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Comparing performance and complexity of TCHB and CHB multilevel inverters using NLC technique

Md. Showkot Hossain[1,2], Nurul Ain Mohd Said[1,2], Wahidah Abd Halim[1,2], Md. Hasnat Hossain[3]
[1]Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[2]Center for Robotics and Industrial Automation, Universiti Teknikal Malaysia, Melaka, Malaysia
[3]Faculty of Engineering, Universiti Putra Malaysia, Selangor, Malaysia

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ABSTRACT

This paper presents a modulation strategy applied to a 13-level three-phase transistor clamped H-bridge (TCHB) inverter, aimed at a renewable and electric vehicle drives application. A comparison is performed between the TCHB inverter and a traditional cascaded H-bridge (CHB) inverter, considering circuit complexity, switching losses, and total harmonic distortion (THD) attained from each multilevel inverter topologies. The TCHB inverter achieves a 13-level output with only 15 switches, whereas the conventional CHB inverter requires 24 switches. The modulation technique, employing a nearest level control, yields improved output quality for both the TCHB and CHB multilevel inverters. The results demonstrate that this strategy effectively minimizes the overall THD. Notably, previous modulation techniques mainly focused on carrier-based PWM or SVPWM, making this approach distinctive. The FFT analysis reveals a voltage THD of 5.49% for TCHB and 5.15% for CHB, indicating a marginal difference in THD content for each multilevel inverter. Despite the CHB inverter experiencing double the switching stress compared to TCHB, since less switches are required in the TCHB inverter, consequently, the system's total cost and complexity are reduced. The achieved results are verified through the use of simulations carried out in the MATLAB Simulink.

Corresponding Author:

Nurul Ain Mohd Said
Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
Email: nurulain@utem.edu.my

1. INTRODUCTION

A multi-level inverter is composed of several switching and DC source components, resulting in a waveform output that is stepped by a number of DC levels. Numerous topologies by various controller strategies have been produced over the previous few decades [1], [2]. For applications involving medium and high-voltage, there is a choice of various different topologies for multilayer inverters. Neutral-point-clamped (NPC), flying-capacitor (FC), and cascaded h-bridge (CHB) are the most popular topologies among them [3]–[6]. The complexity of NPC and FC multilevel inverters rises with the number of voltage levels, requiring more switches, diodes, and capacitors. Balancing voltage is another issue with both inverters. The CHB inverter is more reliable while producing larger voltages when compared to the other two topologies [7], [8]. The CHB inverter arrangement is made up of several single-phase inverters linked in series, with the total number of inverters in series being determined by the desired amount of output power. It takes (n -1) series-connected single-phase inverters to make up a multilevel inverter for an n-level CHB [9], [10]. However, the cost rises since each h-bridge inverter needs its own dedicated DC power source [11], [12]. Having this problem is critical for the CHB inverters. One of the potential answers to this problem is transistor clamped h-bridge (TCHB). The TCHB inverter utilizes a smaller DC sources and fewer switches to achieve the same number of levels as a standard CHB multilevel inverter [13], [14] illustrated in Figure 1, where Figure 1(a) for five-level TCHB and Figure 1(b) for five-level CHB inverter. The first publication to mention the TCHB inverter was [15]. Additionally, the response of the TCHB inverter successfully reduces the harmonic content of voltage and current output [16].

Due to the modulation strategy influencing the system's harmonics of voltage and current, the efficiency of these multilevel inverters is highly dependent on the modulation technique. Modulation techniques used in a multilevel inverter have an effect on the inverter's efficiency, switching losses, and reductions in harmonics. To enhance the shape of the output voltage waveform with reduced switching losses and minimal harmonic distortion, many modulation approaches have been proposed. Space vector modulation (SVM), selective harmonic elimination (SHE), and sinusoidal pulse width modulation (SPWM) are some examples of modulation techniques used in multilevel inverters [17], [18]. Despite their advantages in generating high-quality output, SPWM and SVM are dominated by switching losses. Low-frequency modulation is effective in improving the efficiency of high-power applications. By using the SHE technique, not only the low-order harmonics reduced, but total harmonic distortion (THD) is also significantly reduced. Still, it necessitates using iterative techniques like the Newton-Raphson method, partial swarm optimization, to solve complicated, non-linear transcendental equations.

The nearest level control (NLC) method is straightforward, which makes it a feasible choice for high-level multilevel inverters [19]. The NLC technique is proposed and used in a multilevel inverter with asymmetrical cascaded h-bridges (A-CHB) configuration [20]. The results indicate a substantial drop in THD even without filtering. At high levels, the NLC technique also significantly reduces switching losses. The result in [21], for a 27-level asymmetrical cascaded h-bridge inverter, the author developed the NLC method. According to the findings, the NLC modulation method achieves the lowest THD, about 3% for the staircase output voltage. Saleh *et al*. [19] investigate a TCHB inverter operating on 13th-level single-phase system. The findings demonstrate that the THD 5.18% was at its lowest is, attained with a modulation index of M = 1.044, and that the NLC technique improves in efficiency with the amount of level rises. As a consequence of this, it is clearly shown that a considerable amount of investigation was carried out on the single-phase TCHB inverter. So far, only a small amount of research is available this time that applied the NLC method for the three-phase TCHB inverter. This research makes an effort to find a solution to the mentioned issue of creating an NLC method for a three-phase TCHB inverter.

