which result from the SPWM are sent to the switching devices which are the IGBTs in the three phase inverter circuit. The SPWM technique controlled the output voltage of the three phase inverter and produce an output of a sinusoidal waveform at a specific frequency. The completed circuit of the three phase inverter and proposed SPWM control topology is implemented in the MATLAB Simulink software as shown in Figure 3.

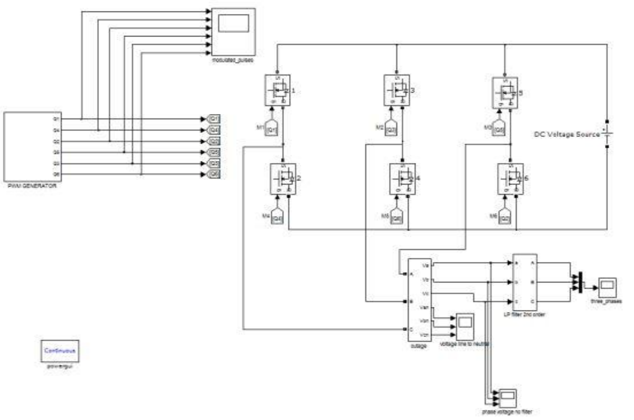

Fig. 3: Three phase inverter with SPWM controller circuit

The mode conduction used is 120-degree conduction. The proposed SPWM control topology that is implemented with the DC input voltage to the inverter at 400 Volts, with an inverter frequency of 50 Hertz. The amplitudes of both the carrier and sine wave is 1. The addition of a nonlinear load serves to satisfy conditions in which harmonics exist.

The fast Fourier transform (FFT) analysis is carried out in Simulink to determine the THD by varying the modulation index (MI) from 0.5 to 1. The value of the THD will be based on the different amplitudes of modulation index. Simulation parameters are presented in Table 1.

Table 1: Parameters used during simulation

Parameter	Value
Conduction mode	120 degree conduction
DC supply voltage	400 Volts
Fundamental frequency	50 Hz
Carrier wave amplitude	1
Sine wave amplitude	1
Cut off frequency (filter)	5 KHz
Modulation index	0.5 - 1

C. Filter Design

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 filter circuit is an LC circuit. 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. The capacitor is chosen to correspond with the noticeable voltage drop originating from load transients.

The inductive and capacitive reactance are derived leading to the chosen cut off frequency of 5 KHz

$$X_L = 2\pi fL \tag{1}$$

$$X_C = \frac{1}{2\pi fC} \tag{2}$$

$$\frac{V_{ripple\max}}{V_{ac}}. = \frac{X_C}{X_L + X_C} \tag{3}$$

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

$$Z = \sqrt{\frac{L}{C}} \tag{5}$$

Where,
X_L is the inductive reactance,
f is the frequency,
L is the inductance,
X_C is the capacitive reactance,
C is the capacitance,
$V_{ripplemax}$ is the filter's maximum ripple output,
V_{ac} is the inverter's maximum ripple output,
fc is the chosen cut off frequency of the low pass LC filter,
Z is the characteristic impedance of the filter.
For the low pass filter, a simple pi configuration is applied in Simulink in order to mitigate the level of harmonics.

D. Experimental Verification

The hardware part is successfully developed as shown in Figure 7.

The SPWM control topology in the MATLAB Simulink is used to control the switches in the three phase inverter circuit. The three phase inverter circuit in the MATLAB Simulink is replaced by the real-time circuit.

The prototype is performed with the following conditions:
Input DC Power Supply = 10 V
The amplitude of carrier wave = 1
The amplitude of sine wave = 1

A dc supply is used as the input to the inverter hardware. The code from MATLAB is processed by the signal processor and forward-ed to the gate driver. The gate driver in addition to supplying the pulses to the IGBTs, provide some form of isolation to the switching circuit. The capacitor is used as the filter in the hardware part.

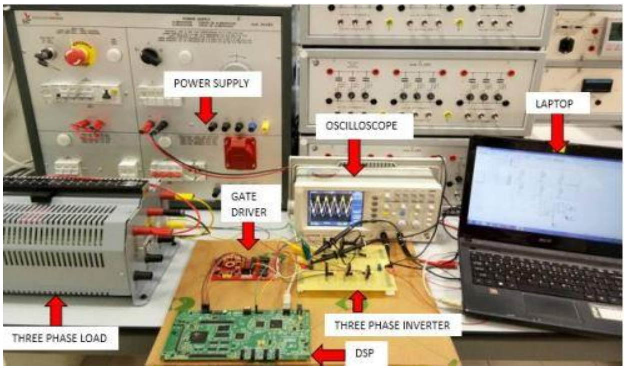

Fig. 4: Hardware experimental setup

Table 2 highlights the experimental parameters used in this work.

