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# Simulation of Indirect DC-AC-DC Converter Using Cascaded H-Bridge Multilevel Inverter

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**Abstract**

This paper aims to design and analyze the indirect DC-AC-DC converter with multiple inputs that generates higher DC voltage output by using several cascaded H-bridge multilevel inverters. An intermediate AC stage is adopted for the purpose to rectify the high voltage AC level from H-bridge inverter using a three-phase controlled rectifier. A switching algorithm has been developed to obtain the best switching time and duration based on the sinusoidal equation. By optimizing the multilevel concept and equal voltage distribution, the overall total harmonic distortion is reduced, and the overall efficiency is high. This study also comprehensively analyzes the converter's performance under different number of cascaded H-bridge inputs. It is shown that at a high number of cascaded H-bridge, the voltage THD value decrease to 7.57% and the efficiency remains high at above 90%.

## 1. Introduction

DC-to-DC energy conversion can be executed using DC Choppers. This form of DC-to-DC conversion is a direct energy conversion as it does not require an intermediate stage. It is simpler in construction but with limitation as the output power is within certain range of its input value depending on the types of DC chopper. Three most common DC Choppers are Buck, Boost, and Buck-Boost. Respectively, based on the circuit, the DC output voltage of the Chopper can be lower, higher, or both lower and higher than the input DC voltage [1].

Alternatively, the DC-to-DC conversion can be executed indirectly by converting to an AC stage [2, 3]. By employing indirect energy conversion of DC-AC-DC using an intermediate stage of inverting power from DC to AC and then rectifying back from AC to DC, the low voltage supplied by the H-bridge cascaded multilevel inverter can be increased to a higher DC value. This is an advantageous approach as it can be applied to PV solar module [4] as the input to produce high DC power for the use of Electric Vehicle (EV) for example or for any high-power DC applications. The capability to convert energy form is of utmost importance in various applications, including renewable energy systems [5], electric vehicles [6], battery-operated devices, and industrial processes.

The purpose of this work is to investigate the feasibility of increasing the low DC voltage to a higher DC voltage via an intermediate AC power. This is important due to the increased interest by the public and advancement by the manufacturer of electric vehicle. Electric vehicle can be charge using AC power but the charging time is slow compare to a faster high DC voltage. Charging time becomes shorter when charging at high DC power. The intermediate AC power is significant as the low DC voltage can be accumulated from PV solar panels or batteries and then added them up before converting the power back to DC high power.

In this project, the performance of the proposed indirect DC-AC-DC conversion is simulated and investigated. The proposed circuit make use of a cascaded H-bridge as the input of DC supply. With the H-bridge connected in cascaded, multiple DC low voltage supply is being added and converted to a higher AC value which is then converted back to DC by the rectifier. The proposed circuit is designed for three-phase system. With this proposed

circuit arrangement, transformer is not needed, thus can reduce the cost and size of the converter. The switching algorithm of the cascaded H-bridge multilevel inverter is designed based on the sinusoidal equation.

## 2. Multilevel Inverter

Multilevel inverters (MI) have attracted much interest especially in applications involving high voltage and high power such as utility and large motor drive applications [7]. This increased recognition of multilevel inverter is due to the limitations of the conventional two-level output inverters in handling high power conversion [8]. There are three main Multilevel Inverters; Neutral-Point-Clamped (NPC), Flying Capacitor (FC) and Cascaded H-Bridge (CHB) Multilevel Inverter [9]. NPC and FC Multilevel Inverter involve elaborate and complicated circuit design especially at high number of level as it utilizes an array of series switching devices to perform the power conversion in a small increase of voltage steps. It synthesizes the staircase voltage from several levels of DC capacitor voltages [10]. The setback of these structures is as the number of levels are increased, the amount of switching devices and other components is also increased tremendously. This will make the inverter becoming more complex and costly. A complicated controller with a proper related gate drive circuit is needed to control and synchronize the switching devices.

While CHB is based on the series connection of single-phase inverters with separate DC sources. The resulting phase voltage is synthesized by the addition of the voltages generated by the different cells. Each single-phase full-bridge inverter generates three voltage levels at the output, i.e. $+V_{dc}$, 0 and $-V_{dc}$. This inverter can avoid extra clamping diodes of voltage balancing capacitors and it needs separate DC sources for real power conversion.

## 3. Design of Indirect DC-AC-DC Converter

This section describes the design process of the proposed indirect DC-AC-DC Converter. It starts with the construction of the Cascaded H-Bridge, calculation of switching time and duration, switching algorithm and three-phase controlled rectifier switching algorithm. Fig. 1 show the block diagram of the proposed circuit design.

The proposed circuit design consists of 3 three-phase cascaded H-bridge inverters that convert the DC voltage to AC voltage and then connected to a three-phase controlled rectifier that will convert back to DC voltage. There are three phases in total which includes phase A, phase B and phase C. These three phases will be connected as the input to the three-phase controlled rectifier. Several H-bridge inverters are connected in cascade to become multilevel inverter that can converts multiple inputs of DC input voltage into a higher AC voltage. The number of H-bridge inverter is investigated from 1 to 5. The input to the H-bridge can come from several DC voltage supply or combination of DC supply, batteries, or any renewable energy supply. Table 1 shows the converter parameters used in this proposed circuit.

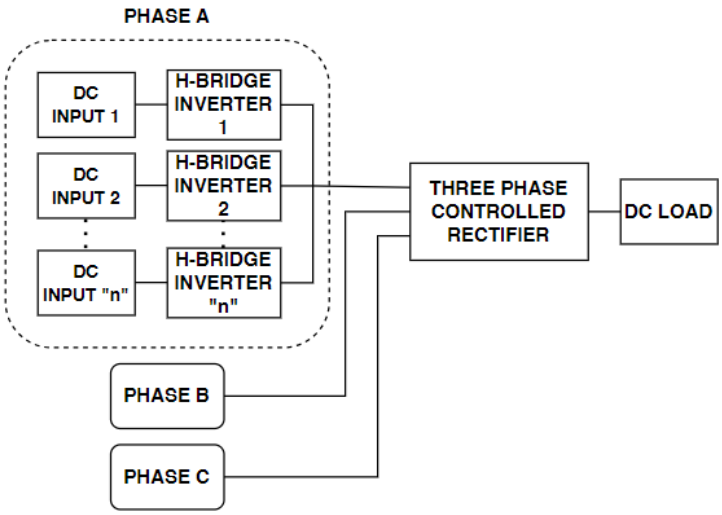


**Fig. 1** *Block diagram of the proposed circuit design*

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**Table 1** *Converter parameters*

| | |
|---|---|
| Frequency | 50Hz |
| DC input voltage | 20V |
| Number of inputs | 5 |
| Load value | 10Ω |

The scope of this work is to simulate the proposed circuit design using Matlab/Simulink software and applying the proposed switching algorithm to the Cascaded H-bridge Multilevel Inverter in order to increase the input DC voltage to a higher DC value via an intermediate AC stage. Insulated Gate Bipolar Junction Transistors (IGBTs) are selected as the switching devices and pulse generators block as the triggering signals.