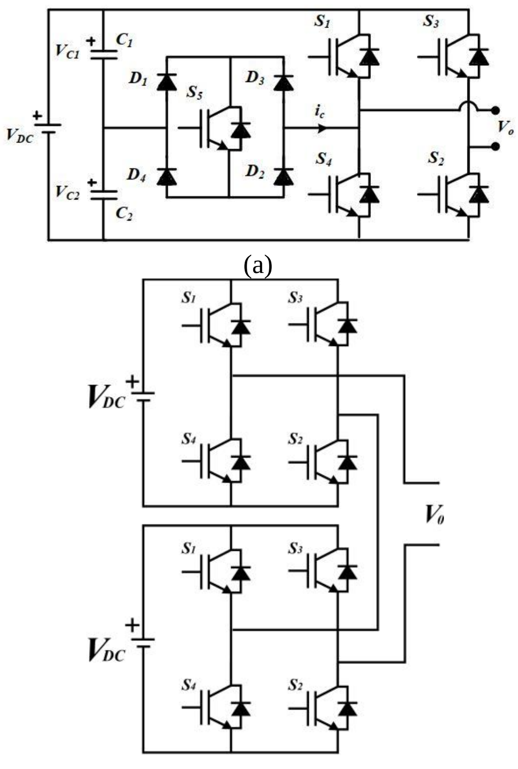


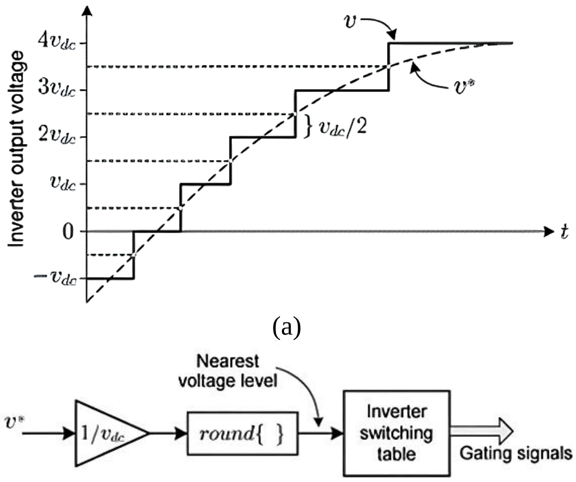
Figure 1. Basic MLI circuits: (a) five-level TCHB inverter and (b) five-level CHB inverter

2. NEAREST LEVEL CONTROL MODULATION TECHNIQUE

Nearest level control, also referred to the rounded approach, uses the voltage level that is most closely equivalent to the required output voltage reference [22]. Using NLC approach, each of the three phases may have their own individual adjustment depending on the results of their own independent comparison. Figure 2 shows the nearest level selection where Figure 2(a) for webform generation and Figure 2(b) for control diagram. It can be seen in Figure 2(a), by comparing the reference waveform with an existing voltage, a staircase can be developed. We can estimate the nearest output voltage level v with as (1).

$$v = v_{dc} * round_{0.5}(^{v\,*}/_{v_{dc}}) \tag{1}$$

Where, v^* is the reference and $0.5v_{dc}$ is the capacitor voltage. The function rounds the number to the next integer and returns that value (for example, round (3.40) = 3, round (3.60) = 4) [23]. The nearest level to the reference produced by the inverter is the nearest integer multiplied by $0.5v_{dc}$ [24]. Figure 2(b) illustrates the implementation of the nearest level synthesis.



(a)

(b)

Figure 2. Nearest level selection process: (a) waveform generation and (b) control diagram

Using the NLC approach, the following equation is used to determine the switching angles for any number of levels:

$$\theta_i = sin^{-1}(\frac{i-0.5}{x}) \tag{2}$$

where i = 1,2..., $\frac{n-1}{2}$, the total number of levels is represented by the value of n and $x = \frac{n-1}{2}$. When number of levels rises, the switching angles θ_i become closer to one another, producing a waveform that is nearly sinusoidal.

