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ORIGINAL ARTICLE

Comparison of Various Aspects of Neutral Point Clamped and Cascaded H-Bridge Inverters for Use in Photovoltaic Systems

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Abstract
Among the various inverter structures, multilevel inverters are widely used in photovoltaic systems today due to their numerous advantages. However, different performance indicators provide multiple options for photovoltaic systems, each with specific strengths and limitations. In this paper, two common topologies—Neutral Point Clamped (NPC) and Cascaded H-Bridge (CHB)—are evaluated at five and nine levels. The comparison covers several criteria including structural complexity, number of components, type of DC sources, electrical losses, weight, and cost. In addition, performance-related indicators such as Total Harmonic Distortion (THD) and compliance with grid-connection standards are studied. Simulation-based evaluations were conducted using Matlab, with an induction motor used as a reference load to analyze losses under varying mechanical conditions. Filtering requirements were also considered to ensure THD remains below the 5% threshold. Ultimately, the results show that although increasing the number of voltage levels improves output quality, it significantly increases the weight and cost. After including the filter design, the 5-level NPC inverter demonstrated the best overall performance, offering a suitable balance of efficiency, compliance, cost, and structural simplicity for photovoltaic applications.
Keywords: NPC-MLI, CHB-MLI, Losses, Harmonic, Cost.

1. Introduction

The use of solar energy as an electrical energy source in distributed generation systems has increased the focus on optimizing and developing inverter structures. According to a 2023 report by the European Photovoltaic Industry Association, photovoltaic systems held the largest share of energy production among renewable energy sources. In the same year, more than 1600 GW of photovoltaic power plants were put into operation worldwide, representing a 25% increase compared to the previous year's 1200 GW (IEA PVPS, 2023).

The task of converting the DC voltage from solar panels into grid-appropriate AC voltage is carried out by inverters. Among the various inverter structures in PV systems, multilevel inverters are a key technology that, due to their numerous advantages compared to other inverters, are now widely used. Multilevel inverters come in different types, with significant differences in their structure and performance. Therefore, to optimize the performance of PV systems, it is necessary to identify the appropriate structure among multilevel inverters. In this regard, this paper examines the structure of multilevel converters

for extracting AC voltage from solar panels with minimal harmonics, cost, and complexity.

With the increase in the number of voltage levels in these converters, the output waveform will consist of more voltage steps, and as it approaches a sinusoidal waveform, harmonics are reduced. However, increasing the number of levels, due to the need for more switches, increases the system's complexity, cost, and losses. Therefore, although increasing the number of steps can result in an output with a better harmonic spectrum, practical and economic constraints require selecting an optimal structure and number of levels that minimize cost and complexity while ensuring the output waveform meets the required standards for connection to the distribution grid or consumer operation.

The aim of this paper is to examine the various aspects of Neutral Point Clamped (NPC) and Cascaded H-Bridge (CHB) inverters to identify the optimal structure and number of levels for connecting solar panels to the grid. Given the wide range of factors involved in this research, achieving the optimal structure is based on previous studies and simulations of the harmonic spectrum of the output voltage using Matlab software. Ultimately, by analyzing different levels of the two structures, an optimal structure in terms of cost, weight, losses, and THD for connecting PV systems to the grid is proposed.

2. Multilevel inverter structures

Although electrical isolation between the PV system and the grid, typically achieved by using a transformer-inverter combined structure, is generally recommended, removing the transformer from the PV system inverter can enhance the inverter's performance. Some disadvantages of transformer-inverter systems include increased costs, reduced overall efficiency due to losses and leakage in the transformer, as well as the increased size and weight caused by the transformer (Khan et al. 2020).

By eliminating the transformer and isolating the PV system from the grid, these disadvantages are reduced; however, parasitic capacitance introduces leakage current to the ground, which is the major drawback of transformerless inverter systems (Amirinezhad et al. 2025).

To address this issue, new transformerless inverter structures have been introduced for connecting PV systems to the grid, aiming to reduce leakage current, improve efficiency, and enhance reliability. The H-bridge-based multilevel inverters and diode-clamped multilevel inverters (NPC) are two of the main transformerless inverter configurations currently used in the industry (Subarnan. 2018).