MATLAB Simulink simulation for power electronic converters provide sufficient efficiency as the proposed circuit model is medium in complexity, components used are modelled as basic switching model and the solver setting is set at variable step. Overall, MATLAB Simulink is widely used in industry and academia for power electronic converter simulation due to its flexibility, extensive libraries, and integration with MATLAB for analysis and design. The accuracy achievable with Simulink simulations can be very high when appropriate models and simulation settings are used, but it ultimately depends on the user's expertise in modeling and simulation practices. As this work is to investigate the feasibility of increasing the low DC voltage to a higher DC voltage via an intermediate AC power, the software is suitable.

## 3.1 Design of the Cascaded H-Bridge Multilevel Inverter Circuit

Fig. 2 illustrates a Simulink model of a single cell H-bridge inverter which contains 4 IGBTs that are controlled by the gate signals (S1, S2, S3 and S4) for its operation. This single cell H-bridge forms as one subsystem block of H-bridge inverter. IGBT switches are selected due to their high voltage and current handling capabilities in practical applications. The IGBTs can withstand high voltage and current levels, making them suitable for applications that requiring high power levels. In addition, pulse generators are used to create the switching signal for the gate signals. The gate signal needs a suitable control strategy to obtain a good AC conversion. Therefore, switching time and duration are calculated to obtain an accurate value to achieve a low Total Harmonic Distortion (THD) value.

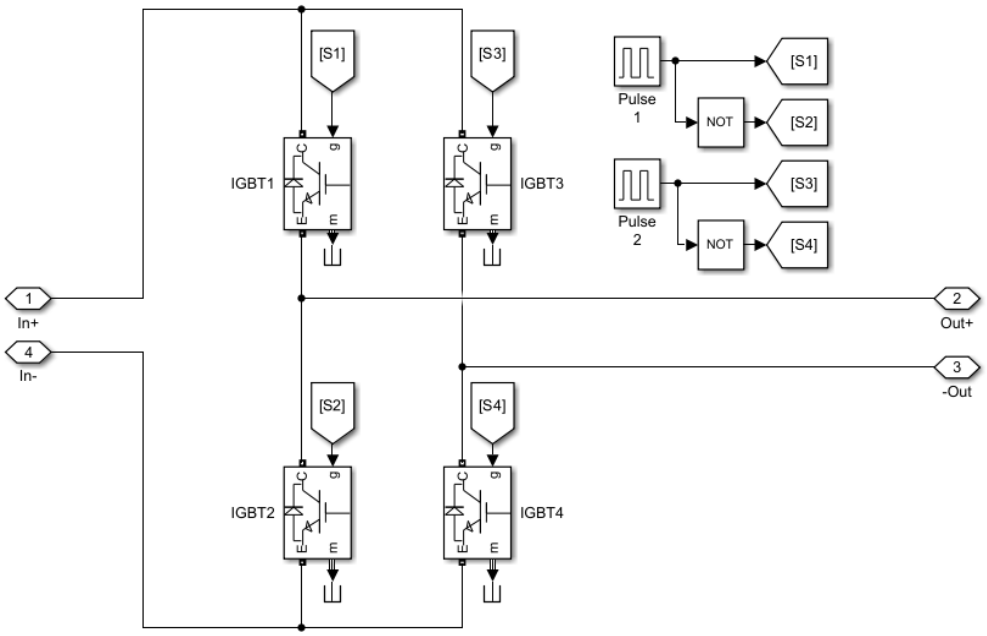


**Fig. 2** *Simulation model of a single cell H-bridge inverter*

Cascaded H-bridge multilevel inverters consist of multiple numbers of H-bridge inverters. Fig. 3 shows two subsystem block of H-bridge inverters (HBA1 and HBA2) that are cascaded to form a multilevel inverter. The cascading is formed by connecting negative output terminal of the first cell to the positive output terminal of the second cell. This will result in a 5-level outputs represented as +2Vdc, +Vdc, 0, -Vdc, and -2Vdc in the form of

stepped AC. The AC output level will differ based on the number of cascaded inverters. In this work, up to 5 cascaded H-bridge inverters is investigated to evaluate its performance.

One of the advantages of using a cascaded H-bridge inverter is that it has higher voltage capability. A multilevel inverter can cascade the low DC input voltage into a higher AC output voltage. Plus, it can generate higher output voltage levels without requiring extremely high voltage-rated components. By using a series of lower voltage-rated devices, they can achieve higher voltage capability, making them suitable for high-voltage applications such as high-power electric drives, renewable energy grid integration, and high-voltage direct current (HVDC) transmission systems.

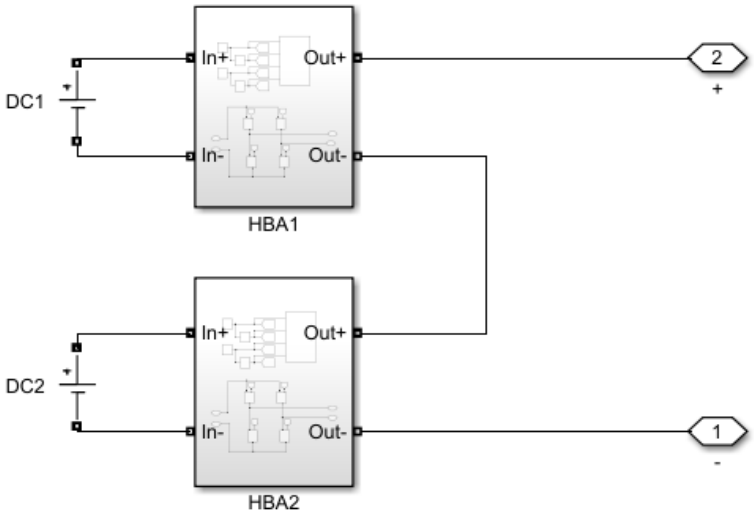


**Fig. 3** *Subsystem block of cascaded H-bridge multilevel inverter*

In comparison to the other multilevel inverters that are Neutral Point Clamped and Flying Capacitor, cascaded H-bridge inverters use fewer switching devices for the same voltage level, which also reduced the voltage unbalancing problem [6]. Since the voltage output are connected in series, the multilevel inverter output combines the cell voltage outputs [2]. In addition, the AC harmonic component relies on the voltage quantization level in the typical switching scheme, a higher level multilevel cascaded voltage source inverter will always yield a less distorted output. It is determined that as the level of cascading increases, the harmonic distortion decreases [10].