3. THREE-PHASE 13-LEVEL TRANSISTOR CLAMPED H-BRIDGE INVERTER

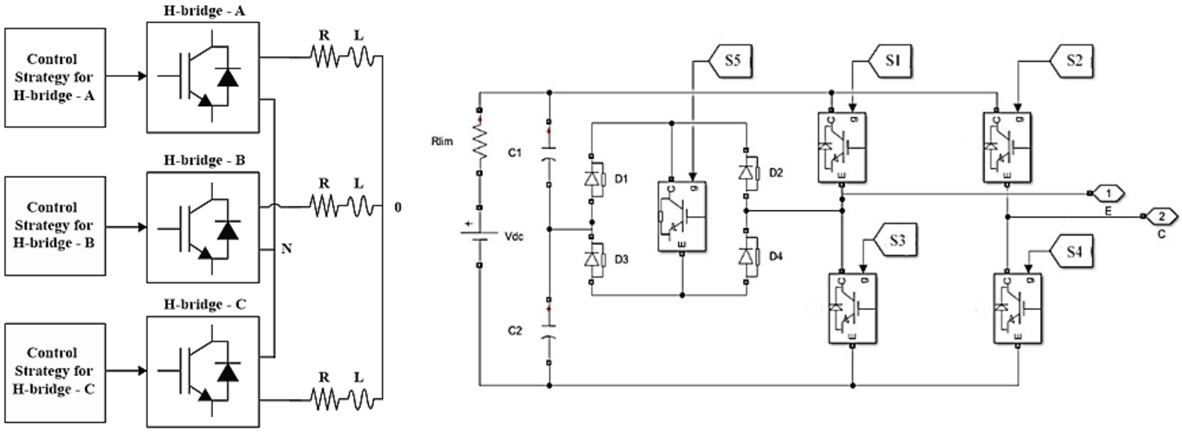
Figure 3 illustrates a 13-level three-phase TCHB multilevel inverter, where Figure 3(a) [25] shows a basic arrangement for the 13-level three-phase TCHB multilevel inverter and Figure 3(b) [25] shows the configuration for five-level TCHB inverter for each h-bridge cell. The power circuit for an TCHB multilevel inverter with these three h-bridge configurations is sufficient to produce a 13-level output voltage using a lesser number of power switches.

According to the configurations of the switches presented in Table 1, five distinct output voltage levels may be generated with an additional bilateral switch attached between the initial section of the H-bridge and the capacitor's midpoint. Furthermore, Table 2 will illustrate the switching operations for this 13-level voltage output. Figure 4 [26] illustrates the inverter output voltage waveform with the intervals during the switches are activated. One cycle of the output waveform from a TCHB inverter can be separated into six distinct regions, as shown in Table 3 [26]. In order to prevent a short circuit problem from occurring through the DC voltage supply, the switches S_1 and S_3 or S_2 and S_4 shouldn't be switched on at the same time.

In general, the maximum level of an output voltage of the inverter, based on the number of h-bridge, are given by (3):

$$V_{out} = 4N_{h-b} + 1 \quad (3)$$

where, 'N_{h-b}' is the number of h-bridges connected.



(a) (b)

Figure 3. 13-level three-phase TCHB multilevel inverter: (a) general circuit diagram and (b) circuit for each h-bridge

Table 1. 5-level TCHB inverter switching states

No.	ON switches	Voltage level
1	S_1, S_4	$+V_{dc}$
2	S_4, S_5	$+{}^{1}/_{2}\,V_{dc}$
3	S_1, S_2 Or S_3, S_4	0
4	S_2, S_5	$-{}^{1}/_{2}\,V_{dc}$
5	S_2, S_3	$-V_{dc}$

Table 2. Divisions of a single TCHB inverter output cycle

Region	Interval	Voltage level
1	$0 \le \omega t \le \theta_1$ and $\pi - \theta_1 \le \omega t \le \pi$	0
2	$\theta_1 \le \omega t \le \theta_2$ and $\pi - \theta_2 \le \omega t \le \pi - \theta_1$	$+V_{dc}$
3	$\theta_2 \le \omega t \le \pi - \theta_2$	$+{}^{1}/_{2}\,V_{dc}$
4	$\pi \le \omega t \le \pi + \theta_1$ and $2\pi - \theta_1 \le \omega t \le 2\pi$	0
5	$\pi + \theta_1 \le \omega t \le \pi + \theta_2$ and $2\pi - \theta_2 \le \omega t \le 2\pi - \theta_1$	$-{}^{1}/_{2}\,V_{dc}$
6	$\pi + \theta_2 \le \omega t \le 2\pi - \theta_2$	$-V_{dc}$

Table 3. The 13-level TCHB inverter switching states

State	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{31}	S_{32}	S_{33}	S_{34}	S_{35}	V_{inv}
1	1	0	0	c	0	1	0	0	1	0	1	0	0	1	0	$3V_{dc}$
2	1	0	0	1	0	1	0	0	1	0	0	0	0	1	1	$2{}^{1}/_{2}\,V_{dc}$
3	1	0	0	1	0	0	0	0	1	1	0	0	0	1	1	$2V_{dc}$
4	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1	$1\,{}^{1}/_{2}\,V_{dc}$
5	0	0	0	1	1	0	0	0	1	1	0	0	1	1	0	V_{dc}
6	0	0	0	1	1	0	0	1	1	0	0	0	1	1	0	${}^{1}/_{2}\,V_{dc}$
7	0	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0
8	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0	0
9	0	1	0	0	1	1	1	0	0	0	1	1	0	0	0	$-{}^{1}/_{2}\,V_{dc}$
10	0	1	0	0	1	0	1	0	0	1	1	1	0	0	0	$-V_{dc}$
11	0	1	0	0	1	0	1	0	0	1	0	1	0	0	1	$-1\,{}^{1}/_{2}\,V_{dc}$
12	0	1	1	0	0	0	1	0	0	1	0	1	0	0	1	$-2V_{dc}$
13	0	1	1	0	0	0	1	1	0	0	0	1	0	0	1	$-2\,{}^{1}/_{2}\,V_{dc}$
14	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0	$-3V_{dc}$

