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Cascaded H–Bridge Multilevel Inverter: Review of Topologies and Pulse Width Modulation

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Keywords:
Cascaded H–Bridge Inverter; Leakage Current; Multilevel Inverters; Pulse-Width Modulation; Selective Harmonic Elimination; Space Vector Modulation.

Highlights:

- *Reviewing of various topologies of CHBMLI.*
- *Reviewing of different PWM techniques of CHBMLI including, carrier based PWM, SVM, NLM, and SHE.*
- *Review for various applications for CHBMLI including, renewable energy systems, pumps and fans, traction, electric vehicles, and liquefied natural gas (LNG) Plant.*

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Abstract: Multilevel inverters (MLIs) have become more popular for medium-voltage and high-power applications. The cascaded H-bridge multilevel inverter (CHBMLI) is one of the three most popular topologies of MLIs. It was more reliable due to its fewer components per level. The number of possible output voltage levels is more than twice the number of DC sources, the most suitable topology for integration with renewable energy sources, easy to design, and has good performance with modularity. The main disadvantage of CHBMLI is the need for separate DC sources for each H-bridge. However, this can be considered as an advantage to be employed in renewable energy applications. This paper provides a review of CHBMLI topologies and pulse width modulation (PWM) techniques, including fundamental and high switching frequency techniques, such as selective harmonic elimination (SHE), space vector modulation (SVM), nearest level modulation (NLM), and Carrier-Based PWM.

العاكس متعدد المستويات نوع قنطرة H: استعراض البنيات وتضمين عرض النبضة

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قسم الهندسة الكهربائية / كلية الهندسة / جامعة بابل / بابل – العراق.

الخلاصة

أصبحت العواكس المتعددة المستويات أكثر شيوعا للتطبيقات ذات القدرة العالية والفولتية المتوسطة، ويعتبر العاكس متعدد المستويات المتتالي من نوع قنطرة إتش أحد أشهر ثلاثة بنيات للعواكس متعددة المستويات والذي يعتبر أكثر وثوقيه لإمتلاكه أقل عناصر للمستوى الواحد وعدد مستويات الفولتية الخارجة منه أكثر من ضعف عدد مصادر الفولتية الثابتة المغذية له، كذلك يعتبر من أنسب البنيات للإندماج مع مصادر الطاقة المتجددة، بالإضافة إلى تميزه بسهولة التصميم وإمتلاكه أداء عالي وإمكانية زيادة عدد مستويات الفولتية الخارجة منه بسهولة. أما السلبية الرئيسية الموجودة فيه فهي إحتياجه إلى مصدر فولتية ثابت لكل قنطرة إتش والتي تعتبر كفائدة عظمى له في تطبيقات الطاقة المتجددة. هذا البحث يوفر مراجعة لبنيات العاكس متعدد المستويات المتتالي من نوع إتش وكذلك تقنيات تضمين عرض النبضة الخاصة به والمتضمنة: حذف التوافقيات الإنتقائي، تضمين متجه الفراغ، تضمين المستوى الأقرب، وتضمين عرض النبضة المستند على الناقل.

الكلمات الدالة: عاكس متتالي من نوع قنطرة إتش، تيار التسرب، عواكس متعددة المستويات، تضمين عرض النبضة، حذف التوافقيات الإنتقائي، تضمين متجه الفراغ.