Multilevel inverters are a set of inverters that, by using multiple low-voltage input levels, have the ability to produce AC output voltage at the desired level. In a multilevel inverter, voltage levels are summed together to achieve the desired output voltage. Unlike conventional two-level voltage source inverters, multilevel inverters are not limited to just two voltage levels for their output. Multilevel inverters are highly efficient in medium and high voltage and power applications and are widely used. Low switching frequency, low harmonic content, and simpler control circuits are among the advantages of multilevel inverters (Fouda et al. 2024).

For multilevel inverters, various structures such as diode-clamped, capacitor-clamped, cascaded with separate DC sources, H-bridge, hybrid-level, ladder, and soft-switching inverters have been introduced (Ezhilarasan et al. 2023).

Among these, Neutral Point Clamped (NPC) and Cascaded H-Bridge (CHB) inverters, which will be explained further, are more commonly used in solar systems compared to other types.

2.1. Neutral point clamped (NPC) inverter

This structure, also known as the diode-clamped inverter, was introduced in 1980 (Teodorescu et al. 2011), and is widely used in both single-phase and three-phase inverters. Some inverters based on this structure include the full-bridge NPC inverter, half-bridge NPC inverter with capacitor divider, wide NPC, active NPC, and floating capacitor NPC, each with its own advantages and characteristics. For example, the half-bridge NPC inverter, a version of the diode-clamped half-bridge

structure, is used in low-voltage applications and can produce three voltage levels at the output. In this inverter, two switches operate at high frequency, and the other two switches operate at grid frequency (Mollahasanoglu et al. 2024).

The advantage of this structure is its high efficiency, low switching losses, and minimal leakage current in PV systems. However, it has a high number of components. Diodes are used in these inverters to reduce voltage stress. These inverters are composed of multiple two-level inverters stacked on top of each other. In multilevel NPC inverters, the voltage tolerance range and the number of output voltage levels can be increased by adding power switches and clamping switches (Y, V. S., & Vijayapriya, R. 2024).

Diode-clamped multilevel inverters are more effective in applications where switching is performed at the fundamental frequency, and the number of clamping diodes corresponds to the number of output voltage levels (Colak et al. 2011).

The general layout of an NPC inverter is shown in Fig. 1. In these inverters, the switching angle must be calculated to minimize the THD of the output voltage as much as possible. One method for calculating this angle is the harmonic elimination method (Latran, M. B., & Teke, A 2015).

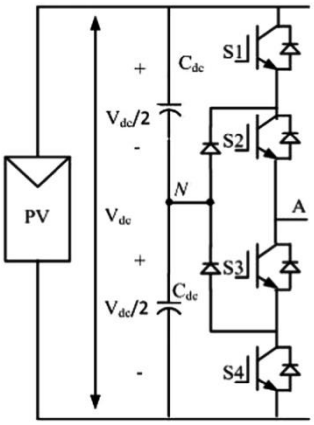


Fig. 1. Structure of the neutral point clamped inverter

2.2. Cascaded H-bridge inverter

These inverters are divided into two main categories: separate and common input (Omede, 2015). In the cascaded H-bridge multilevel inverter, the series connection of the H-bridge cells on the AC side of the inverters is arranged such that each cell is fed by a separate DC source. Various types of these inverters exist, differing in how the DC source is isolated from the cells. Fig. 2 shows the cascaded H-bridge inverter.

Cascaded H-bridge multilevel inverters, or series H-bridge multilevel inverters, are constructed by connecting two or more single-phase H-bridge inverters in a modular series arrangement. The cascaded H-bridge inverter can create more switching states compared to diode-clamped multilevel inverters and capacitor-clamped multilevel inverters.

These additional switching states, along with the modular nature of the neutral point in CHB multilevel inverters, enhance their fault tolerance (Siddique et al. 2024).

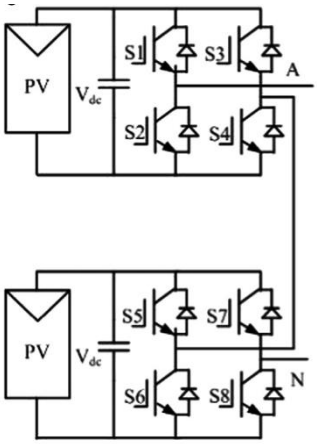


Fig. 2. Structure of the Cascaded H-Bridge Inverter

Since separate voltage sources are used in the cascaded H-bridge inverters, this structure is very suitable for PV or fuel cell applications, where the power generation sources are distinct from each other. Given the use of separate voltage sources, this structure is particularly appropriate for PV applications where the power generation sources are isolated from one another (Tolbert et al. 2024).