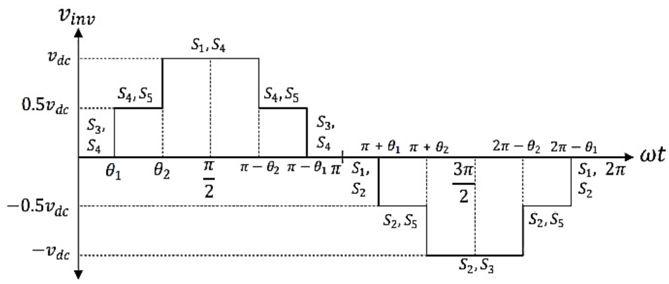


Figure 4. Five-level TCHB inverter output voltage waveform

4. TRADITIONAL THREE-PHASE 13-LEVEL CASCADED H-BRIDGE INVERTER

A multilevel CHB inverter with 13-levels is shown in Figure 5, where Figure 5(a) shows a traditional three-phase 13-level cascaded h-bridge multilevel inverter following the switching combination shown in Tables 4 and Table 5. It made up of six h-bridge inverters connected in series, along with six DC power supply. Three levels of output voltage will be produced for each cell of CHB inverter configurations so there were six cells needed in order to produce thirteen levels of output level from this type of inverter. Figure 5(b) shows the configuration for h-bridge circuit for each h-bridge cell. In order to create a voltage waveform, switching pulses are generated using the nearest level control modulation method.

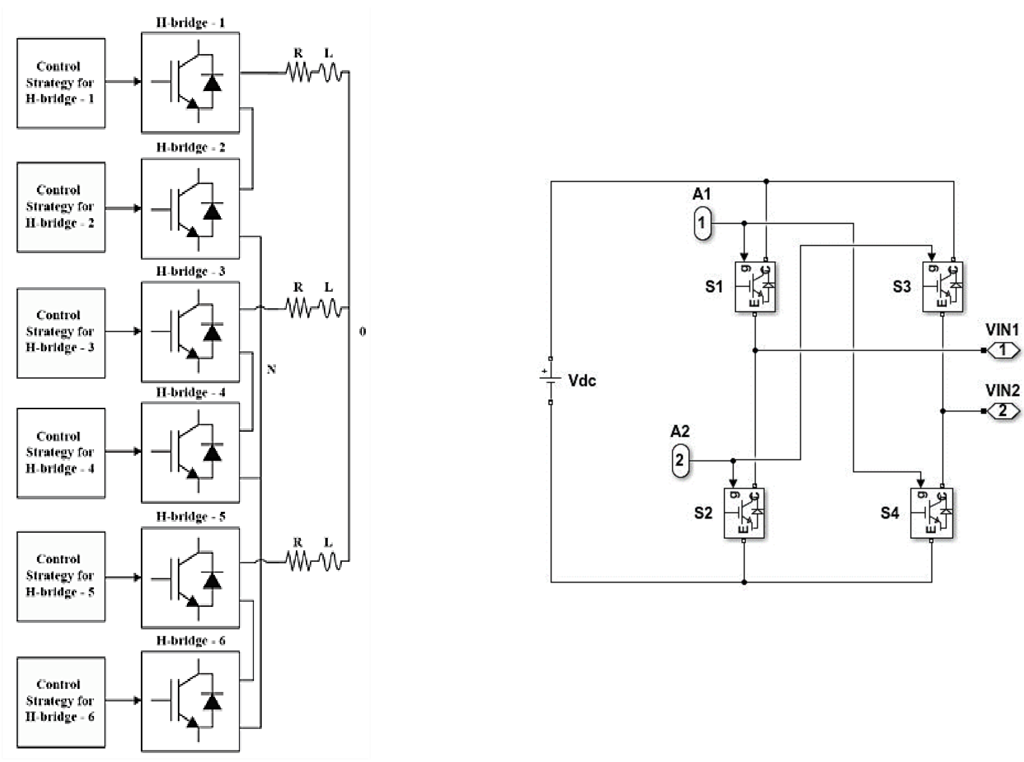
According to (4), a 13-level cascaded h-bridge multilevel inverter output voltage is equal to the total of the six independent DC supplies provided by every one of the symmetric h-bridges.

$$V_O = V_{dc1} + V_{dc2} + V_{dc3} + V_{dc4} + V_{dc5} + V_{dc6} \tag{4}$$

The range of available output voltage levels is provided by (5).

$$N_{steps} = 2n + 1 \tag{5}$$

Where 'n' refers to the overall quantity of H-bridge inverters.