Fig. 4 shows the simulation model of three-phase controlled rectifier circuit. The rectifier receives a three-phase AC input power supply provided by the three sets of cascaded H-bridge multilevel inverter. There are three phases labelled Phase A, Phase B, and Phase C. Each phase of the AC input is connected in series with IGBTs. By triggering the IGBTs selectively, the rectifier can regulate the AC power transferred to the DC side. The control strategy for a three-phase controlled rectifier can be controlled by adjusting the firing angles of the IGBTs. Modulating the firing angles makes it feasible to control the average output DC voltage.

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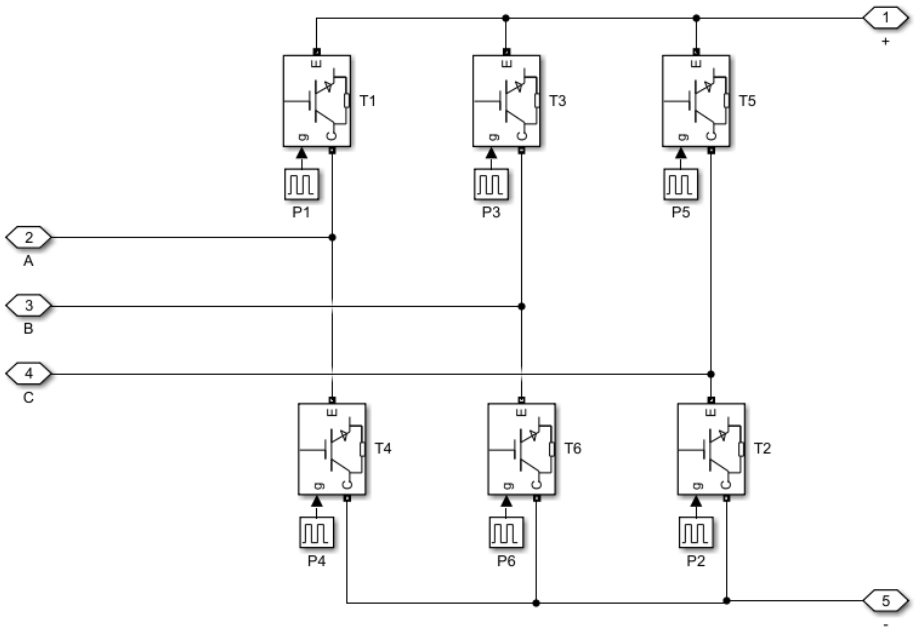


**Fig. 4** *Simulation model of three-phase controlled rectifier circuit*

## 3.2 Calculation of Switching Time and Duration of Cascaded H-Bridge Multilevel Inverter

The control strategy of an H-bridge inverter is crucial for achieving optimal performance and functionality in the inverter system. It plays a vital role in regulating voltage and frequency, ensuring compatibility with the load requirement. The control strategy generates a high-quality output waveform that closely resembles a sinusoidal wave, minimizing distortion and harmonics. In order to avoid too much stress on one switching device, the duty cycle for each switching device needs to be distributed evenly. This will help in temperature distribution among the switching devices to be more uniform, while enhancing the system reliability, efficiency, and safety.

To achieve these, several formulas have been derived from the general sine equation to calculate the switching time and duration required for each IGBTs. Equation [1] is the general sine equation, V(t) to be the basis for deriving the equation to calculate the triggering time delay.

$$V(t) = A \sin 2\pi f t \tag{1}$$

where, $V(t)$ = instantaneous voltage, $A$ is the magnitude of cascaded CHB, $f$ is the frequency and $t$ is the instantaneous time.

Then, the switching time, $t_n$ and midpoint voltage, $V_{mid}(t)$ are given by Equation [2] and [3] respectively.

$$t_n = \frac{sin^{-1}\left(\frac{V_{mid}(t)}{A}\right)}{2\pi f} \tag{2}$$

$$V_{mid}(t) = \frac{V_{dc}}{2} + (n_{inv} - 1)V_{dc} \tag{3}$$

where, $V_{dc}$ is the DC input voltage of each H-bridge and $n_{inv}$ is the H-bridge inverter's number. Inverter's number corresponds to voltage step stage starting from x-axis.

Equation [4] and [5] is the duty cycle, $d$ and the duty cycle or pulse width percentage of inverter "n" for half cycle of operation, $D_{n\_half}$.

$$d = \frac{t_{on}}{T} x\ 100 \tag{4}$$

$$D_{n\_half} = \left[\frac{T}{2} - \left(t_n + t_{n_{max}+1}\right) x\ 100\right] / T \tag{5}$$

where the $t_{on}$ is the duration during which the switching device is turned on or conducting current, $T$ is period and $t_{n_{max}+1}$ is the time of flip of $t_{on}$.

## 3.3 Cascaded H-Bridge Multilevel Inverter Switching Algorithm

Fig. 5 indicates the strategy on how the duty cycle for 5 input converter is distributed. The duty cycle can be determined by calculating the switching time, $t_n$ for the switching device to trigger on and off. The duty cycle can be calculated based on Equation [4] and [5]. Consequently, it is necessary to first calculate the time delay for the switching devices. This switching signal is activated at the midpoint of the input voltage. For example, if the DC input voltage is 20V, the triggering signal, $t_1$ should be initiated at the 10V point of its the sinusoidal waveform. In the case of two cascaded inputs, each with a DC voltage equal to 20V, the triggering signal for the second input, $t_2$ is activated at the midpoint between the voltages of the two inputs. In this example, the midpoint voltage would be 30V, which lies between the 20V from the first input and the 40V from the second cascaded input. The switching time is calculated from $t_1$ till $t_{10}$ starting from the rising positive voltage to falling positive voltage.