3. Conclusion control methods for multilevel inverters

Control of multilevel inverters is commonly achieved using several methods, among which the most widely used are Hysteresis Control Modulation, Sinusoidal Pulse Width Modulation (SPWM), Specific Harmonic Elimination Pulse Width Modulation (SHE-PWM), and Space Vector Pulse Width Modulation (SVPWM) (Bushra et al. 2024).

Naturally, more complex modulation methods provide greater control capabilities; however, since connecting solar systems to the grid requires only a fixed frequency and amplitude at the output, the simplest method, namely SPWM modulation, has been used. The SPWM switching is carried out according to Table I.

Table 1. Parameters used in SPWM switching simulation

Parameter	5-level inverter	9-level inverter
Reference voltage amplitude	10	12
Carrier voltage amplitude (V)	5	3
Modulation index	1	1
Reference wave frequency (Hz)	50	50
Carrier wave frequency (Hz)	2550	2550
DC voltage source (V)	110	55

4. Comparison of Inverters

Due to the different structures of multilevel inverters, each has its own specific features, along with advantages and disadvantages.

The NPC-MLI inverter has controllable reactive power flow and a simple control method, and due to its capability of switching at base frequency, it exhibits high efficiency. However, it has a complex structure due to the large number of clamping diodes required for high output voltage levels.

Additionally, because of the capacitor voltage balancing issue, mixed modulation must be used, and there are challenges with active power flow.

On the other hand, the CHB-MLI inverter, despite requiring independent DC sources and lacking a common DC bus, has advantages such as simple voltage balancing with straightforward modulation, the possibility of using soft switching, a modular structure without clamping, and a low ratio of components to output voltage levels (Alsolami 2022).

These characteristics, depending on the application, can make one inverter superior to the other. In the following sections, the structural comparison, losses, cost, and weight of various inverters are examined.

4.1. Comparison of component electrical stress

One of the advantages of multilevel inverters over two-level inverters is the distribution of voltage among more components. Therefore, cheaper components with lower voltage ratings can be used. For comparison, it is assumed that the maximum output voltage is V_a and the output current is I_a for all structures. In Table II, the required voltage and current ratings for each multilevel inverter structure are shown (Nordvall 2011). According to Table II, the voltage rating for both inverters is the same and is proportional to the input DC voltage and the number of output voltage levels. However, the minimum DC voltage for the CHB inverter is half of that for the NPC structure, which is one of the advantages of the cascaded H-bridge multilevel inverters.

Table 2. Voltage and current rating for each component

Structure	NPC-MLI	CHB-MLI
Voltage rate of components	$V_{dc}/(m-1)$	$V_{dc}/(m-1)$
Minimum DC voltage	$2V_a$	V_a
Current rate of	I_a	I_a

The rated voltage that components can withstand in current source inverters remains constant at all levels, while in voltage source inverters, the rated voltage of components decreases as the number of output voltage levels increases. The opposite is true for the current rating of the components (IEEE standards coordinating committee 21, 1986).

For comparing the two structures, the following components have been used: IGBTs FD300R06KE3, FF200R12KE4, and FMG2G300US60; capacitors FFV34E0107K and C4DEFPQ6380A8TK; diode 85HF60; and MOSFET STE250NS10 (Derakhshanfar 2010).

4.2. Comparison of the number of components

One of the criteria that will influence the complexity of the structure and the selection of the inverter type is the type and number of components required. According to Table III, in the structure of CHB inverters, not only is there no need for a clamping diode, but the number of input DC sources is half that of the NPC structure.

Table 3. The number of different components in various types of m-level inverters

Structure	NPC-MLI	CHB-MLI
DC inputs	3(m-1)	3(m-1)/2
Main diodes	6(m-1)	6(m-1)
Main switches	6(m-1)	6(m-1)
Clamp diodes	3(m-1)(m-2)	0

Although this may seem like an advantage of CHB inverters compared to the other structure, it should not be forgotten that the DC sources in CHB inverters must be separate from each other, whereas the sources in the other two structures can be created using a single DC source and a specified number of capacitors.

4.3. Comparison of losses

One of the important indicators in studies related to power systems is losses, which is also unavoidable when comparing different inverters. Therefore, calculating the losses of various inverters is essential for their comparison.