(a) (b)

Figure 5. 13-level CHB multilevel inverter: (a) general circuit diagram and (b) circuit for each h-bridge

Table 4. Switching states of the 5-level CHB inverter

No	ON switches	Voltage level
1	S_1, S_4	$+V_{dc}$
2	S_1, S_2 Or S_3, S_4	0
3	S_2, S_3	$-V_{dc}$

Table 5. Switching states of the 13-level CHB inverter

No	ON switches	Voltage level
		Cell 1
1	S_{11}, S_{14}	$+V_{dc}$
2	S_{11}, S_{12} or S_{13}, S_{14}	0
3	S_{12}, S_{13}	$-V_{dc}$
		Cell 2
1	S_{21}, S_{24}	$+V_{dc}$
2	S_{21}, S_{22} or S_{23}, S_{24}	0
3	S_{22}, S_{23}	$-V_{dc}$
		Cell 3
1	S_{31}, S_{34}	$+V_{dc}$
2	S_{31}, S_{32} or S_{33}, S_{34}	0
3	S_{32}, S_{33}	$-V_{dc}$
		Cell 4
1	S_{41}, S_{44}	$+V_{dc}$
2	S_{14}, S_{42} or S_{43}, S_{44}	0
3	S_{42}, S_{43}	$-V_{dc}$
		Cell 5
1	S_{51}, S_{54}	$+V_{dc}$
2	S_{51}, S_{52} or S_{53}, S_{54}	0
3	S_{52}, S_{53}	$-V_{dc}$
		Cell 6
1	S_{61}, S_{64}	$+V_{dc}$
2	S_{61}, S_{62} or S_{63}, S_{64}	0
3	S_{62}, S_{63}	$-V_{dc}$
		$6V_{dc}$, $5\,V_{dc}$, $4V_{dc}$, $3\,V_{dc}$, $2\,V_{dc}$, $1\,V_{dc}$, 0, $-1\,V_{dc}$, $-2\,V_{dc}$, $-3V_{dc}$, $-4\,V_{dc}$, $-5V_{dc}$, $-6\,V_{dc}$

5. SIMULATION RESULTS AND DISCUSSION

The reduced switching count TCHB multilevel inverter is designed and simulated using the MATLAB-Simulink environment. The simulation is conducted with a modulation index between 0.85 and 1.0. It is expected that the TCHB multilevel inverter will be fed by an RL load. Using similar modulation indices and load parameters, the result that is achieved is compared to a traditional CHB inverter. A three-phase 13-level transistor clamped h-bridge inverter simulation system design specification is shown in Table 6. Table 7 provides the system design specifications for the simulation of a traditional 13-level cascaded h-bridge inverter.

Table 6. System parameter used for TCHB simulation

Parameter	Value
DC supply for h-bridge 1,2,3	60 V
DC link capacitor	2200 µF
Modulation Index (m)	0.85 < m < 1.0
Resistive load	100 Ohm
Inductive load	20 mH
Fundamental frequency	50 Hz

Table 7. System parameter used for CHB simulation

Parameter	Value
DC supply for h-bridge 1 to 6	60 V
Modulation Index (m)	0.85 < m < 1.0
Resistive load	100 Ohm
Inductive load	20 mH
Fundamental frequency	50 Hz

5.1. Results obtained with TCHB multilevel inverter

Figures 6 and 7 show the waveforms of the simulation output voltage and output current using RL load, respectively. It shows how 13-level voltage output are synthesized. The presence of a load that is inductive causes the waveforms of the current output to be more sinusoidal. Figures 8 and 9 show the output voltage and current harmonic spectrum produced by a TCHB multilevel inverter with a modulation index of 0.94, respectively. With a transistor clamped h-bridge architecture, the THD for the voltage is 5.49%, while the THD for the current is 5.19%.