1.INTRODUCTION

The demand for energy production is growing every day. Recently, renewable energy resources, including wind, solar, and tidal, have played a vital role in pollution-free and endless energy sources compared to conventional fossil fuel resources. Photovoltaic (PV) energy systems are one of the significant renewable energy resources developed to extract DC output from sunlight effectively. However, most equipment used in homes and businesses runs on an AC source. Therefore, to convert the DC output of the PV into AC power, an inverter is required [1-5]. To overcome the conventional inverter problems, including low output voltage, high total harmonic distortion, and high voltage stress on semiconductor switches, a multilevel inverter (MLI) is employed [6-8]. Because they can meet power rating and power quality specifications as well as have lower distortions in the output waveforms caused by harmonics and electromagnetic interference levels, power systems are currently incorporating multilevel inverters. MLIs offer numerous advantages compared to conventional two-level inverters that use PWM with a high switching frequency. MLIs are currently under investigation as a viable industrial solution for systems that demand exceptional dynamic performance and power quality from 1 to 30 MW. Because they can produce increased electrical potentials using a restricted equipment capacity and low total harmonic distortion (THD) in the output voltages, MLIs are perfectly suitable for utilization in applications involving high-voltage. A multilevel converter system can communicate in different ways with renewable energy sources, including wind, fuel cells, and solar cells. It is mainly based on the control algorithm employed with MLIs' PWM that dictates their specific applications, power ratings, operations, and effectiveness [9]. Three common topologies of MLIs are available: Diode Clamped Inverter or Neutral Point Clamped multilevel inverter (NPCMLI), Flying Capacitor multilevel inverter (FCMLI), and Cascaded H-Bridge multilevel inverter (CHBMLI). From the topologies above, the CHBMLI is considered the most appropriate for integrating a PV system. CHBMLI has a separate DC source for each bridge. A PV panel can replace the DC sources. CHBMLI has advantages over the other two kinds of multilevel inverters because it requires fewer components and permits using an unsymmetrical DC source. Maintaining the same input voltage, the output voltage from a cascaded H-bridge multilevel inverter is twice that from a diode-clamped and flying capacitor [6]. The organization of this paper is as follows: Section 1 describes the introduction. Section 2 describes Cascaded H-Bridges MLI, its features, and the voltage produced at the H-bridge output. Section 3 brings the operational modes of the five-level CHBMLI. Section 4 presents the Cascaded H-Bridge (CHB) based MLI topologies. Section 5 presents the CHBMLI modulation techniques. Section 6 describes suppressing leakage current in the transformerless grid-connected cascaded H-bridge inverters. Section 7 focuses on the application of MLIs. Finally, Section 8 reports the conclusions.

2.CASCADED H-HBRIDGE MLI

CHB-MLIs are created by serially connecting multiple single-phase H-bridge inverters with (SDCS) [9-13]. As illustrated in Fig. 1, every CHB contained one DC source and four unidirectional power switches. There are three voltage outputs set up for each H-bridge. (+Vdc, 0, and –Vdc). By connecting the DC source to the AC output, the required output voltage is obtained by employing different configurations of the four switches (S1-S4). Turning S11 and S41 switches ON generates (+Vdc) output, while when S21 and S31 are in ON state, (−Vdc) output is generated. To generate the zero-level voltage, either S11, S31, or S21, and S41 must be ON. The waveform of the output voltage created by the full-bridge inverter is connected in serial so that the output voltage waveform represents the sum of the outputs of all the single-phase H-bridge inverters. In a cascaded H-bridge inverter, m = 2s + 1 indicates the output voltage levels' quantity per phase, where s is the number of DC sources. In addition, the cascaded H-bridge is free from voltage balancing issues because it does not have DC link capacitors. In contrast, different sustainable energy sources can be used to replace various individual DC sources [9].

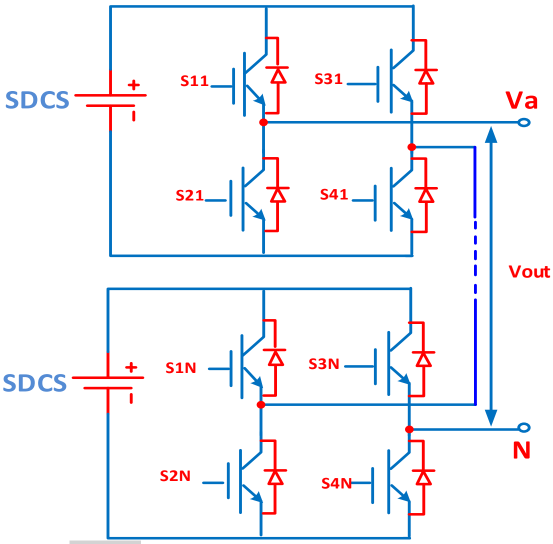

Fig. 1 Single Phase N- Level CHBMLE Topology [9].

