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# Design of Cascaded H-Bridge Multilevel Inverter Topology for Integrated Portable Power Pack Application

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**Abstract:** This paper presents the necessity of portable power supplies that can be carried and cater to all the users' demands. Since the energy storage of the portable power pack are coming from DC supply, it needs an inverter to convert the DC voltage into AC voltage. Most of the low-priced inverters in the market have a simple build and are inefficient, resulting in high THD that can cause the electrical appliance not to work properly. This project was focused on the most suitable inverter type where the cascaded H-bridge multilevel inverter with PWM switching technique was proposed. This type of inverter will produce a better THD and a higher output voltage level when the inverter level is increased. This theory was proved where 3-level, 5-level and 7-level of Cascaded H-Bridge Multilevel Inverter has a 52.05 %, 29.98 % and 21.94 % of voltage THD. These results prove that by increasing the output voltage level can reduce the voltage THD. For the hardware implementation, a 5-Level Cascaded H-Bridge Multilevel Inverter with PWM switching technique is chosen because it has a lower voltage THD compared to 3-Level Cascaded H-Bridge Multilevel Inverter and at the same time use less of semiconductor devices compared to 7-Level Cascaded H-Bridge Multilevel Inverter and has fewer semiconductor losses compared to the inverter with SPWM switching technique. The voltage THD of circuit models hardware when reaches 24 $V_{pk}$ is 28.3 % which is slightly better to simulation result, 29.98 %. This inverter was then connected with a step-up transformer with a ratio of 1:10 to reach standard electrical voltage supply in Malaysia of 230 $V_{rms}$ with a voltage THD of 28.4 % without load and 30 % with load. This proves that the circuit model can work properly as the 5-Level Cascaded H-Bridge Inverter simulation and hardware results show a good agreement.

**Keywords:** Portable power pack, Cascaded H-Bridge multilevel inverter, PWM, SPWM, Voltage THD

## 1. Introduction

An electrical supply is essential and considered a vital part of our daily life. Most of the everyday use equipment needs an electrical power supply to operate. Without an electrical supply, most of our work cannot be done. Thus, a continuous power supply, such as a portable power supply, is needed at all times. The technologies of portable power packs are widespread in multipurpose usage. For instance, the application of a portable power pack was found in the monitoring system and grinding analytical tool [1]. The working principle of a portable power pack started from a source from DC battery. There are wide of terminal voltage variation available that suite for its application such as sealed lead acid (SLA) battery varies from 6V-12V, nickel-cadmium (NiCd) battery varies from 0.9V-1.8V and lithium-ion (Li-ion) battery varies from 2.7V-4.2V. From the battery source, the voltage is then converted into several types that suites for its application.

Generally, a typical portable power pack has two or three power outlets. It can be 5V Direct Current (DC) output,

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12V Direct Current (DC) output and 240V Alternating Current (AC) output. The portable power pack that is built in a 24V DC battery to store electrical energy and consume for other electrical appliances. However, if the electrical appliances need 5V DC or 240V AC output, the portable power pack needs two types of converters. A buck converter is used to convert higher DC voltage input into a lower voltage output. As an example, converting 12V DC input into 5V DC output.

But, in a case where the electrical appliances need AC voltage, an inverter will be used to change a DC input voltage to a symmetrical ac output voltage of desired magnitude and frequency [2]. For instance, this project will convert 24V DC input into 240V AC output. As the input source of inverter from the DC battery itself, it is important to make sure the input voltage at the inverter is at an acceptable voltage threshold. For example, if the inverter needs 24V DC at the input, buck-boost converter is required to allow the battery to be drained to its lowest level [3]. The concept of utilizing small voltage levels to perform power conversion was presented by a MIT researcher [4][5]. Nowadays, the power inverter has a variety of topology. The H-bridge design [6] was the first introduced earlier. It then was followed by the diode-clamped inverter [5][6][7], which uses a bank of capacitors to break the DC bus voltage. Then, the flying-capacitor [8] topology continued for few years next. However, in a practical implementation, most inverters are non-sinusoidal and contain harmonics [2].

In particular, an inverter with a cascaded H-bridge design topology will be used in this project. This works by arrangement of power semiconductor devices to generate the stepped output voltage waveform [9]. The higher the level of the inverter, the higher the output voltage while producing a lower percentage of total harmonic distortion (THD). However, designing a higher level of inverters has some disadvantages. The primary disadvantages are the significant number of power semiconductor needed and power loss associated with the high switching frequency [10]. This may cause the overall design to be more complex and expensive. In practical implementation, reducing the number of switches and gate drivers circuit is very important.

## 2. Methodology

In this section, describes the methodology of this overall project including appropriate method and step. It comprises several elements needed in order to achieve the objectives of the project. In designing the inverter, two important elements that affected the performance are the inverter level and method in controlling the power switches.

## 2.1 Project Description

The portable power pack is powered by 24V SLA battery, and producing 12V DC output, 5V DC output by using buck converter and 240V AC output by using an inverter. The highlight of the project will be focused on the inverter, which is the conversion from 24V DC input to 240V AC output. For this project, the load voltage must be operated in 230 $V_{rms}$. To boost up the AC voltage of the inverter, it uses a step-up transformer to which has a turning ratio of 1:10. Fig. 1 shows the block diagram of complete inverter system. However, the main focus in this project is designing and testing of cascaded multilevel inverter part only.