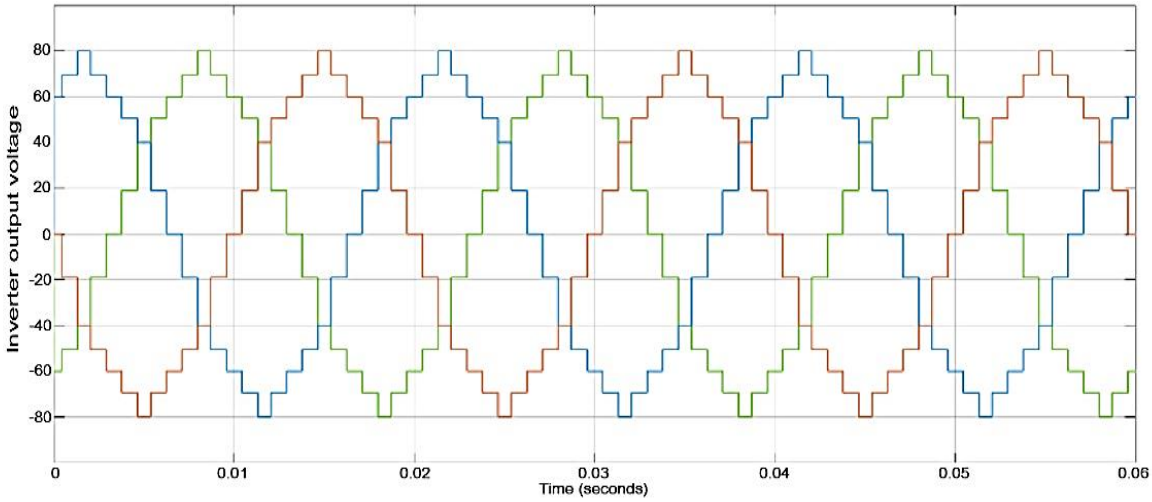


Figure 6. Output voltage of TCHB multilevel inverter for M=0.94

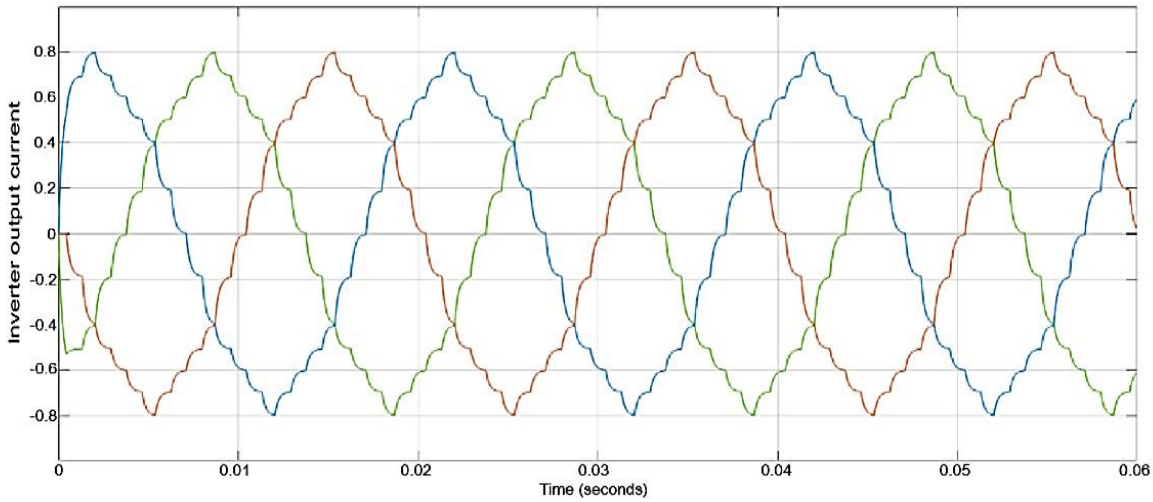


Figure 7. Output current of TCHB multilevel inverter for M=0.94

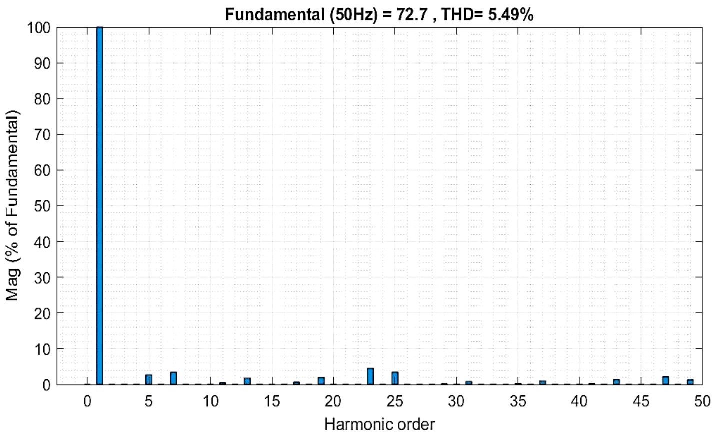


Figure 8. Inverter voltage harmonic spectrum of TCHB multilevel

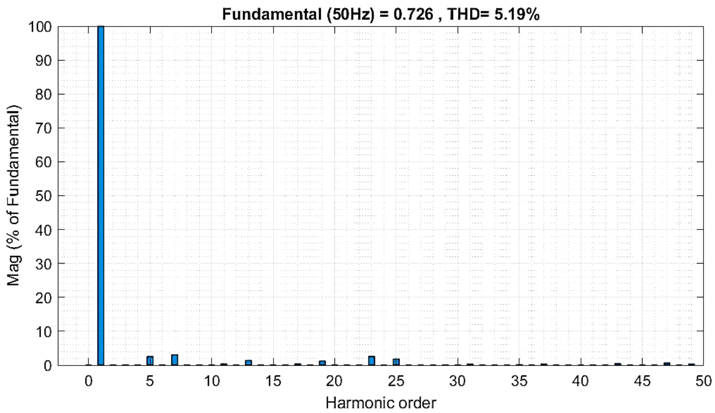


Figure 9. Inverter current harmonic spectrum of TCHB multilevel

5.2. Results obtained with CHB multilevel inverter

Figures 10 and 11 show the waveforms of the simulation output voltage and output current using RL load, respectively. It illustrates how 13-level voltage output are synthesized. The presence of a load that is inductive causes the waveforms of the current output to be more sinusoidal. Figures 12 and 13 show the output voltage and current output harmonic spectrum produced by a CHB multilevel inverter with a modulation index of 0.94, respectively. With a traditional cascaded h-bridge architecture results in a THD of 4.13% for the current and 5.15% for the voltage achieved.