For this purpose, an induction motor with specifications according to Table IV has been considered as the load for all three structures. In these inverters, the IGBT FD300R06KE3 switch and the 85HF60 diode are used, and the losses of the inverters under the specified load are presented in Table V.

The method for calculating the switching losses of the inverters is explained in (Derakhshanfar 2010). To calculate the losses in both five-level and nine-level inverters, mechanical loading has been applied to an induction motor.

Table 4. Motor load specifications

Parameter	Value	Parameter	Value
Nominal power	75 kW	Stator resistance	0.0355 Ω
Number of pair poles	2	Rotor resistance	0.02092 Ω
Frequency	50 Hz	Stator inductance	0.335 mH
Self inductance	15.1 mH	Rotor inductance	0.335 mH
Effective line-to-line voltage	400 V	Nominal speed of rotor	1484 rpm

Table 5. The losses of the inverters with the IGBT FD300R06KE3 switch (W)

Type	5-level inverter		9-level inverter	
	CHB	NPC	CHB	NPC
Switches losses	1491.2	417.15	2498.2	1725.4
Diodes losses	209.359	254.51	407	490.09
Total losses	1700.60	681.66	2905.20	2215.46

By varying the mechanical load, the power drawn from the system and, consequently, the rotor speed of the induction motor changed. With these loading variations, the input and output power of the inverters were measured, and their difference was considered as the losses.

The results of the analysis of the changes in losses for each structure, based on variations in rotor speed as an indicator of load changes, are shown in Fig. 3.

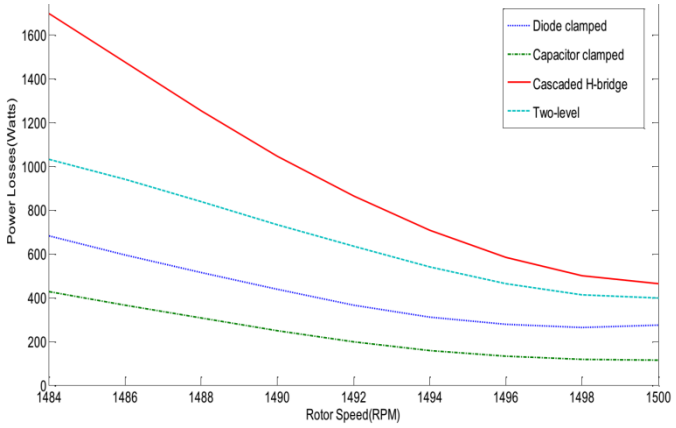


Fig. 3. Losses of five-level inverters as a function of motor speed changes

Under the mentioned conditions, the total power loss for a two-level inverter is 1031.2 W.

Additionally, the losses of three five-level inverters and a conventional two-level inverter have been analyzed based on changes in motor speed (load variations), as shown in Fig. 3. Table V also presents the losses of the five-level and nine-level NPC and CHB inverters for the specified load, using the IGBT FD300R06KE3 switch. Fig. 4 illustrates the losses of the nine-level NPC, FC, and CHB inverters based on variations in the induction motor rotor speed.

Based on Table V and Fig. 4, it is evident that the CHB inverters exhibit the highest power losses at 9 levels, while the losses of NPC inverters remain relatively low.

4.4. Comparison of cost and weight

To complete the comparison, the weight and cost of each structure, including all its components, should be considered. The weight of the IGBT in all structures is 340 grams, but

the weight of the capacitors varies depending on the structure (Derakhshanfar 2010).

The five-level inverters use the C4DEFPQ6380A8TK capacitor, which weighs 419 grams, while the nine-level inverters use the FFV34E0107K capacitor, which weighs 90 grams. This difference is due to the higher input DC voltage in the five-level inverters, requiring capacitors with a higher voltage tolerance. Table VI and Fig. 4 present the weight and cost of the inverters.