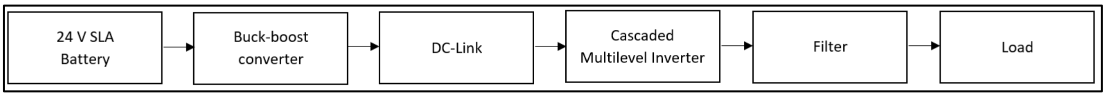


**Fig. 1 - Block diagram of complete inverter system**

In designing multilevel inverter, several factors need to be taken into account. It depends on the application type, load and required voltage. The important parameters of inverter are the voltage output, current output and voltage THD percentage. To build a basic functional inverter, the basic elements needed are a DC voltage source such as battery, MOSFETs and transformer. It needs an input at gate such as pulse generator to enable the switch to ON and OFF at desired time and duration for power switches. In the Fig. 2 below shows flowchart in designing the multilevel inverter in this project. Firstly, the parameters of the load must be identified. This includes, the voltage, current, and sensitivity of the load. Next, determine the optimum voltage level and number of switches. It needs at least 4 switches to make a full-bridge inverter. Then, choose the technique to control the operation of the switches. Finally, the output of the inverter such as voltage, current and THD percentage are observed. As the input voltage of the inverter is set at 24 V DC, it needs a transformer to step-up the voltage to reach the desired output voltage. In this case, the output voltage must reach a 230 $V_{rms}$ which equivalent to 323 $V_p$ AC. If the step-up transformer with turning ratio of 1:10 is used, it will convert a 24 $V_p$ AC to 240 $V_p$ AC. The DC input voltage at the inverter must have at least 32 V DC in order to get a 230 $V_{rms}$. Thus, a step-up transformer with a turning ratio of 1:10 will be connected to the output inverter to boost the voltage from 32 $V_p$ AC to obtain a 230 $V_{rms}$.

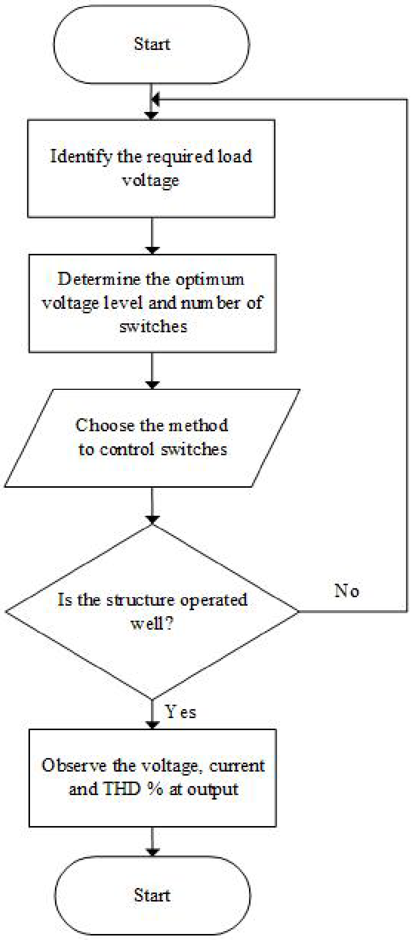


**Fig. 2 - Flowchart in designing inverter**

### 2.1.1 Multilevel Cascaded Inverter H-Bridge Topology Configuration

The multilevel inverter circuit as in the Fig. 3, the higher the voltage level will also result in the THD percentage at the output of the inverter. There are a few parameters need to be determined before designing a multilevel cascaded H-bridge topology inverter such as number of switch and number of VDC source. Below is the formula to find these parameters:

$$\text{No of switch, } S_n = 2(m-1) \tag{1}$$

$$\text{No of VDC source, } V_n = \frac{m-1}{2} \tag{2}$$

Where $m$ is the level of inverter applied.

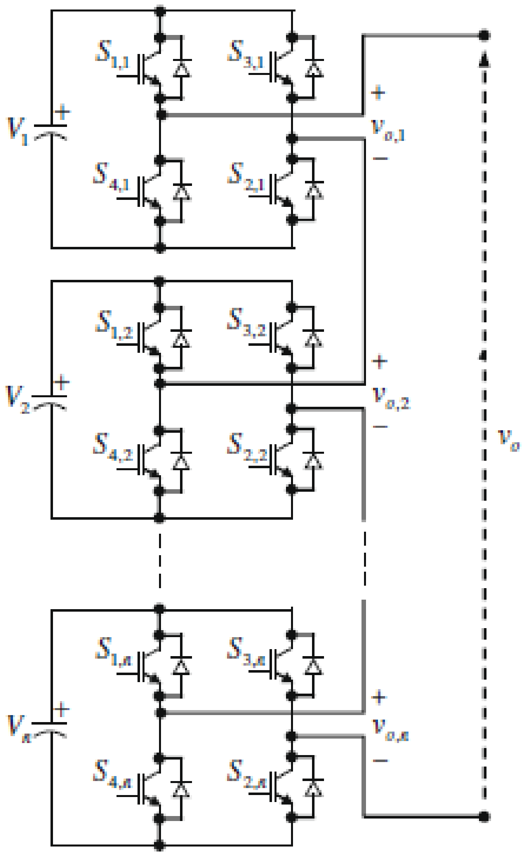


**Fig. 3 - Configuration of cascaded multilevel inverter**

The output voltage of the inverter is known as:

$$V_o = V_{o,1} + V_{o,2} + \cdots + V_{o,n} \tag{3}$$

The maximum output voltage $V_{o,max}$ of this $m$ cascaded multilevel inverter is:

$$V_{o,max} = m \; x \; V_{dc} \tag{4}$$

## 2.1.2 Pulse Width Modulation Technique

A pulse width modulation (PWM) is one of the techniques in producing AC voltage output from DC voltage input. The PWM technique are possess MOSFETs in the switching stage of the output. This technique is capable to generate AC voltage at varying magnitudes and frequencies. Regardless of the type of load connected, these inverters are capable of maintaining the output voltage depending on the rated voltage of the applications. The example of PWM output as in Fig. 4 below. The higher the duty cycle, the wider the pulse width.

The duty cycle, $D$ of the switch is given by:

$$D = \left(\frac{V_{out,ideal}}{V_{in}}\right) \tag{5}$$

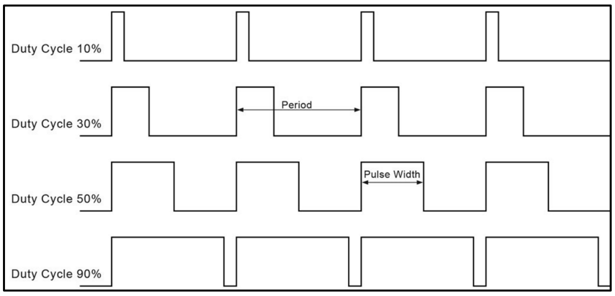


**Fig. 4 - PWM output**

### 2.1.3 Sinusoidal Pulse Width Modulation Technique

A sinusoidal pulse width modulation (SPWM) is a typical pulse width modulation (PWM) technique. Compared to PWM technique, SPWM technique is by adding another signal which is a sinusoidal signal. The sinusoidal AC voltage $V_{ref}$ is compared with the high-frequency triangular carrier wave $V_c$ in real time to determine switching states for each switch of the inverter [14]. The two signals are the compared based on the following rule:

- Voltage reference $V_{ref}$ > Triangular carrier $V_c$ : positive side of switch is turned ON $\frac{V_{DC}}{2}$
- Voltage reference $V_{ref}$ < Triangular carrier $V_c$ : negative side of switch is turned ON $-\frac{V_{DC}}{2}$

The Fig. 5 illustrate the combination of two signals. The peak-to-peak value of the triangular carrier wave is given as the DC-link voltage $V_{DC}$. As this PWM technique uses a high frequency carrier wave to modulate the voltage, this type of PWM technique is known as carrier-based PWM technique. This carrier-based technique is called SPWM as the reference signal is in sine wave shape.

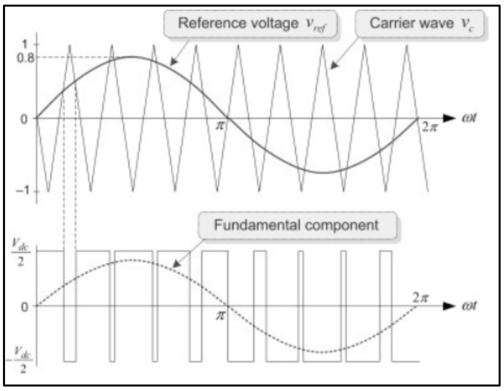


**Fig. 5 - Combination of sine wave signal and carrier signal**

The signal of carrier wave, $V_C$ can be configured in this SPWM technique. This includes the magnitude and frequency, and the amplitude of overlapping signal within two signals.

## 3. Result and Discussion

This chapter discusses the obtained results by using simulation software MATLAB SIMULINK R2016B and experiment result along with detailed analysis. The results are divided into several parts. The first part discusses the simulation and results which then become a guide for comparing it with experimental results. The output result including the output waveform of inverter, output voltage and THD percentage will be observed too. In the end, the experimental results are used to prove the operation principle of cascaded H-bridge multilevel inverter.

### 3.1 Simulation Implementation

While designing the inverter, there are few factors that need to be take into account. But the most important thing is the percentage of total harmonic distortion (THD) at the output of an inverter. Because of some of AC electrical appliances have different sensitivity, it requires a stable and reliable electrical source. Thus, in this section the output of inverter will be monitored and discussed more especially on the percentage of THD.

In this project, two main switching techniques are being applied in designing inverter which are PWM and SPWM that varies from 3-Level, 5-Level and 7-Level of Cascaded H-Bridge Multilevel Inverter. Firstly, the input of the switches is chosen between PWM and SPWM method. Then, the data will be observed and collected. The simulation is later continued by adding more level of the inverter. Lastly, all the data will be analyzed and concluded.

### 3.1.1 Pulse Width Modulation Technique

For PWM technique, the pulse width is adjusted according to the inverter level. The PWM is produced by using pulse generator in the MATLAB SIMULINK as shown in the Fig. 6. The output voltage waveforms for 3/5/7 level of Cascaded H-Bridge Multilevel Inverter with PWM switching technique with a frequency of 50 Hz are shown in the Fig. 7 below.