The NLC technique showed that this control technique is not able to eliminate particular harmonics like the SHE method, which is able to eliminate some low-order harmonics rather than reducing the entire THD of the inverter output voltage and current. From the harmonic spectrum, it shows that both TCHB and CHB are good with overall harmonic elimination with NLC technique.

It has been noticed that the THD content of both multilevel inverter is almost the same. The switching stress acquired with a TCHB inverter is twice as great as that obtained with a CHB inverter, however a TCHB multilevel inverter needed a smaller number of switches. Table 8 shows the analysis between the three-phase traditional CHB multilevel inverter and the proposed three-phase TCHB multilevel inverter. It is found that isolated DC supply, power switches is double for conventional CHB compared to the TCHB multilevel inverter, and switching losses for TCHB is less than CHB multilevel inverter. Nevertheless, as a matter of maintenance, a more substantial number of components in CHB are challenging to maintain for the long term; hence, more financial costs are needed for the maintenance services in the real implementation. This paper focused on NLC technique for both CHB and TCHB inverter topologies.

Recent advancements and trends easily indicate the rapid growth of grid-tied photovoltaic system applications. In conjunction with the constant rise in capacity and power output of wind turbines, these types of multilevel inverters have become a possible solution. However, the drive systems of electric vehicles and hybrid electric vehicles will also benefit from these converters for better power quality and increased efficiency.