The pure sinusoidal wave is going to be the reference for switching the cascaded H-bridge multilevel inverters. Equation [2] has been derived from general sine equation to calculate the switching time, $t_n$ for triggering the inverter. While Equation [3] has been developed to determine the voltage at midpoint between the voltages of the two inputs. By combining these two equations, the switching time for triggering the cascaded H-bridge inverter that closely resembles a sinusoidal wave can be calculated as shown in Fig. 6 where it shows the switching time of five inputs cascaded H-bridge multilevel inverter.

Equation [5] is developed to calculate the duty cycle for the positive or negative half cycle of each inverter. The time delay and the duty cycle obtained is used as a parameter for the pulse generator to generate the signal to the IGBT's gate. In order to maintain symmetry and balance in the waveform, the duty cycle for the negative half cycle is set to the same value as the duty cycle for the positive half cycle. This is achieved through a strategy where the triggering time for the duty cycle on the negative half cycle is intentionally delayed by half of the period. By delaying the triggering time, the duty cycle for the negative half cycle aligns with the positive half cycle, ensuring equal duty cycles for both halves of the waveform. For example the first inverter pulse width will be $(((0.02/2) - t_1 - t_6)x100)/0.02=30.5841\%$. Table 2 shows the time delay and pulse width of the switching signals.

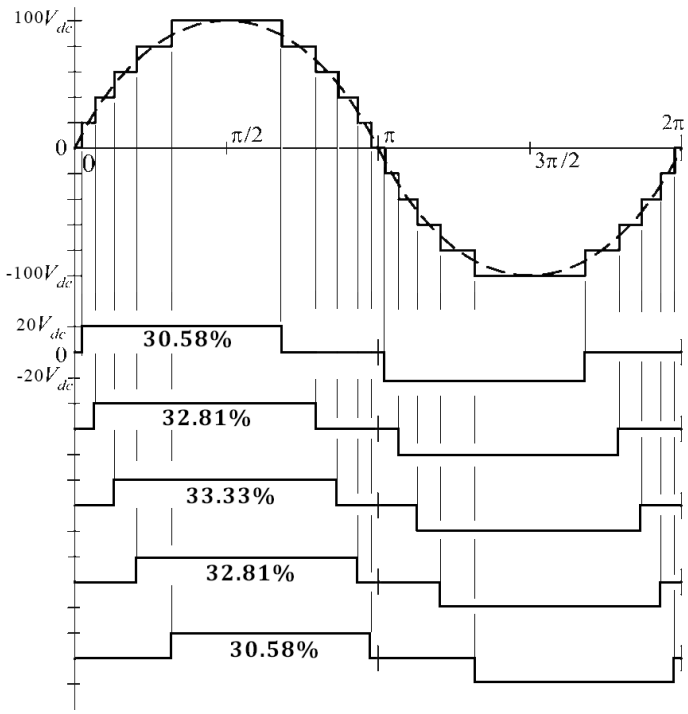


**Fig. 5** *Switching algorithm for cascaded h-bridge multilevel inverter*

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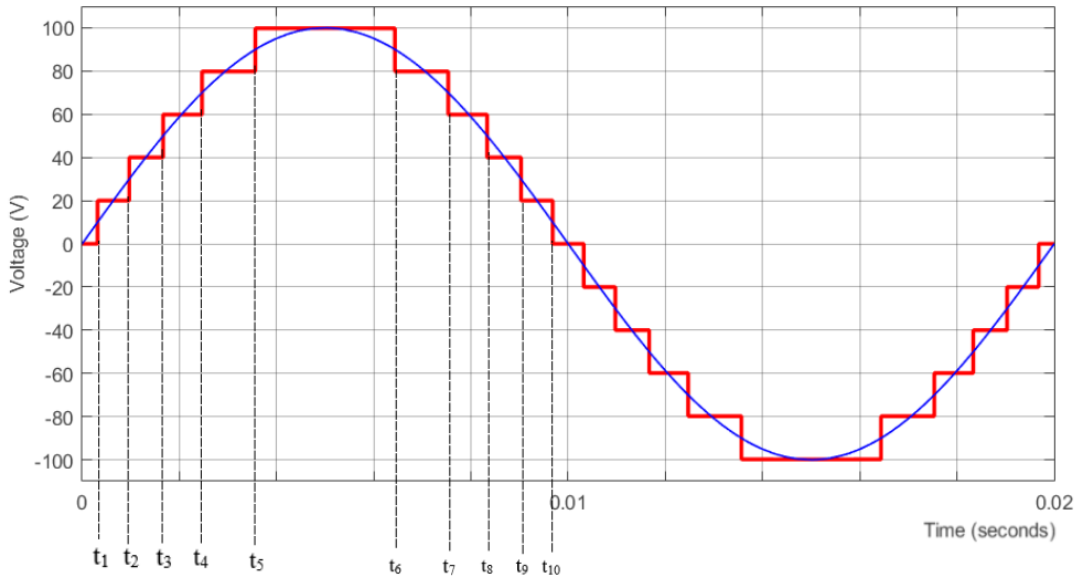


**Fig. 6** *Switching time for five inputs of cascaded H-bridge inverter*

**Table 2** *Time delay and pulse width of the switching signals*

| Number of H-bridge input | Time delay of the IGBT switches | | Pulse width for half cycle (%) |
|---|---|---|---|
| | S1 & S2 | S3 & S4 | |
| 1 | 0.00032s | 0.01032s | 30.5841 |
| 2 | 0.00097s | 0.01097s | 32.8098 |
| 3 | 0.00170s | 0.01170s | 33.3333 |
| 4 | 0.00250s | 0.01250s | 32.8098 |
| 5 | 0.00360s | 0.01360s | 30.5841 |

## 3.4 Three-phase Controlled Rectifier Switching Algorithm

The switching algorithm for the three-phase controlled rectifier is based on Fig. 7, where the duty cycle for each switching device (IGBT) is 33.3333% or equal to 120° of the cycle, respectively. The same or nearly identical duty cycle will avoid too much stress on a single switching device. A three-phase controlled rectifier switching algorithm determines the sequence and timing of triggering the IGBTs to perform the desired control of the rectification operation. The three-phase rectifier conducts the line voltage as its output, which is generally higher than the phase voltage. The operation of the three-phase controlled rectifier is described based on the firing angles and the triggering of the IGBTs, T1, T2, T3, T4, T5 and T6.