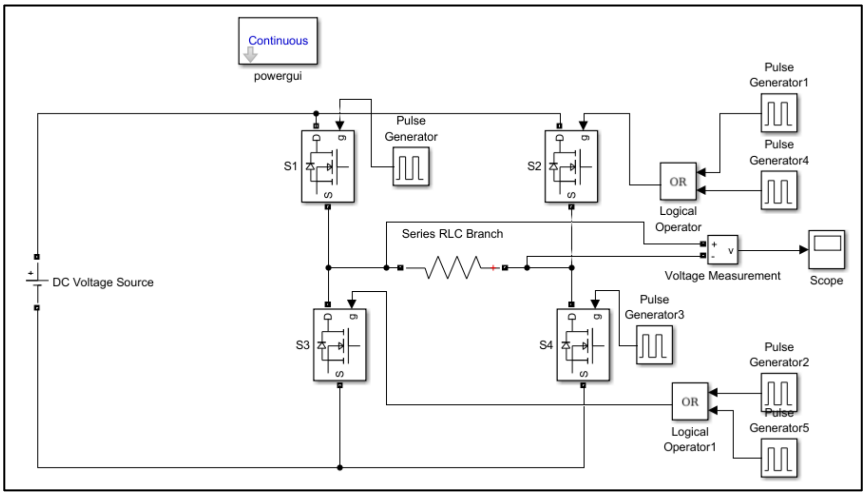
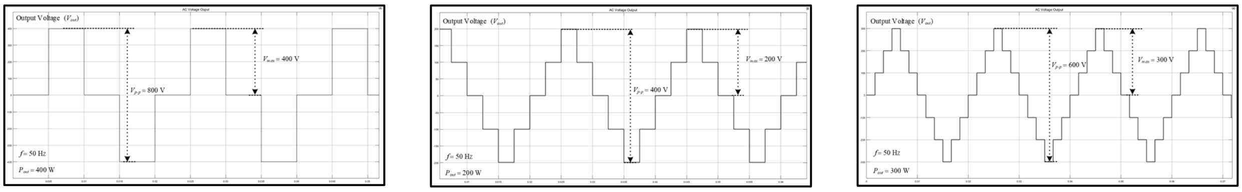


**Fig. 6 - General circuit setup of Cascaded H-Bridge Multilevel Inverter with PWM switching technique in MATLAB SIMULINK**



(a) (b) (c)

**Fig. 7 - Output voltage of (a) 3-Level (b) 5-Level (c) 7-Level Cascaded H-Bridge Multilevel Inverter with PWM switching technique**

The voltage THD reading for 3-level, 5-level and 7-level Cascaded H-Bridge Multilevel Inverter with PWM switching technique are 52.06 %, 29.98 % and 21.94 % respectively. The voltage THD reading will not be affected by the output voltage at any value. However, the voltage THD are decreasing when the inverter level is increasing.

### 3.1.2 Sinusoidal Pulse Width Modulation Technique

The Fig. 8 shows the general circuit setup to produce Cascaded H-Bridge Multilevel Inverter with SPWM switching technique in MATLAB SIMULINK, the pulses for the switches are generated by using repeating sequence and sine wave signals. Relational operator then compares these two signals to produce pulse width. The output voltage waveforms for 3/5/7 level of Cascaded H-Bridge Multilevel Inverter with SPWM switching technique with a frequency of 50 Hz are shown in the Fig. 9 below.

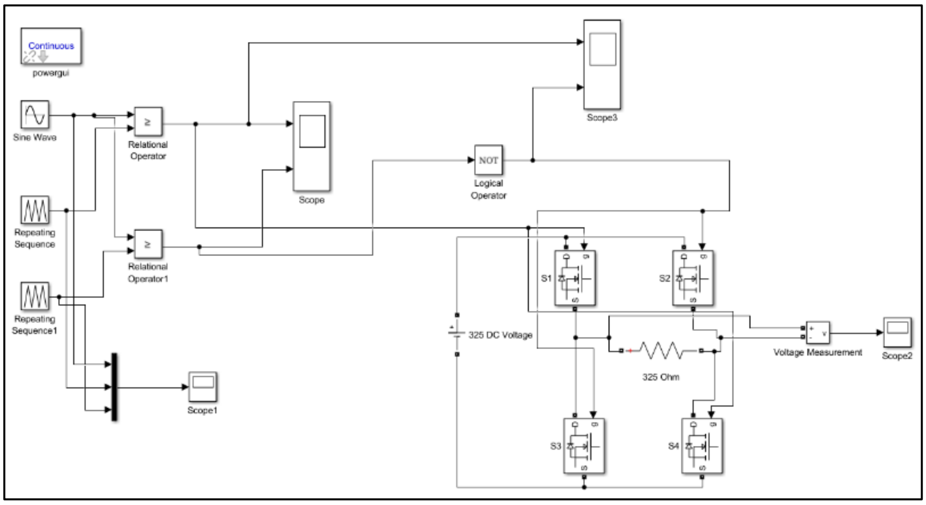
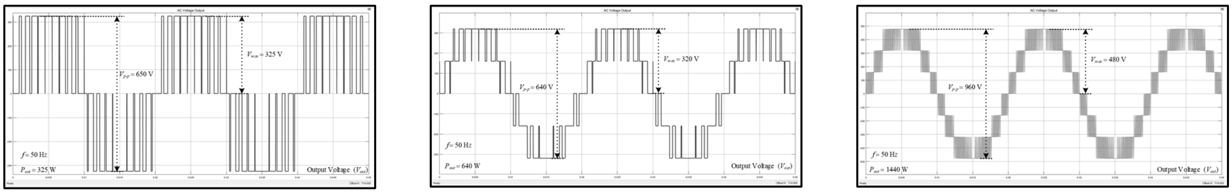