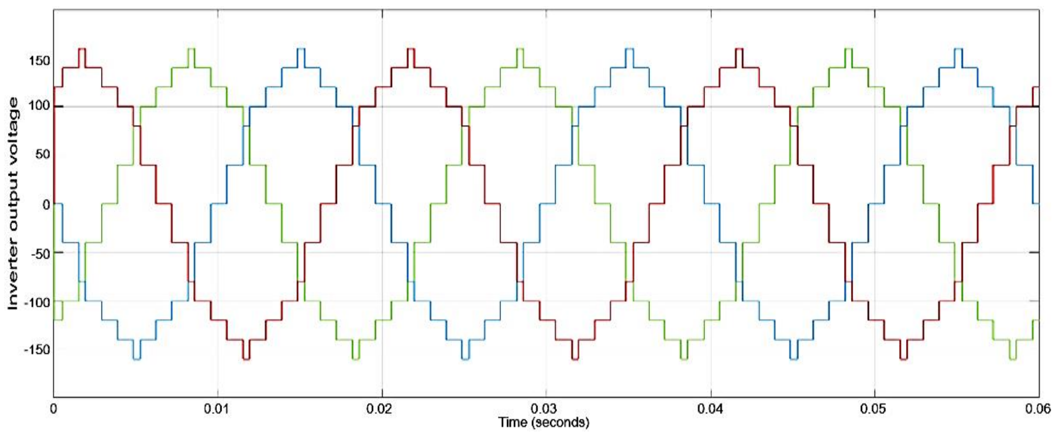


Figure 10. Output voltage of CHB multilevel inverter for M=0.94

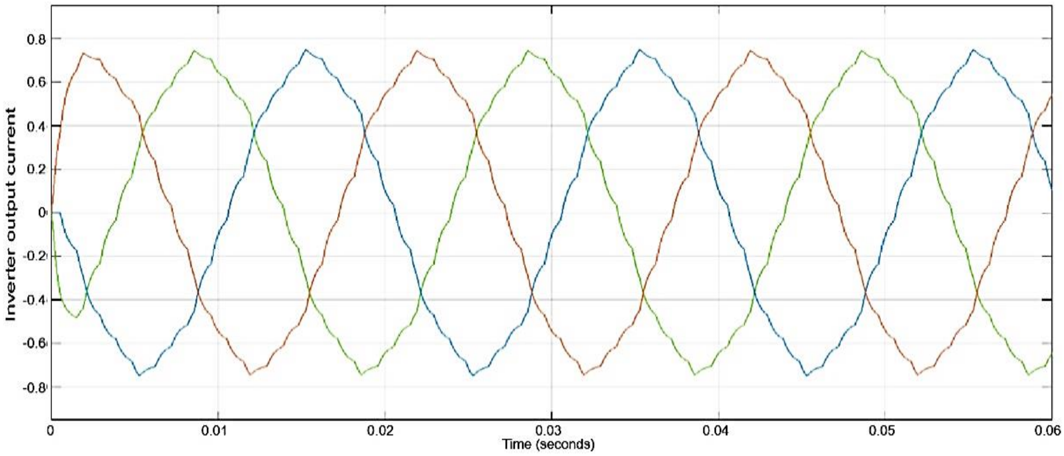


Figure 11. Output current of CHB multilevel inverter for M=0.94

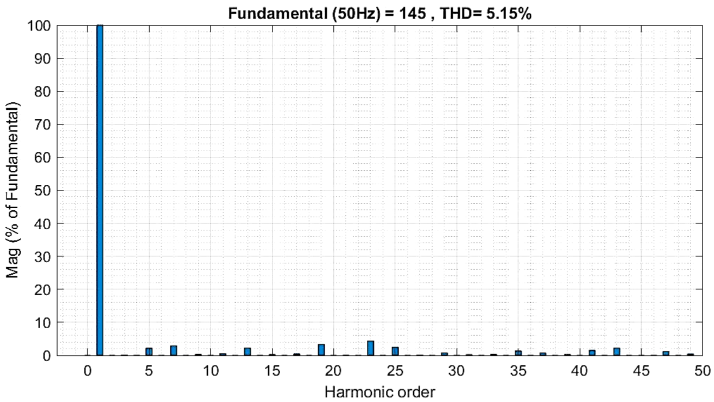


Figure 12. Inverter voltage harmonic spectrum of CHB multilevel

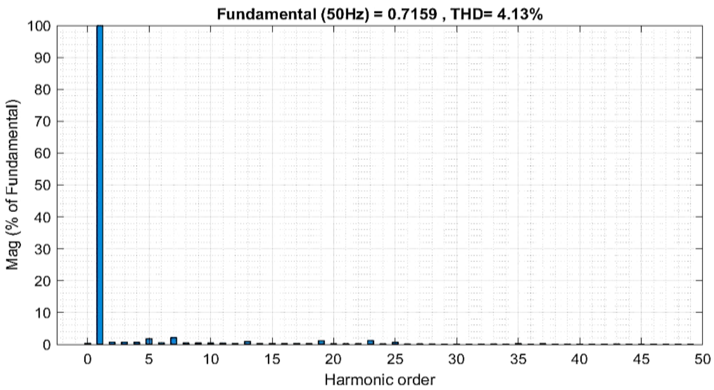


Figure 13. Inverter current harmonic spectrum of CHB multilevel

Table 8. Comparison of three-phase TCHB and CHB multilevel inverter topology

Parameter	TCHB Multilevel Inverter	CHB Multilevel Inverter	Parameter	TCHB Multilevel Inverter	CHB Multilevel Inverter
Number of cells	3	6	Capacitor	6	-
Voltage levels	4n + 1	2n + 1	Switching losses	Low	High
Isolated DC supply	3	6	Cost of implementation	Low	high
Power switch	15	24	Simplicity of circuit	Simple	Complex
Bi-directional switch	3	-	Maintenance	Easy	Difficult

6. CONCLUSION

In this study, an analysis of a 13-level TCHB inverter topology is presented. This configuration depends on a five-level TCHB power unit and utilizes the nearest level control modulation method. In terms of DC supply, power switches, and power losses, detailed comparisons between the suggested three-phase TCHB multilevel inverter and the traditional CHB multilevel inverter were provided. For a modulation index of 0.94, both the multilevel inverter output voltage and current were analyzed and found voltage THD is 5.49% for TCHB and 5.15% for CHB. From the findings, the proposed TCHB multilevel inverter synthesizes the same amount of output level as a traditional CHB multilevel inverter, although having a lower number of switches. In terms of the harmonic, the NLC approach provides simplicity in technique and better quality with reduced overall output THD for both CHB and TCHB inverter topology. It is necessary to do more research with the aim to examine the performance of the approach in closed-loop applications.

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BIOGRAPHIES OF AUTHORS

Md. Showkot Hossain received a B.Sc. degree in Electrical and Electronic Engineering from Daffodil International University in 2019. He is pursuing a master's degree from Universiti Teknikal Malaysia, Melaka. In 2022, he started working as a Graduate Research Assistant with the UTeM Electric Vehicle Drives Lab. His research interests include power electronics, multilevel inverter topology, nearest-level control, electric vehicle drives, and renewable energy. He can be contacted at email: hossain33-2682@diu.edu.bd.

Nurul Ain Mohd Said received the B.Eng. and the M.Sc. degrees from Universiti Teknologi Malaysia, Skudai, Malaysia, in 2009 and University of Strathclyde, Glasgow in 2011, respectively, and the Ph.D. degree from University of New South Wales, Sydney, Australia in 2017, all in electrical engineering. She is currently a senior lecturer at the Universiti Teknikal Malaysia Melaka, Malaysia. Her research interests include power electronics, drives, and energy conversion. She can be contacted at email: nurulain@utem.edu.my.

Wahidah Abd Halim was born in Kuala Lumpur, Malaysia, in 1977. She received her B. Eng. degree (with Honors) in Electrical Engineering from the Universiti Teknologi Malaysia, Johor, Malaysia, in 2000 and her M.Sc. degree in Electrical Power Engineering from the Universiti Putra Malaysia, Serdang, Selangor, Malaysia, in 2005. She did her Ph.D. degree at the University of Malaya, Kuala Lumpur, Malaysia, in 2015. She is a Senior Lecturer at the Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia. Her research areas include power electronics, power systems, and digital signal processing. She can be contacted at email: wahidahhalim@utem.edu.my.

Md. Hasnat Hossain received a B.Sc. degree in Electrical and Electronic Engineering from Daffodil International University in 2019. He is pursuing his master's degree from Universiti Putra Malaysia, Selangor. In 2021, he started working as a Graduate Research Assistant with the Research Centre for Nano-Materials and Energy Technology under the School of Engineering and Technology in Sunway University, Malaysia. His research interests include power electronics, renewable energy, and green energy storage. He can be contacted at email: hasnatnayem95@gmail.com.