Switches T1 and T6 are turned on at the angle of 30° until 90°. This configuration allows them to conduct at the highest line voltage period between phases A and B. During this period, the rectifier converts the AC input voltage from phases A and B into a positive DC output voltage. At the angle of 90° to 150°, switches T1 and T2 are turned on. This configuration enables the rectifier to conduct the negative portion of the line voltage between phases C and A. However, since the AC waveform is reversed during this period due to the connection, the rectifier effectively converts it into a positive DC output voltage, providing a positive voltage value to the load.

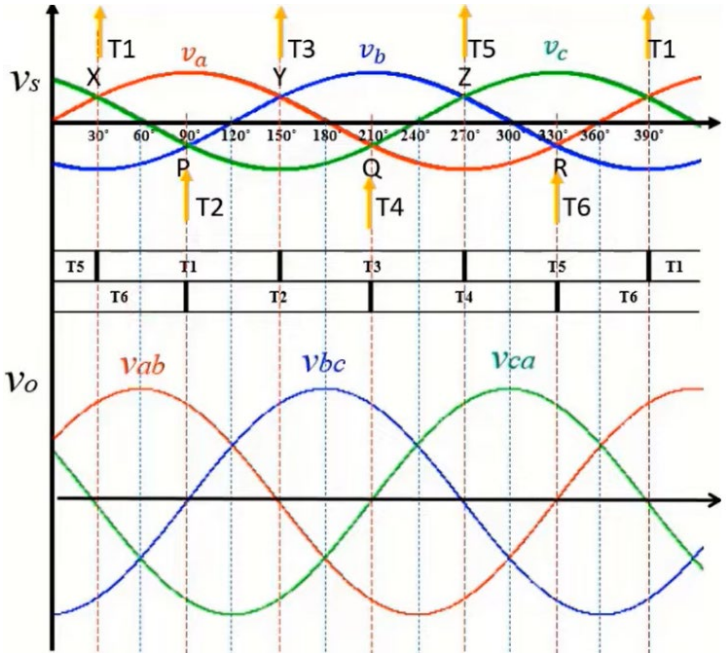


**Fig. 7** *Three-phase rectifier waveform and switching time*

At angles 150° to 210°, switches T2 and T3 are turned ON, allowing the rectifier to conduct the line voltage between phases B and C. During this period, the rectifier converts the AC input voltage BC into a positive DC output voltage. Following that, between angles 210° and 270°, switches T3 and T4 are turned ON. This configuration enables the rectifier to conduct the negative line voltage AB. Nevertheless, through the rectification process, the rectifier effectively converts this negative voltage into a positive DC output voltage, providing a positive value to the load.

Continuing the cycle, from angle 270° to 330°, switches T4 and T5 are turned ON, allowing the rectifier to conduct the line voltage between phases C and A. Again, the rectifier converts this AC voltage CA into a positive DC output voltage. Finally, from angle 330° to 390°, switches T5 and T6 conduct the negative line voltage BC. As before, the rectifier reverses this negative voltage and converts it into a positive DC output voltage. This repeating cycle ensures that all line voltages (AB, BC, and CA) are properly rectified and converted into positive DC output voltage. By carefully controlling the timing and conduction of the switches, the rectifier provides a continuous and stable DC output to the load.

## 4. Results and Discussions

Fig. 8 shows the overall circuit diagram of Simulink's simulation for the DC-AC-DC converter. The parameters like voltage waveforms, current waveforms, and other signals can be monitored using the scope, which is crucial to understanding the behavior of the DC-AC-DC converter during the simulation. The three-phase CHB multilevel inverter, three-phase controlled rectifier and load are indicated in the Figure in dotted line.

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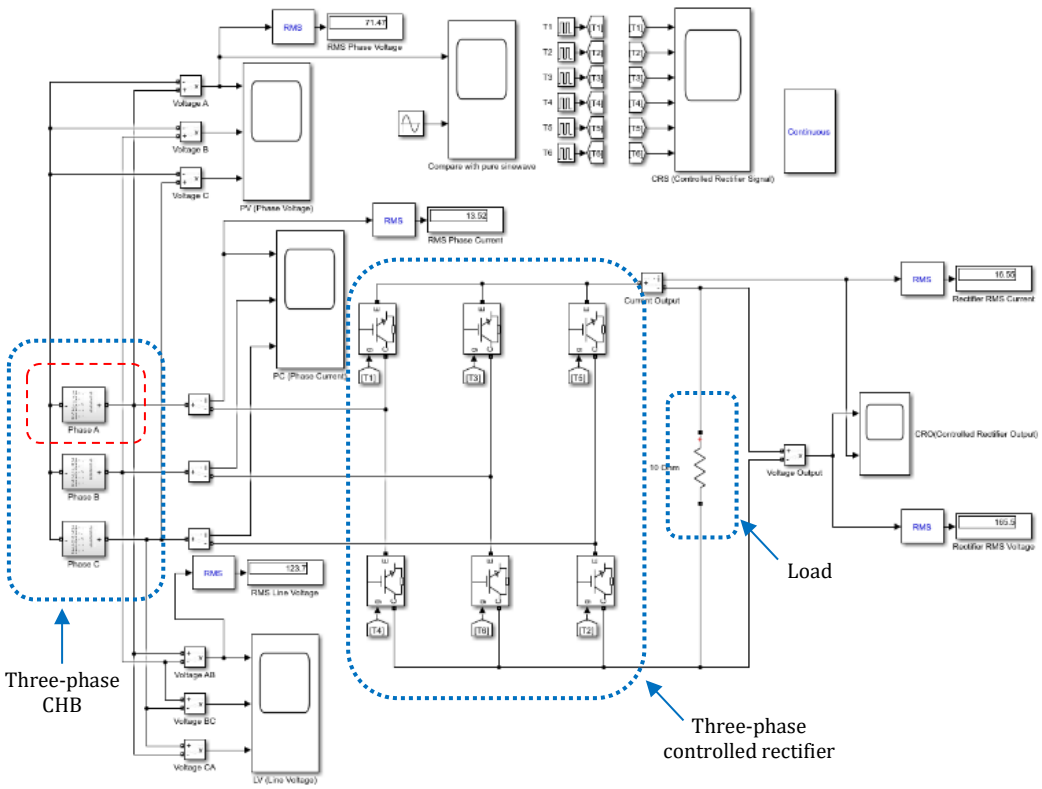
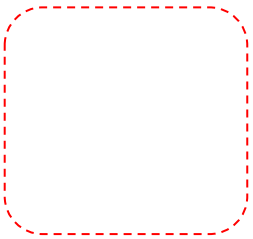