**Fig. 8 - General circuit setup of Cascaded H-Bridge Multilevel Inverter with SPWM switching technique in MATLAB SIMULINK**



(a) (b) (c)

**Fig. 9 - Output voltage of (a) 3-Level; (b) 5-Level; (c) 7-Level Cascaded H-Bridge Multilevel Inverter with SPWM switching technique**

The voltage THD reading for 3-level, 5-level and 7-level Cascaded H-Bridge Multilevel Inverter with PWM switching technique are 52.05 %, 26.84 % and 18.20 % respectively.

## 3.2 Experimental Setup

After all simulations are carried out, hardware testing is conducted to prove the theory discussed. However, after considering other factors such as number of semiconductor devices used as well as semiconductor losses and efficiency, the 5-Level Cascaded H-Bridge Multilevel Inverter is chosen with the PWM technique to perform in this experiment. The laboratory DC power supplies are used as $V_{DC1}$ and $V_{DC2}$ of the circuits. The desired output voltages are varies depending on the voltage measures before and after the implementation of a step-up transformer. Resistors and other household appliance are used as the load of the circuits while the semiconductor devices are MOSFETs. Table 1 shows the general parameters used in this experiment and Fig. 10 shows the experimental setup configuration.

**Table 1 - Parameters used in the experiment**

| Parameter | With Transformer | Without Transformer |
|---|---|---|
| Output Voltage | $24\ V$ | $230\ V_{rms}$ |
| Resistance load | $24\ \Omega$ | $400\ \Omega$ |
| Output power | $24\ W$ | $100\ W$ |
| Output current | $1\ A$ | $500\ mA$ |

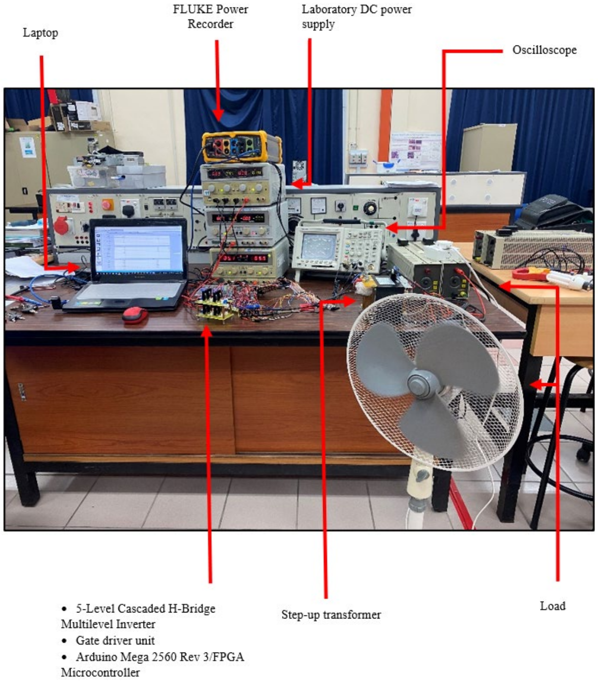
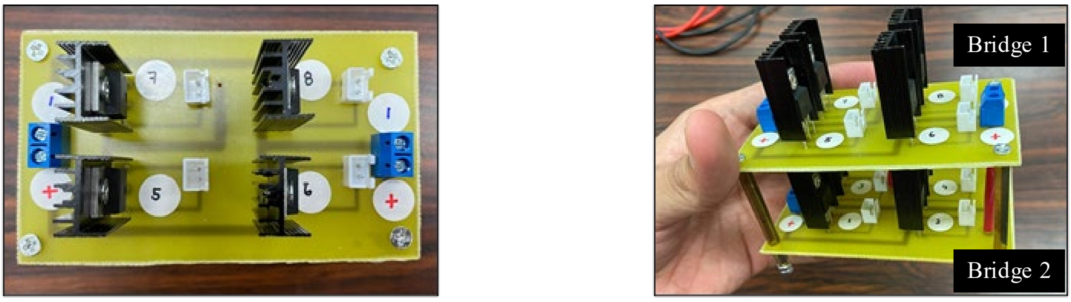


**Fig. 10 - Experimental setup configuration**

### 3.2.1 Circuit Design of 5-Level Cascaded H-Bridge Multilevel Inverter

A printed circuit board (PCB) is designed by using PCBWiz software. The PCB is used for 5-Level Cascaded H-Bridge Multilevel Inverter that consists of 2 voltage input, 1 voltage output 8 MOSFETs as well as input for gate driver unit. The MOSFETs are soldered on the PCB together with the heatsink for each MOSFET in order to keep it from overheating condition thus will damage itself. Fig. 11 shows the designated PCB for 5-Level Cascaded H-Bridge Multilevel Inverter circuit that are staged between Bridge 1 and Bridge 2.