3. OPERATING MODES OF CHBMLI

Assuming a five-level CHBMLI, the operating modes are:

- Mode 1: The switches S11, S41, S12, and S42 are turned on to achieve (+2Vdc).
- Mode 2: Output voltage of (+Vdc): Switches S11, S41, S22, and S42 are turned on, whereas switches S21, S31, S12, and S32 are turned off.
- Mode 3: Output voltage (zero) when switches S21, S41, S22, and S42 are turned on, while switches S11, S31, S21, and S32 are turned off.
- Mode 4: Output voltage of (-Vdc), switches S21, S31, S22, and S42 are turned on, whereas switches S11, S41, S12, and S32 are turned off.
- Mode 5: Output voltage of (-2Vdc). Switches S21, S31, S22, and S32 are turned on, whereas switches S11, S41, S12, and S42 are all turned off [1].

The five voltage levels at the output are produced by the 16 distinct switching configurations in the CHBMLI structure depicted in Fig. 1. Table 1 provides a list of potential pairings [14].

Table 1 Switching States for the CMI [14].

Output Voltage	S11	S21	S31	S41	S12	S22	S32	S42
VDC1+VDC2	1	0	0	1	1	0	0	1
VDC1	1	0	0	1	1	0	1	0
VDC2	1	0	1	0	1	0	0	1
VDC1	1	0	0	1	0	1	0	1
VDC2	0	1	0	1	1	0	0	1
0	1	0	1	0	1	0	1	0
0	0	1	0	1	0	1	0	1
VDC1-VDC2	1	0	0	1	0	1	1	0
-VDC1+VDC2	0	1	1	0	1	0	0	1
0	0	1	0	1	1	0	1	0
0	1	0	1	0	0	1	0	1
-VDC1	0	1	1	0	0	1	0	1
-VDC2	1	0	1	0	0	1	1	0
-VDC1	0	1	1	0	1	0	1	0
-VDC2	0	1	0	1	0	1	1	0
-VDC1-VDC2	0	1	1	0	0	1	1	0

4. CASCADED H-BRIDGE-BASED MULTILEVEL INVERTER TOPOLOGIES:

This section explores converter topologies derived from classical H-bridge inverters. Various innovative topologies have been reported for module-integrated inverters [15-19].

4.1. *H5 Inverter (SMA)*

The H5 inverter was developed in 2005 by SMA. Fig. 2 shows this topology, which has a fifth switch interface, a DC-link positive terminal, and an H-bridge. Therefore, it has more switches than a conventional H–Bridge inverter.

- Advantages: more effective, up to 98%, low EMI and leakage current, and decreased core losses.
- Drawbacks: Increased conduction losses due to the additional switches.

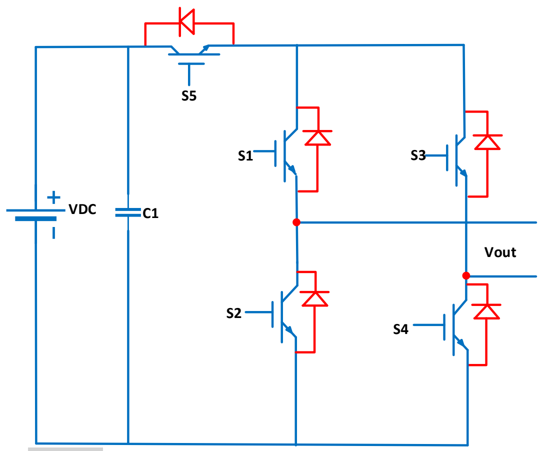

Fig. 2 H5 Inverter Topology (SMA) [15].