Table 6. Comparison of weight and cost of inverters

Type		No. of switches	No. of capacitors	No. of diodes	Weight (kg)	Cost (€)
5	NPC	24	12	36	13.800	4493.3
	CHB	24	6	0	10.670	3722.5
9	NPC	48	24	72	19.704	7415.0
	CHB	48	12	0	17.400	6659.2

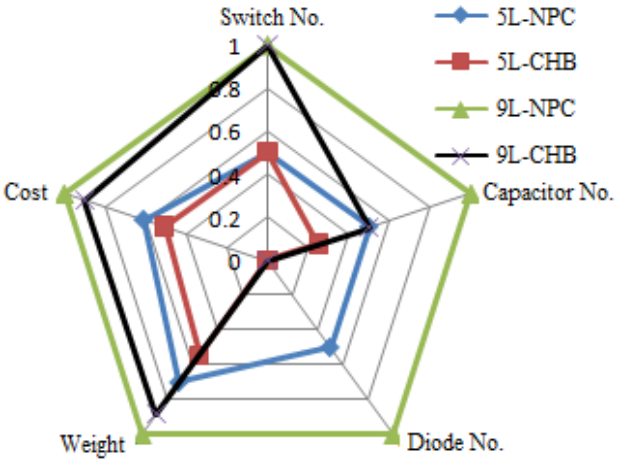


Fig. 4. Comparison of different levels of CHB and NPC inverters

4.5. Comparison in terms of harmonics

The comparisons made so far have primarily focused on the inverters; however, when connecting photovoltaic systems to the grid, other critical factors such as voltage and frequency limits, power factor, voltage balance, and safety must also be considered. One of the most important requirements is the Total Harmonic Distortion (THD) index, which, according to the guidelines for connecting distributed generation resources to the grid, must remain below a permissible limit of 5%. Therefore, it is necessary to calculate the THD, and if it exceeds the allowable limit, it must be reduced using a filter. Consequently, the weight and cost of the filter for each inverter need to be added to their previous values and then compared again. For this purpose, all three structures of 5-level and 9-level inverters have been simulated, and the output filter has been shown to reduce the voltage THD to below 5%. If the combined weight and cost of the 5-level inverters and their filter are less than those of the 9-level inverters with their filter, it is evident that the 5-level inverters will be the optimal choice. Otherwise, a new comparison between the higher-level inverters should be conducted. The harmonic distribution of voltage for the various structures is shown in Fig. 5. Additionally, the simulation results for all four structures are presented in Table VII.

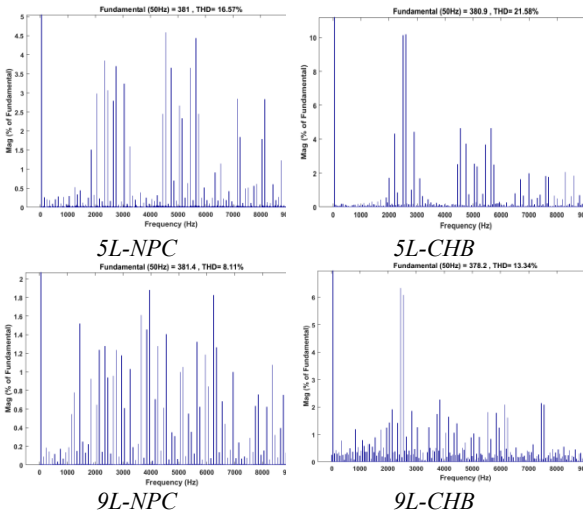


Fig. 5. Harmonic spectrum of phase-to-phase voltage of the inverters

Table 7. Voltage resulting from each inverter structure

Voltage		5		9	
		NPC	CHB	NPC	CHB
THD	Phase	26.36%	27.02%	13.51%	15.25%
	Line	26.57%	21.58%	8,11%	13.34%
Amp.	Phase	220	219.7	220.3	218.5
	Line	381	380.9	381.4	378.2

The results indicate that, given the allowable 5% threshold for voltage THD, none of the structures are permitted to connect to the grid under these conditions. Therefore, either a higher number of levels must be employed, or filtering must be applied to control the harmonic levels, both of which will lead to increased costs.

If it is possible to reduce the THD of the five-level inverters using a filter such that the

combined cost and weight of the five-level inverter with the filter is less than that of the nine-level inverter with its filter, then the five-level inverter with the filter can be selected as the optimal structure. Otherwise, the comparative process must be repeated for structures with higher levels.