(a) (b)

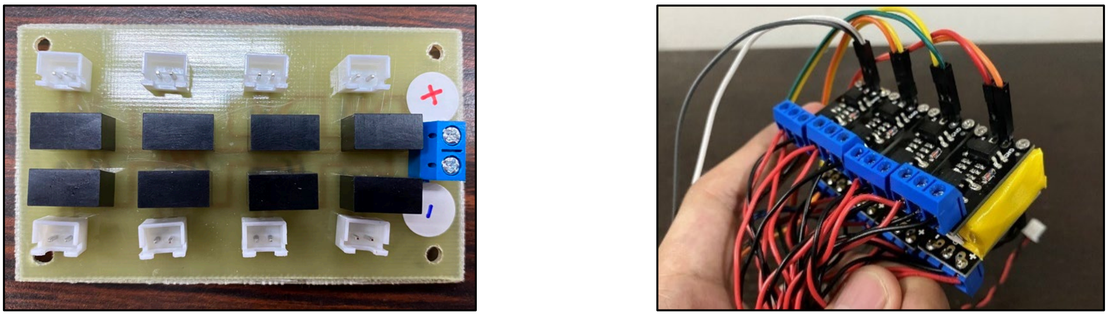
**Fig. 11 - PCB design for 5-Level Cascaded H-Bridge Multilevel Inverter (a) Top view; (b) Side view**

### 3.2.2 Microcontroller Unit

The PWM signals are generated using 2 types of microcontrollers which are Arduino Mega 2560 Rev 3 and Field Programmable Gate Arrays (FPGA). The coding and block diagram are designed to produce PWM switching signals with desired value of frequency. Due to limitation of hardware, the Arduino Mega 2560 Rev 3 only able to produce 60 Hz of frequency. However, the FPGA can be easily setup at 50 Hz as the microcontroller has a wider range of clock frequency. Both of the microcontrollers need to code through Arduino Nightly and Quartus Prime 21.1 for Arduino Mega 2560 Rev 3 and FPGA respectively.

### 3.2.3 Gate Driver Unit

In order to run and turn ON the MOSFETs properly, the Gate Driver Unit (GDU) must be used. This GDU will boost the input voltage which are coming from microcontroller units Arduino Mega 2560 Rev 3 or FPGA to reach minimum output voltage of 10 $V_{pk}$ to turn ON the MOSFETs. This GDU is a combination of isolated power supply and MOSFET control module. There are a total of 8 sets of MOSFET control modules with independent isolated power supply that were connected to gate pin and source pin of each MOSFET. Fig. 12 below shows the (a) Isolated 12 V DC – 12V DC converter PCB and (b) MOSFET control module. The PCB design of 1 W 12 V DC have 1 input for DC supply and 8 outputs of isolated DC supply that will feed into MOSFET control module.



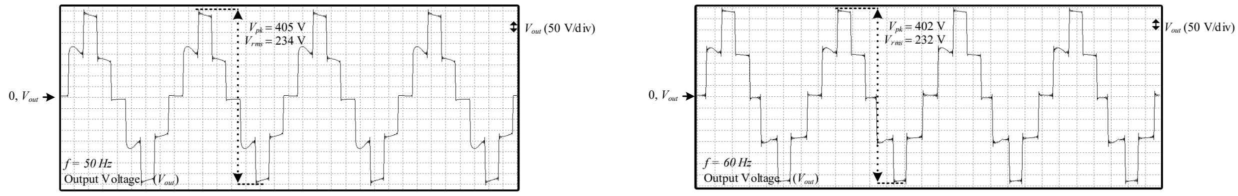
(a) (b)

**Fig. 12 - (a) Isolated 12 V DC – 12V DC converter PCB (b) MOSFET control module**

## 3.3 Experimental Result

To prove the operation principle of cascaded H-bridge multilevel inverter, the experiment is carried out based on the 5-Level Cascaded H-Bridge Multilevel Inverter. There is a fraction of experiment which are by using Arduino Mega 2560 Rev 3 which only has an ability to produce 60 Hz of frequency and 50 Hz of frequency for FPGA as a microcontroller to produce desired PWM signals output. The results were taken with the implementation of a step-up transformer. The main highlight of the experiment is to observe the output voltage level and THD at the output waveform.

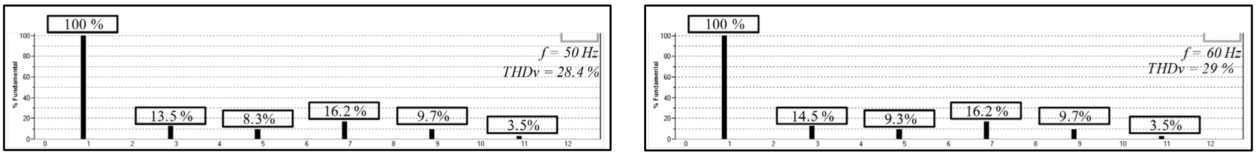
In the experiment, this 5-Level Cascaded H-Bridge Inverter was connected with a step-up transformer. The transformer has a turning ratio of 1:10, which theoretically produces an output voltage 10 times higher than input voltage. The input voltages at the inverter were increased to match out the output voltage at the transformer to produce approximately 230 $V_{rms}$. This inverter was then tested with and without a load. The results are taken as the output voltage ($V_{out}$), output current ($I_{out}$), voltage THD ($THD_v$), and current THD ($THD_i$) of the inverter.