4.2. *Improved H6*

In Fig. 3, an improved H6 topology is demonstrated, featuring an added switch at the neutral side of the PV panel to minimize leakage current compared to H5 configuration. In the H6 configuration, the right bridge side operates at the switching frequency, while the left side operates at the line frequency. The disconnecting switches remained activated for an alternate half-cycle to avoid additional switching losses.

- Advantages: lower THD and leakage current.
- Drawbacks: The calculated efficiency was less than H5's because of the additional switch, and the overall common mode voltage swing differs.

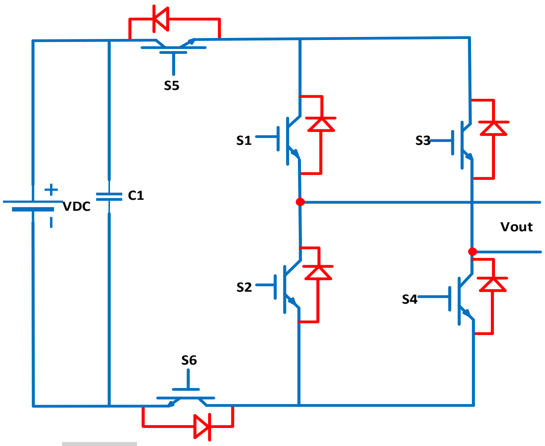

Fig. 3 Improved H6 inverter [16].

4.3.HERIC Inverter (Sunways)

The HERIC converter, a novel converter, was patented by Sunways in 2006 (Highly efficient and reliable inverter concept. It is also derived from the conventional H-bridge by adding two back-to-back IGBTs on the AC side, as shown in Fig. 4.

- Advantages: decrease in core losses, more effective by up to 97%, and very low EMI and leakage current.
- Drawbacks: more switching losses because of two additional switches.

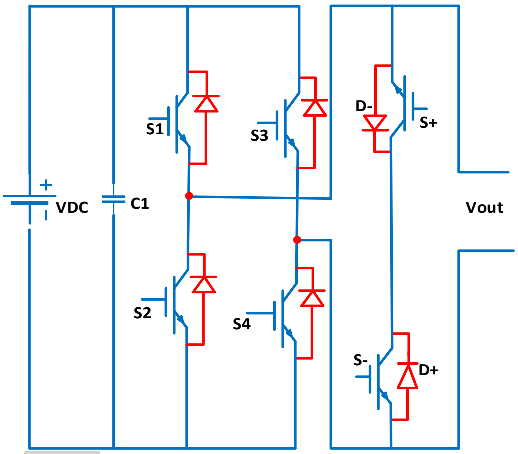

Fig. 4 HERIC Inverter (Sunways) [16].

4.4.REFU Inverter

Refu Solar introduced this topology in 2007, as shown in Fig. 5. The converter combines a half bridge to bypass the AC side and employs a (DC to DC) converter that can be bypassed.

- Advantages: decrease in core losses, more effective by up to 97%, and very low EMI and leakage current.
- Drawbacks: Dual DC voltage and two additional switches are required; however, they were used only at low frequencies.

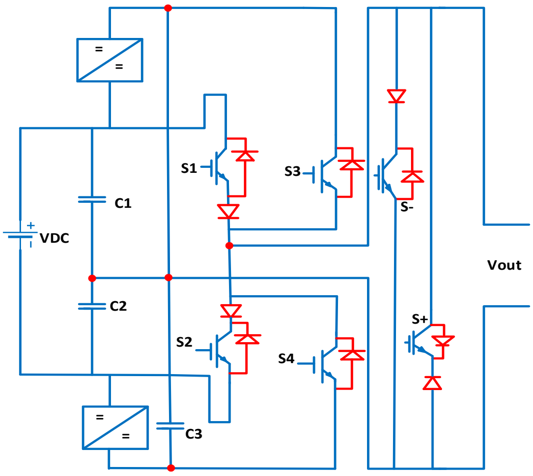

Fig. 5 The REFU inverter [15].