**Fig. 8** *Proposed indirect DC-AC-DC converter circuit diagram*

Fig. 9 shows the detailed simulation model of 5 cascaded H-bridge multilevel inverter for phase A as indicated its location in Fig. 8 in dashed line. This circuit is repeated for Phase B and C. While Fig. 10 shows the output voltage from each H-bridge multilevel inverter at Phase A accordingly. As it can be seen in Fig. 10, each H-bridge has the same waveform but phase shifted from each other in order to produce the staircase waveform of multilevel inverter.

Fig. 11 exhibits the three-phase output phase voltage obtained from the five inputs cascaded H-bridge inverter using the developed switching algorithm. This algorithm has resulted in an staircase sine waveform. Furthermore, by employing multiple cascaded inverters, the voltage levels have been increased, reducing harmonic content and voltage distortion in the output waveform.

According to IEC61000-3-4, IEC61000-3-6 and IEEE519-92, the maximum permissible harmonic voltage is 5% while the maximum permissible harmonic current is 16%. By referring to Table 3, the voltage THD percentage decreases as the number of cascaded inverters increases. The voltage THD for five inputs converter is 7.57% which is still quite high. One common approach to address this issue is incorporating a smoothing capacitor into the circuit. The role of the smoothing capacitor is to mitigate the variations and irregularities in the waveform, resulting in a smoother output with reduced Total Harmonic Distortion (THD). However, this circuit design excludes the installation of a smoothing capacitor. By excluding the smoothing capacitor, the project aimed to examine and understand the pure response of the system without any additional filtering or waveform shaping. It is essential to acknowledge that excluding the smoothing capacitor may result in a higher THD and potentially introduce some distortion or irregularities in the output waveform.