(a) (b)

**Fig. 13 - 230 $V_{rms}$ AC output voltage waveform without load**
**(a) FPGA (b) Arduino**

Fig. 13 represents the output voltage waveform of the inverter using the FPGA and Arduino Mega 2560 microcontrollers. The inverter using FPGA microcontroller produces a 405 $V_{pk}$ and 235 $V_{rms}$ at 50 Hz of frequency. While the inverter uses an Arduino microcontroller, it produces a 402 $V_{pk}$ and 232 $V_{rms}$ at 60 Hz of frequency.



(a) (b)

**Fig. 14 -230 $V_{rms}$ AC output voltage without load THD observation**
**(a) $THD_v$ of FPGA (b) $THD_v$ of Arduino**

The voltage THD was then measured and taken as shown in the Fig. 14. As observed, the inverter using FPGA and Arduino as the microcontrollers produced a 28.4 % and 29 % voltage THD, respectively. The inverter using an FPGA microcontroller has a better voltage THD than Arduino, which is 0.6 % lower.

## 3.4 Number of Semiconductor Devices and Efficiency Analyses

The Fig.15 below shows the graph voltage THD vs the level of the inverter. This observation was taken from the simulation of 3-Level, 5-Level and 7-Level Cascaded H-Bridge Multilevel Inverter using PWM and SPWM switching technique in MATLAB Simulink software. As observed in the graph below, the trend of voltage THD is decreasing along with the inverter level applied. At first, the voltage THD of inverter using PWM and SPWM switching technique in 3-level both has the same voltage THD which is 52 %. Furthermore, once the inverter is increased to 5-level, the inverter with SPWM switching technique perform better than inverter with PWM switching technique which is read at 26.84 % and 29.98 % respectively. However, the voltage THD is significantly improved when the inverter level is at the 7-level. The inverter with SPWM switching technique performed 17 % better than PWM inverter. This is proved by the reading of voltage THD of SPWM inverter is 18.2 % and PWM inverter is 21.94 %. The lower the voltage THD, the better the size, has low volume and reduce the circuit complexity.

However, the higher the inverter level produces lower voltage THD, but it causes a lot of complexity in the designing the inverter. For instance, the 3-level of inverter only use a single of DC input voltage and 4 of semiconductor devices, 5-level of inverter use a twice the DC input voltages compared to 3-level and use 8 of semiconductor devices, 7-level of inverter use a triple the DC input voltages compared to 3-level of inverter and use the most semiconductor devices which is 12 semiconductor devices. This limitation causes the inverter to have much more DC input voltage supply and semiconductor device as the inverter level increases.

The other point is that although the inverter with SPWM switching technique performs better than PWM inverter, the switching technique of SPWM is much more complicated than PWM inverter. The SPWM inverter operates by comparing two signals, sine wave and carrier wave signals. While the PWM inverter only gives a standard square pulse signal. This difference causes the inverter with SPWM switching technique to operates less efficient than inverter with PWM switching technique as the switching losses tend to happen at semiconductor devices. The higher the semiconductor devices, the higher the switching loss occurred.