4.5.Ingeteam Inverter

Ingeteam inverter is also called (Full-Bridge with DC Bypass–FB-DCBP). In this configuration, two extra switches and clamping diodes are added to the DC link of a conventional H-Bridge inverter, as shown in Fig. 6. In contrast to H5 or HERIC, where the zero-voltage is in floating state, while the PV panels are in a zero-voltage state, DC switches allow the PV panels to be disconnected from the grid, and the presence of clamping diodes guarantees that the zero-voltage is connected to the ground.

- Advantages: decrease in core losses, increased efficiency, and very low EMI and leakage current. Also, the DC bypass switches rating is half the DC voltage.
- Drawbacks: Dual DC voltage is required, and two additional switches are used only at low frequencies.

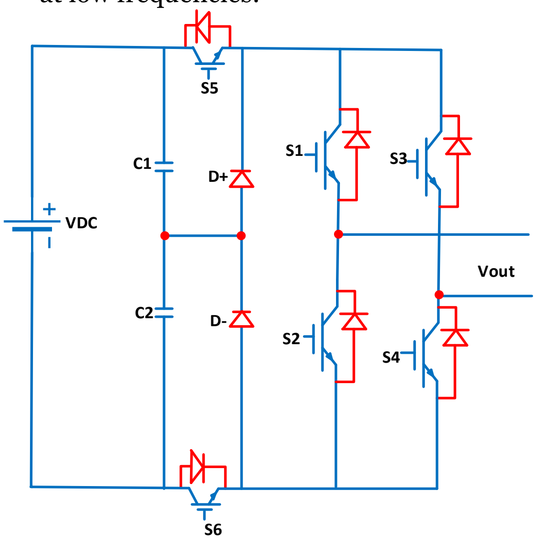

Fig. 6 Ingeteam Inverter [15].

4.6. FB-ZVR

FB-ZVR is also called a Full Bridge Zero Voltage Rectifier using a bridge of diodes, a single switch-S5, and a clamping diode connected to the DC midpoint. A bidirectional grid short-circuiting switch, developed from HERIC, is built in this topology. Turning on S5 and turning off the FB result in zero voltage, as shown in Fig. 7.

- Advantages: decreased in the core losses, increased efficiency up to (96%), and very low EMI and leakage current.
- Drawbacks: The additional switch and four diodes increased conduction losses.

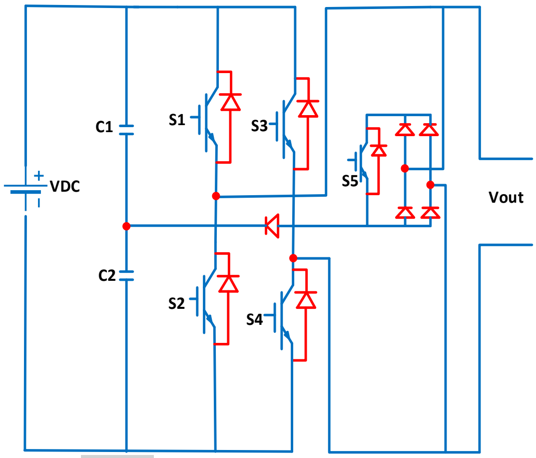

Fig. 7 (FB-ZVR) Inverter [15].

5. CHBMLI MODULATION TECHNIQUES

The procedure of turning on/off the power electronic switches of an inverter in a proper sequence to attain a nearly sinusoidal waveform is known as modulation. Low and high switching frequencies are used in modulation, with a high switching frequency defined above 1 KHz. The classification of the modulation technique is shown in Fig. 8 [20].