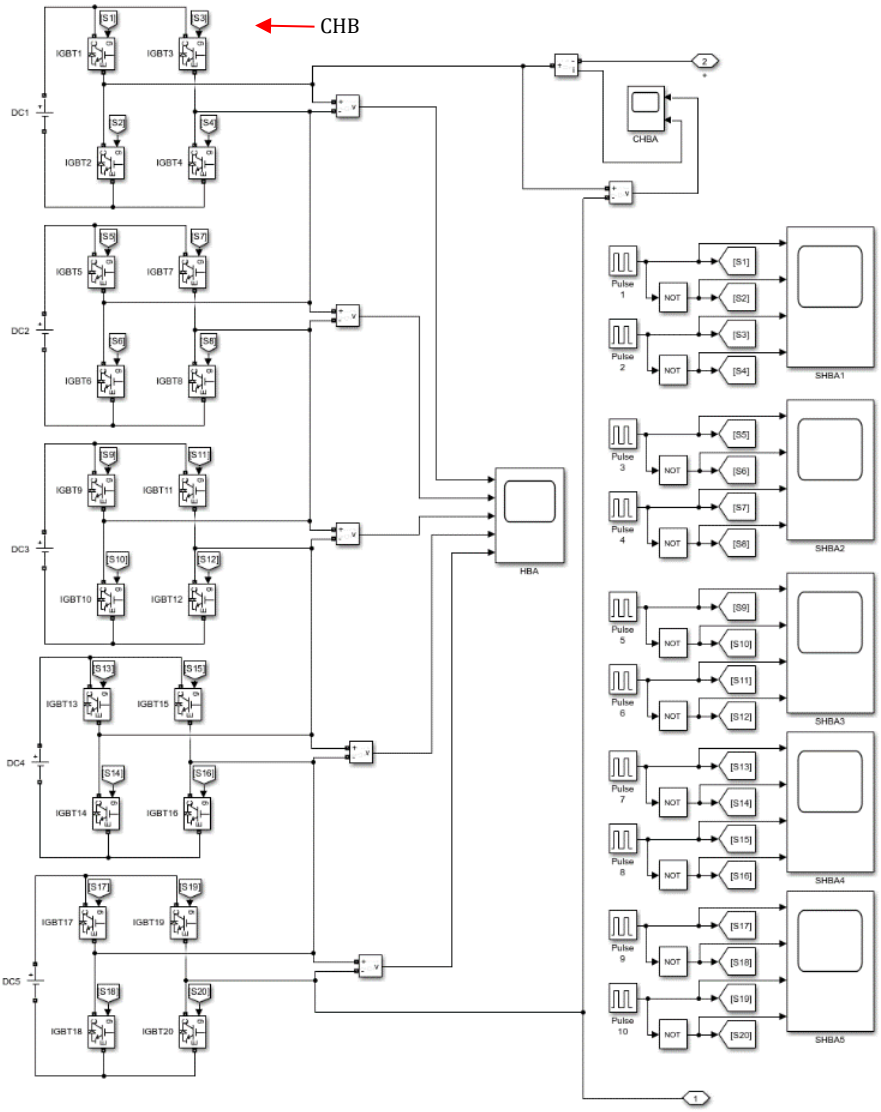



**Fig. 9** *Simulation model of cascaded CHB subsystem of Phase A*

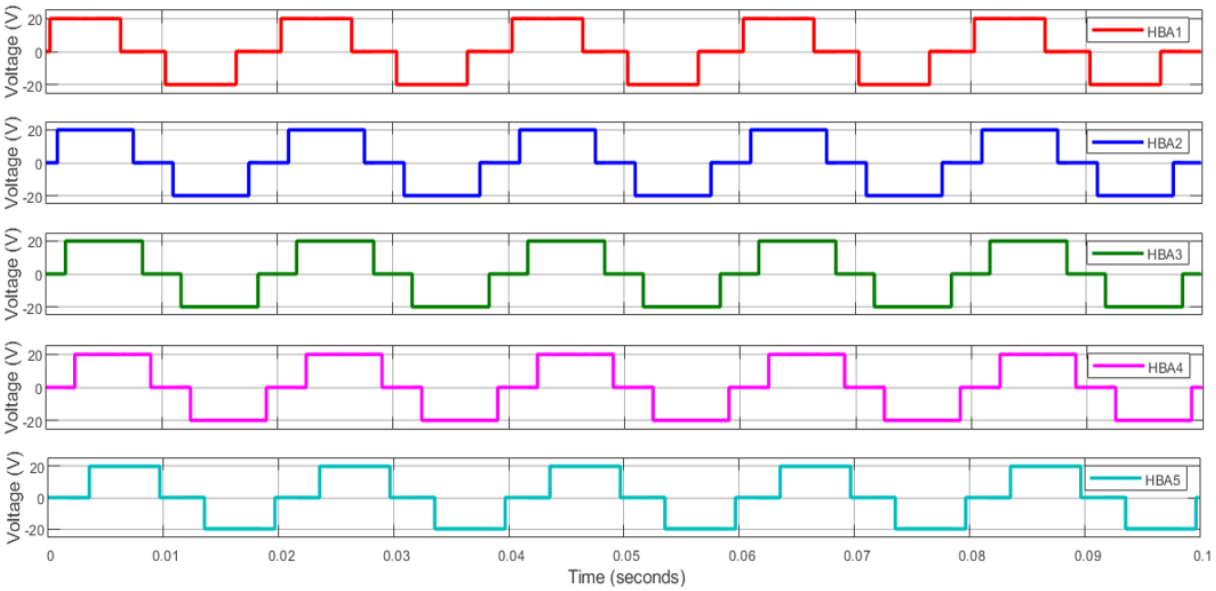



**Fig. 10** *Output voltage from each H-bridge inverter at Phase A*

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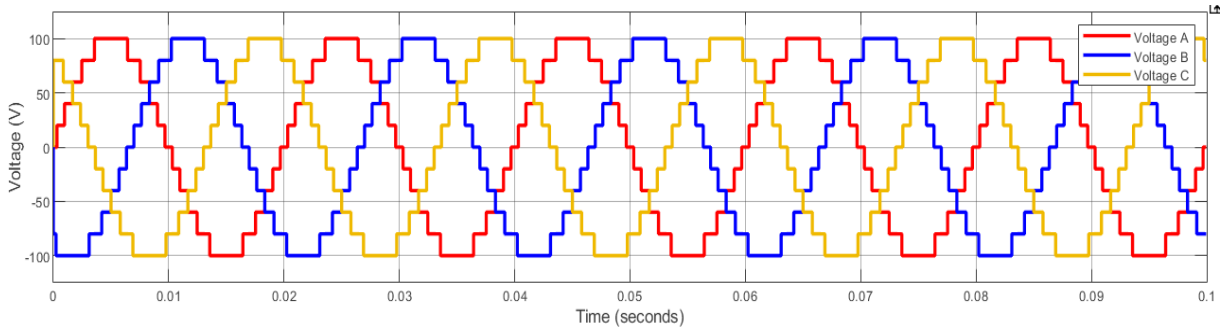


**Fig. 11** *Three-phase output phase voltage for five input CHBMI*

Fig. 12 presents the three-phase output phase current obtained from the five inputs cascaded H-bridge inverters. The peak current measured is 17.77A. However, the current waveforms exhibit distortion which can be attributed to the simultaneous switching actions of both the inverter and rectifier. This phenomenon leads to a high Total Harmonic Distortion (THD) in the current waveform. The observed effect of the distorted current waveform can be attributed to the connection of the cascaded H-bridge inverter to the three-phase rectifier. In advance, due to the double switching action of both the inverter and rectifier, this issue arises as current can only flow when the circuit is complete. The overlapping switching events or timing misalignments can cause disruptions in the current flow, leading to the observed distortion in the waveform.

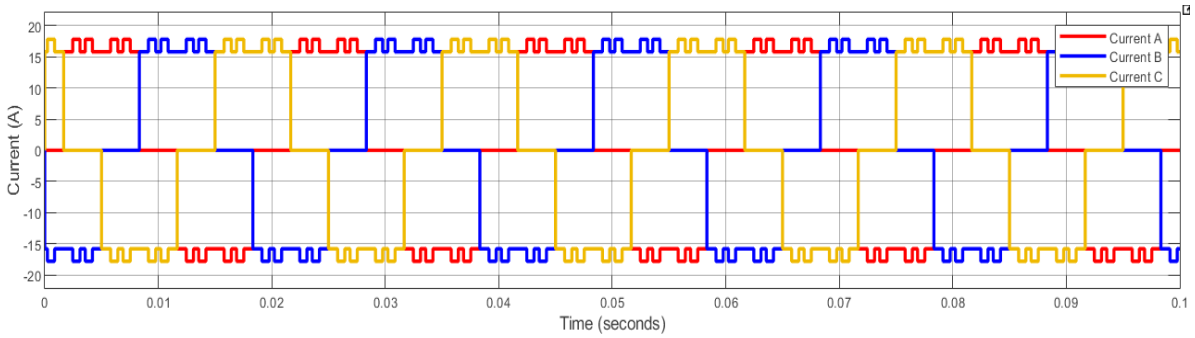


**Fig. 12** *Three-phase output phase current for five input CHBMI*

Fig. 13 shows the three-phase output line voltage achieved from a configuration of the five inputs cascaded H-bridge inverters. By employing a three-phase rectifier, a higher rectified voltage is obtained compared to a single-phase rectifier as shown in Fig. 14. This capability enables the generation of higher DC voltage levels in the system. One advantage of this configuration is that it allows for the use of lower rating devices at the CHB side while still producing a high voltage output at the output of three-phase controlled rectifier. By distributing the power conversion across the three phases, each phase handles a portion of the load, reducing stress and lowering power requirements for individual components. This approach offers improved efficiency and cost-effectiveness by utilizing lower-rated devices that conduct smaller current and voltage ratings. The ability to generate high voltage through a three-phase rectifier configuration enables the system to meet the voltage requirements of various applications without the need for larger or more expensive components.

Fig. 14 displays the rectified voltage and current waveforms derived from a cascaded H-bridge inverter configuration employing five inputs. The obtained results reveal a DC ripple percentage of 4.37% and an efficiency of 94.48%. A comprehensive analysis of all the inputs indicates an interesting trend: the cascaded inverter configuration with an odd number of inputs exhibits a lower ripple percentage and higher efficiency compared to the configuration with an even number of inputs. This observation suggests that the choice of an odd number of cascaded inputs contributes to a more stable output voltage with reduced ripple for this configuration design.