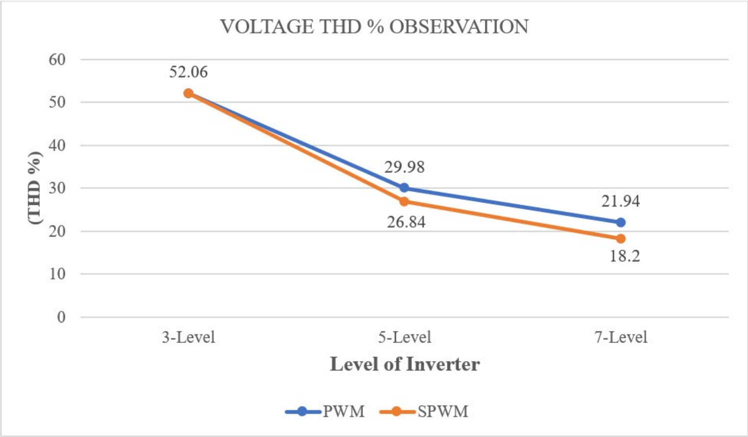


**Fig. 15 - Voltage THD % against level of inverter based on the simulation results**

## 3.5 THD Result Evaluation Analyses

The observed experimental THD results was then collected and displayed in a graph as shown in the Fig.16 below. The voltage THD for both inverters using FPGA microcontroller operated at 50 Hz and Arduino microcontroller operated at 60 Hz has similar voltage THD trend. When the inverter was fed with 24 V DC voltage input and produced 24 $V_{pk}$ voltage output, the voltage THD was measured 28.4 % and 28.5 % for inverter running at 50 Hz and 60 Hz of frequency. The voltage THD is then continued to measure when the inverter produces 230 $V_{rms}$ voltage output, which again has a reading of 28.4 % and 29 % voltage THD before connecting to the load and both at a 30 % of voltage THD when the inverter operated in either 50 Hz or 60 Hz of frequency. This proves that the voltage THD does not significantly differ when the inverter is operated at 50 Hz or 60 Hz of frequency. Hence, some electrical equipment can work and function well either in 50 Hz or 60 Hz in a country like Malaysia because this frequency difference does not affect the waveform quality. However, the current THD for both inverters using FPGA and Arduino can be seen as slightly different when the circuit was connected to the step-up transformer. The inverter using FPGA microcontroller has a better reading of 32 % of current THD and 2 % higher when the inverter uses Arduino microcontroller. This may cause by the step-up transformer that was not designed to work well other than pure sine AC waveform.

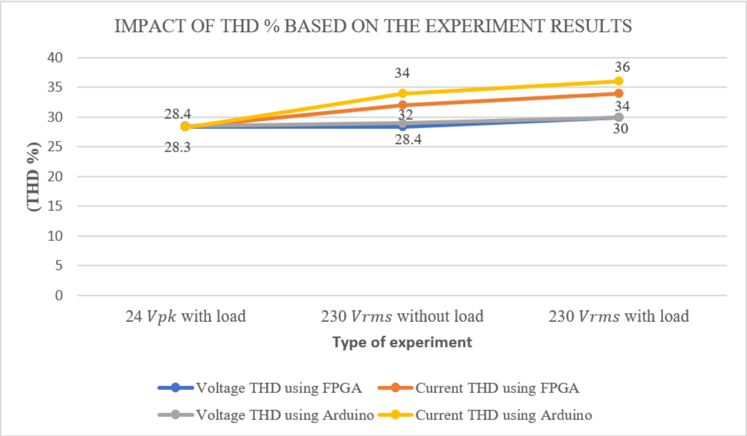


**Fig. 16 - THD % against Type of experiment**

## 4. Conclusion

In a nutshell, this study shows all the inverter results with PWM and SPWM switching techniques, starting from 3-level and up to 7-Level Cascaded H-Bridge Multilevel Inverter. The result is taken and compared between multiple levels and experiments to prove the concept of this Cascaded H-Bridge Multilevel Inverter. The level of Cascaded H-Bridge Multilevel is simulated by using MATLAB Simulink software from 3-level, 5-level and 7-level of Cascaded H-Bridge Multilevel Inverter with PWM switching technique where the voltage THD is at 52.06 %, 29.98 % and 21.94 % respectively. The voltage THD is better when the SPWM switching technique controls the Cascaded H-Bridge Multilevel Inverter. The value is 52.05 %, 26.84 %, and 18.20 % for 3-level, 5-level and 7-level Cascaded H-Bridge Multilevel Inverter with SPWM switching technique respectively. However, due to the complexity and efficiency of the inverter, it can be seen that the inverter with 5-level is the most suitable and practical to be applied in this portable power pack application. Thus, the 5-Level Cascaded H-Bridge Multilevel Inverter with PWM switching technique is the most suitable as it balances the number of semiconductor devices and the number of DC voltage input that affects the semiconductor losses, efficiency and THD compared to other levels of inverter.

## Acknowledgement

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## References

[1] Tian, Y. B., et al. "Development of portable power monitoring system and grinding analytical tool." *Journal of Manufacturing Processes* 27 (2017): 188-197.

[2] Rashid, Muhammad H. *Power electronics: circuits, devices, and applications*. Pearson Education India, 2009.

[3] Sahu, Biranchinath, and Gabriel A. Rincón-Mora. "A high-efficiency, dual-mode, dynamic, buck-boost power supply IC for portable applications." *18th International Conference on VLSI Design held jointly with 4th International Conference on Embedded Systems Design*. IEEE, 2005.

[4] Baker, Richard H., and Lawrence H. Bannister. "Electric power converter." U.S. Patent No. 3,867,643. 18 Feb. 1975.

[5] Baker, Richard H. "High-voltage converter circuit." U.S. Patent No. 4,203,151. 13 May 1980.

[6] Nabae, Akira, Isao Takahashi, and Hirofumi Akagi. "A new neutral-point-clamped PWM inverter." *IEEE Transactions on industry applications* 5 (1981): 518-523.

[7] Fracchia, M., et al. "Optimized modulation techniques for the generalized N-level converter." *PESC'92 Record. 23rd Annual IEEE Power Electronics Specialists Conference*. IEEE, 1992.

[8] Meynard, T. A., and Henry Foch. "Multi-level conversion: high voltage choppers and voltage-source inverters." *PESC'92 Record. 23rd Annual IEEE Power Electronics Specialists Conference*. IEEE, 1992.

[9] Siddique, Marif Daula, et al. "A new cascaded asymmetrical multilevel inverter based on switched dc voltage sources." *International Journal of Electrical Power & Energy Systems* 128 (2021): 106730.

[10] Swaroop, Savita, et al. "Harmonic Reduction in Reduced Power Switch Multilevel Inverter Using Genetic Optimization." *2021 Asian Conference on Innovation in Technology (ASIANCON)*. IEEE, 2021.