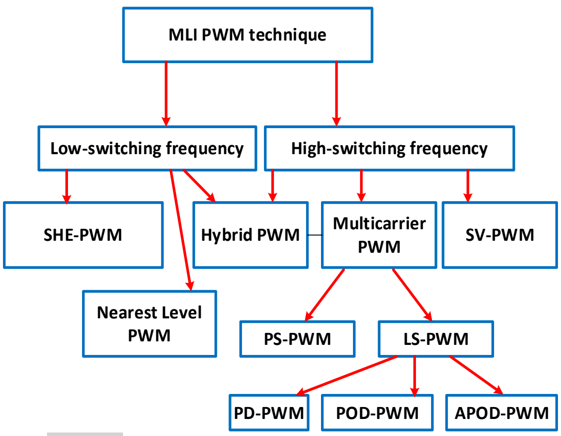

Fig. 8 The Classification of Modulation Techniques [20].

The selection of the specific PWM approach significantly affects the inverter/rectifier conversion systems performance characteristics [21]. CHBMLI modulation techniques are usually an extension of two-level inverter modulation techniques. The CHBMLI modulation techniques can be divided into the following categories based on their switching frequency:

1- Fundamental switching frequency, in which every inverter commutates once every cycle, as in multilevel SHE, SVM, and NLM PWM.
2- High switching frequency, in which every inverter commutates multiple times every cycle, as in carrier-based PWM and SVM.

For CHBMLIs, various modulation schemes have been proposed. Compared to a two-level inverter, complexity increased due to the high density of power electrical devices and redundancies in the switching process. However, this complexity might provide the modulation process with new capabilities, such as minimizing the switching frequency, reducing the common mode voltage, or balancing the capacitor DC link voltages [22].

5.1. Multilevel Carrier-Based PWM

Multilevel carrier-based PWM or Multi-Carrier Pulse Width Modulation (MCPWM) uses some triangular carrier signals that may be changed for phase and/or vertical location to minimize the harmonic of the output voltage. Two widely used types of carrier-based PWM are level-shifted (LS)-PWM and phase-shifted (PS)-PWM [22]. The carrier-based method is more flexible than others and easy to use. It uses some triangular signals (high-frequency signals) with a single sinusoidal signal for modulation; each pulse is individually modulated, comparing every pulse of the carrier signal to the reference sinusoidal signal. The output waveform is almost identical to the reference sinusoidal signal in LS-PWM. If an n-level inverter is built, an (n-1) carrier signal with the same frequency (fc) and amplitude (Ac) will be required. The zero reference is positioned in the center of the carrier signals. The modulation signal has a sinusoidal amplitude (Am) and frequency (Fm). If the amplitude of the modulation signal is smaller than the carrier signal, the output will take on the structure of a modulation signal; hence, it should be linked to the DC connection's negative terminal. If the carrier signal is weaker than the modulating signal, the output voltage should be linked to the DC connection's positive terminal, as illustrated in Fig. 9 [23].

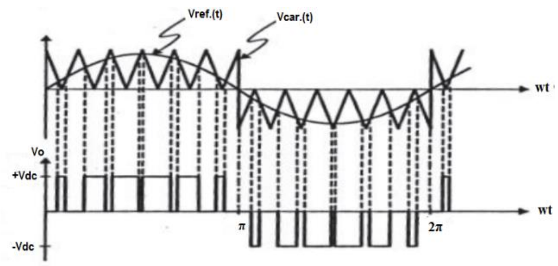

Fig. 9 Carrier-Based PWM [23].

Due to their simplicity, flexibility, and reduced computational requirements compared to SVM, carrier-based methods have been used intensively to switch multilevel inverters [24]. CB-PWM has two types:

a. Level Shifted (LS)-PWM Method

Level shifted (LS)-PWM method uses N-1 carrier signals vertically shifted from one another. LS- PWM can be classified into three types [24-29]:

1- Phase disposition (PD-PWM): All carrier signals arranged in a phase disposition have the same phase. Compared to other disposition techniques, this method provides the least harmonic distortion at higher modulation indices. This method is also suitable for use with cascade inverters [24]. The carrier waveform in this technique is shown in Fig. 10.