5. Reducing harmonic index and filtering

The simplest possible filter for use at the inverter output is a second-order low-pass filter. The design method for this filter type in relation to different inverters is outlined in (Parikshith 2009). Based on this method, the values of inductance (L) and capacitance (C) are calculated using the following equations:

The simplest possible filter for use at the inverter output is a second-order low-pass filter. The design method for this filter type in relation to different inverters is outlined in [20]. Based on this method, the values of inductance (L) and capacitance (C) are calculated using the following equations:

$$L_{pu} = \left(V_{dc(pu)} D(1-D)\pi\right) \Big/ \left(f_{sw(pu)} \sqrt{3}\ \Delta i_{rms(pu)}\right) \quad (1)$$

$$C = 1/L\omega_{res}^2 \quad (2)$$

Using (1), the inductance value is obtained as 0.001 H. According to (Kantar, E., & Hava, A. 2016), to optimize the filters, the resonance frequency, as per (3), should fall within a specific range. With a resonance frequency of 750 Hz, the capacitance value is calculated to be 50 µF.

$$10 f_{base} < f_{res} < 0.5 f_{sw} \quad (3)$$

In the first step, filtering is applied to the 5L-NPC inverter, which has the lowest THD value. By adjusting the LC filter, the harmonic levels are reduced, as shown in Fig. 6, and the THD voltage is decreased to 2.41%.

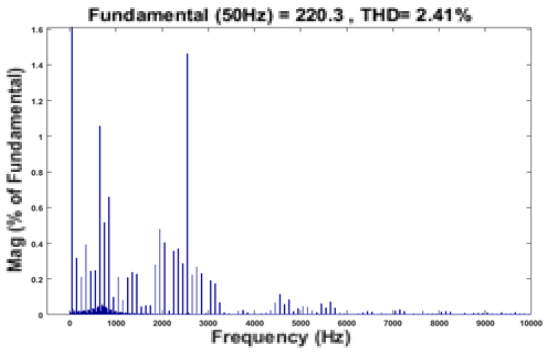


Fig. 6. Harmonic spectrum of the output voltage of the 5L-NPC after filtering

Table 8 shows that the filtering performed has yielded acceptable results, making the inverter suitable for connection to the distribution network.

However, for the 5L-CHB structure, the output filter requires a capacitor of over 380 µF and an inductor of 7.5 mH, which are larger and more expensive compared to the 5L-NPC.

In the 5L-NPC filtering with a total weight of 13.8 kg, three 50 µF capacitors with a nominal voltage of 400 V (with a combined weight of 1.2 kg and a cost of 270 €) and three 1 mH inductors with a nominal current of 16 A (with a combined weight of 1.5 kg and a cost of 300 €) are required.

Fig. 7 shows, through the comparison of the three options, that increasing the number of levels is not cost-effective in terms of price and weight, and therefore, the 5L-NPC with filtering will be the final option for connection to the distribution network.

Table 8. Comparison of allowable (standard) and actual current values after filtering

Current values			Allowed	Real
Total Harmonic Distortion (THD %)			5	3.75
Single harmonic distortion of order n	n<11	Even	1	0.13
		Odd	4	1.17
	11≤n<17	Even	0.5	0.15
		Odd	3	1.83
	17≤n<23	Even	0.4	0.06
		Odd	1.5	0.97
	23≤n<35	Even	0.1	0.04
		Odd	0.6	0.52
	35≤n	Even	0.1	0.01
		Odd	0.3	0.23

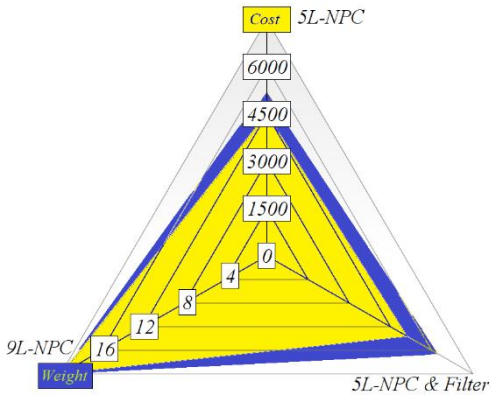


Fig. 7. Comparison of inverter cost and weight

6. Conclusion

In this paper, various inverter structures were studied to select the best option for photovoltaic systems. For this purpose, two common structures, NPC and CHB with 5 and 9 levels, were examined from different aspects such as structural complexity, number of components, losses, weight, and cost. The NPC inverter was chosen among them. Then, the 5 and 9-level structures were evaluated in terms of THD, and the options were narrowed down to 5 and 9-level structures or higher, with and without LC filters. In the final comparison, which was conducted with filtering, weight, cost, and THD indices were reassessed along with the filters, and ultimately, the 5-level NPC inverter was introduced as the more suitable choice for use in photovoltaic systems.

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