Table 2: Experimental parameters used

Parameter	Value
DC supply voltage	10 Volts
Fundamental frequency	50 Hz
Carrier wave amplitude	1
Sine wave amplitude	1
Switch	IGBT
IGBT switching voltage	15 Volts
Gate driver voltage	5 Volts

III. RESULTS AND DISCUSSIONS

The simulation results in MATLAB, experimental results and THD analysis are presented hereafter.

A. Simulation Results

The scopes in the Simulink displayed the result of the three phase inverter and the control topology. The result of the SPWM control topology is shown in Figure 5. The SPWM produce six modulated pulses each for the six switches in the inverter. The modulated pulses of the control topology are sent to each of the switches. The result of the three phase inverter in the Simulink is presented in Figure 6 and Figure 7.

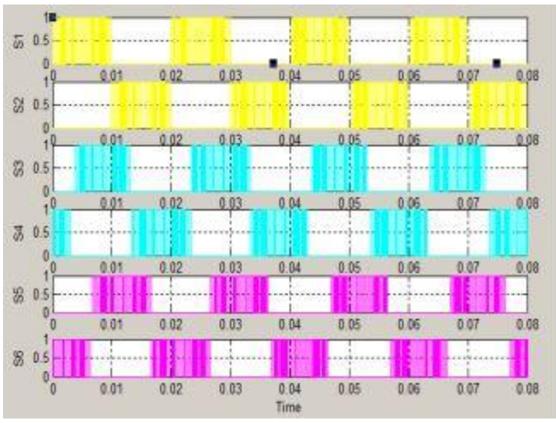

Fig. 5: Modulated pulses of SPWM

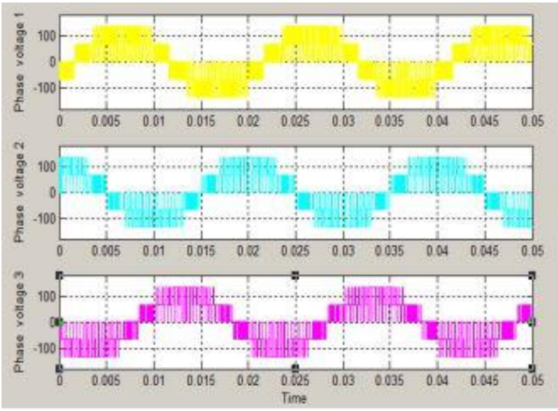

Fig. 6: Three phase output voltage without LC filter

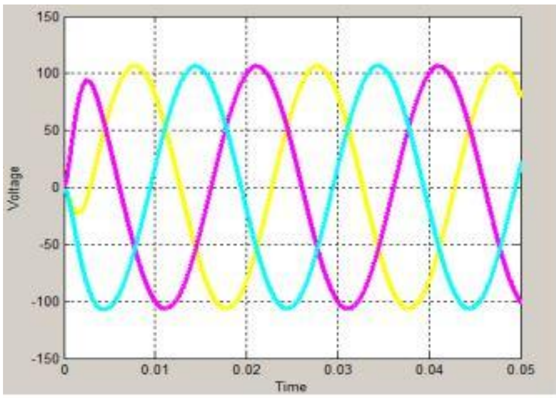

Fig. 7: Three phase output voltage with filter

Based on the Simulink results, the modulated pulses in Figure 5 are obtained because of the SPWM control technique. In the SPWM generator, there are two waves which are the carrier wave and sinusoidal reference wave. The two waves are compared by a comparator to produce modulated pulses. The resulting high and low modulated pulses are sent to the six switches to control the states of the switches. The high modulated pulses turn the switches on and off hence controlling the switches controlled the output voltage of the inverter. In Figure 6, the output voltage of three phase inverter is produced. Switches 1, 3 and 5 conduct during the positive half and switches 2, 4 and 6 are conduct during the negative half.

The wave-form in Figure 6 is not smooth and sinusoidal indicating the presence of harmonics. The insertion of the low pass filter resolved the problem. A low pass filter is used in the MATLAB Simulink to produce a sinusoidal and smooth waveform as Figure 7 depicts

B. Experimental Results

The results of the prototype are displayed in the oscilloscope. The results are shown from the Figure 8 to Figure 10.