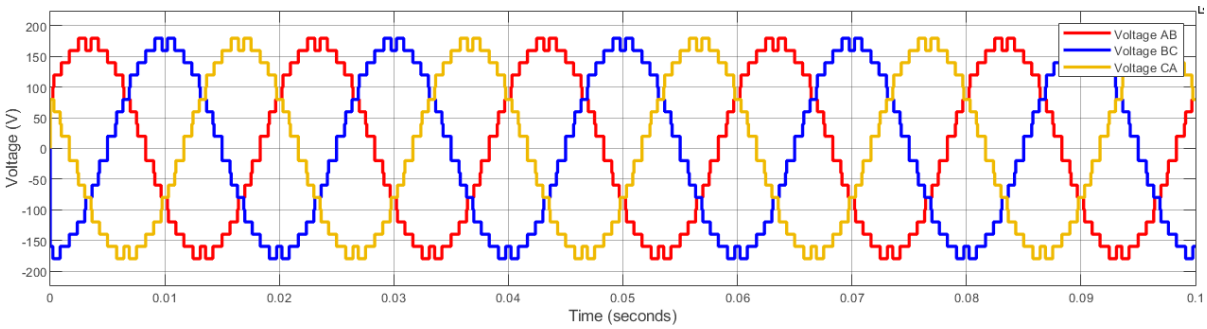


**Fig. 13** *Three-phase output line voltage for five input CHBMI*

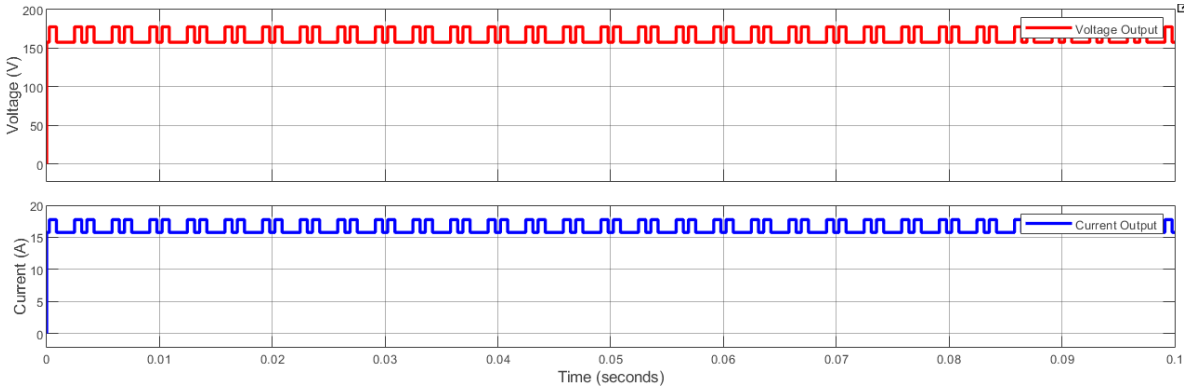


**Fig. 14** *Rectified voltage and current output for five input CHBMI*

Table 3 shows the voltage and current values at the output of CHBMI and rectifier, voltage and current THDs values, DC ripple percentage and efficiency of the proposed indirect DC-AC-DC CHB multilevel inverter. As it can be seen in the Table with the increment of CHB multilevel inverter, the output voltage of the converter is increased. The current is also increased. One of the advantages of multilevel inverter is the THDs value will be decreased at high number of level. From the increased output voltage of CHB, the output voltage and current of the rectifier are also increased.

**Table 3** *Indirect DC-AC-DC converter output value*

| Parameter | Number of H-bridge inverters per phase | | | | |
|---|---|---|---|---|---|
| | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** |
| $V_{rms,inv}$ | 16.32V | 29.78V | 43.58V | 57.5V | 71.47V |
| $I_{rms,inv}$ | 3.102A | 5.411A | 8.203A | 10.75A | 13.52A |
| $THD_{voltage}$ | 31.17% | 17.58% | 12.20% | 9.38% | 7.57% |
| $THD_{current}$ | 31.17% | 33.11% | 31.36% | 31.11% | 31.24% |
| $V_{rms,rec}$ | 37.98V | 66.25V | 100.4V | 131.6V | 165.5V |
| $I_{rms,rec}$ | 3.798A | 6.625A | 10.04A | 13.16A | 16.55V |
| DC Ripple Percentage | 0% | 11.60% | 2.34% | 10.28% | 4.37% |
| Efficiency | 94.98% | 90.79% | 93.99% | 93.39% | 94.48% |

## 5. Conclusions

In conclusion, the designed indirect DC-AC-DC converter allows cascading low DC voltage inputs to generate a high DC voltage output. The traditional way to producing high DC power is by using DC chopper. Another method

is by using cascaded H-bridge where it can produce output at higher and multilevel value. By adopting indirect approach, the low DC voltage power can be amplified to a higher DC voltage power that can be beneficial in providing higher DC power for charging electric vehicle purposes to shorten the charging time. This proposed circuit is suitable for applications requiring high DC voltage levels. The adopted switching algorithm distributes evenly stress among the devices, ensuring no transistor is subjected to excessive heat or overload. The converter design achieves high efficiency and maintains an acceptable ripple percentage, with improved stability seen in odd numbers of cascaded inverters. Additionally, it delivers low voltage Total Harmonic Distortion with an increasing number of cascaded inverters, although the current THD remains high. Further studies need to be conducted to address this issue, which is observed to be caused by the double switching of two connected converters.

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## Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution Statement

*The authors confirm contribution to the paper as follows:* ***Design of Indirect DC-AC-DC Converter:*** *Nashiren Farzilah Mailah;* ***Design of the Cascaded H-Bridge Multilevel Inverter Circuit:*** *Alif Hakimi Omri;* ***Formulation of Cascaded H-Bridge Switching Algorithm:*** *Nashiren Farzilah Mailah;* ***Design and Simulation of Matlab and Simulink Model:*** *Alif Hakimi Omri;* ***Manuscript Preparation:*** *Nashiren Farzilah Mailah. All authors reviewed the results and approved the final version of the manuscripts.*

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