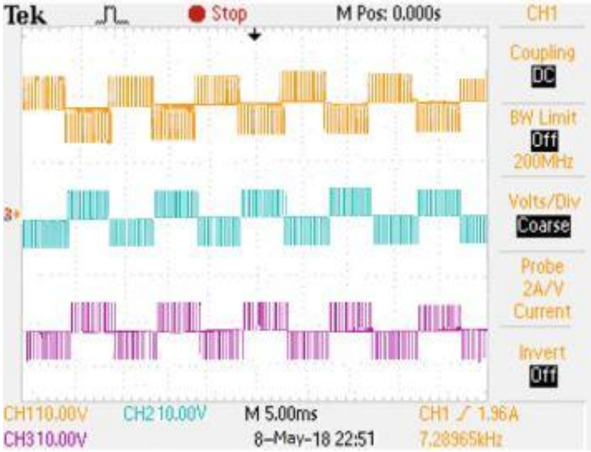

Fig. 8: SPWM switching signal pulses

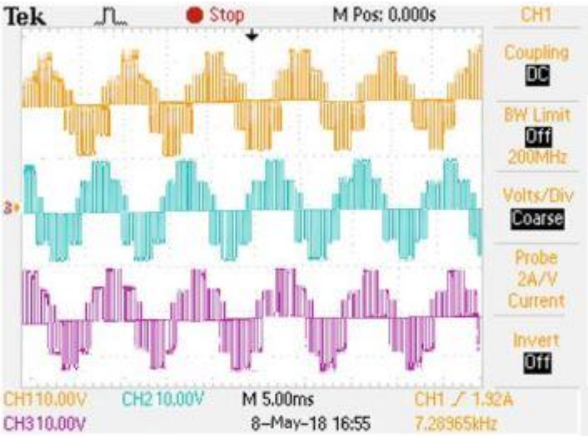

Fig. 9: The experimental results of three phase output voltage without filter

Similar to the simulation results, Figure 8 shows the generated SPWM switching signals as generated by the digital signal processor (DSP). The oscilloscope is the hardware that displayed results of the three phase inverter. The DSP is a smart and programmable microprocessor that converts the digital signal of SPWM modulated pulses from the MATLAB to analogue signals that are sent to the switches in the inverter through the gate driver to control the on and off states of the switches. The first analogue signal produced in the DSP is sent to the gate driver to step up the voltage from 5 V to 15 V because the IGBTs switches work with 15 V. In Figure 9, the three phase inverter output waveform is not sinusoidal and smooth because there is no filter applied. The waveform of the three phase inverter with filter is smooth and sinusoidal as shown in Figure 10. This confirms the outcome of the simulation that the combination of the proposed technique with a filter reduced harmonics

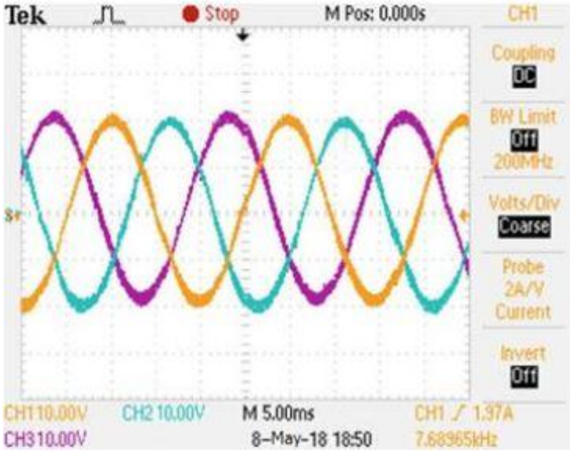

Fig. 10: The experimental results of three phase output voltage with filter

C. THD Results

The FFT analysis is done in the Simulink to determine the THD by varying the modulation index (MI) from 0.5 to 1. The following are the results of the THD based on the different amplitude modulation index. Table 1 below shows the percentage of the THD of the proposed SPWM control technique at different values of MI.

Table 3: THD obtained at selected modulation index values

Modulation Index (MI)	Total Harmonic Distortion (THD)
0.5	0.48%
0.6	0.42%
0.7	0.36%
0.8	0.29%
0.9	0.23%
1.0	0.17%

The modulation index is determined by the ratio of the amplitude of sinusoidal wave to the amplitude of the carrier wave. In the MATLAB Simulink, the modulation index is obtained by changing the amplitude value of sinusoidal wave from 0.5 V to 10 V while the amplitude of carrier wave value remains the same which is 1 V. As presented in Table 1, the higher the modulation index, the lower the percentage of THD. Increases of the amplitude value of sinusoidal wave also lower the THD. Hence the proposed SPWM control technique is able to control the modulation index and thus lower the THD. The lower THD improved the performance of equipment and improved the power quality

D. Comparison with Previous Research

comparison with previous work is presented in Table 4. The harmonics reduction capability of the proposed technique is deemed to be better than the performances of [13] and [14]. This is irrespective of the fact that different conduction modes and input voltages are used in [14]. The THD reduction achieved by this work satisfied the permissible standard [12].

Table 3: THD comparison of previous works

Research	THD reduction performance
[13]	1.65%
[14]	0.88%
This work	**0.17%**

IV. CONCLUSION

The goal of development and modelling of three phase inverter 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 hardware part where each produced satisfactory results. The three phase inverter using proposed SPWM control technique 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 analyser to measure the harmonic. This will be useful in the improvement of the performance of nonlinear loads

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