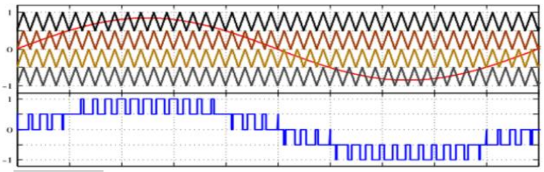

Fig. 10 PD-PWM for five-level inverter [20].

2- Phase opposition disposition (POD-PWM): where all carriers on the vertical axis below zero are in phase; however, they are 180 degrees out of phase with respect to the ones above zero. This method's carriers' waveform is shown in Fig. 11.

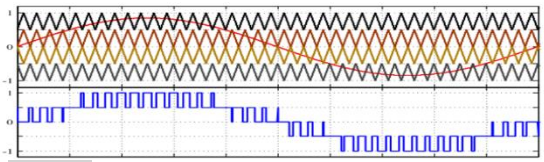

Fig. 11 POD-PWM for five-level inverter [20].

3- Alternative Phase Opposition Disposition (APOD-PWM): where each carrier has a 180° phase difference from its adjacent carriers. This method's carriers' waveform is shown in Fig. 12.

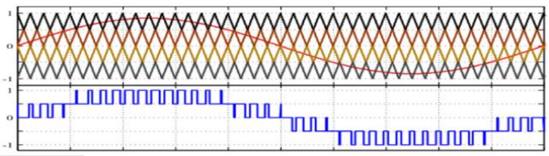

Fig. 12 APOD-PWM for five-level inverter [20].

b. Phase-Shifted (PS)-PWM Method

In this modulation approach, each pair of switches is associated with a carrier signal that changes the phase with each other. In general, (m-1) triangular carriers are needed for MLI with (m) voltage levels. All triangular carriers in this approach share identical frequency and peak-to-peak amplitude, as shown in Fig. 13. however, any two adjacent carrier signals have a phase shift (X), indicated by Eq. (1) [30]. PS-PWM has several attractive features, including low THD, elevated effective switching frequency, balanced power sharing, and semiconductor stress distributions compared to other modulation schemes [31]. For phase-shifted modulation, the N number of cells in CHB multilevel converters requires a (180°/N) phase shift. In contrast, the N number of cells in flying capacitor (FC) multilevel converters requires a (360°/N) phase shift [32].

$$X = \frac{360°}{(m-1)} \quad \textbf{(1)}$$

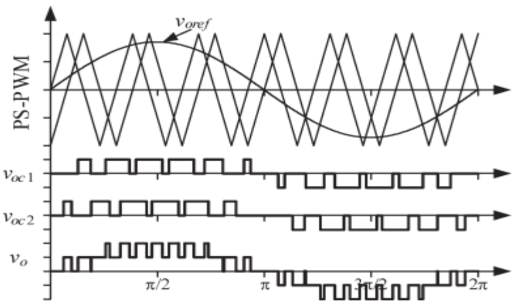

Fig. 13 PS-PWM [22].

Rodrguez et al. [33] demonstrated that the least distorted load voltage was generated by several cascaded cells (Nc) operating in one phase with their carriers shifted by an angle (θc), indicated by Eq. (2).

$$\theta c = \frac{360°}{N_C} \quad \textbf{(2)}$$

for the multicell inverter in a seven-level configuration that uses three series-connected cells in each phase. The angle at which the carriers are shifted produces the least amount of distortion, i.e., θc = (360°/3) = 120°. Sahoo and Bhattacharya [34] illustrated that each H-Bridge of cascaded H-Bridges can handle the same amount of power using the PS-PWM approach with a high switching frequency. However, the unequal power distribution between the cascaded H–Bridges occurred when (P) fell, as indicated by Eq. (3). The reason is that each module received the same current. However, the waveforms of their instantaneous output voltage differed. As a result, different values may be obtained from the instantaneous power integrated over an entire fundamental cycle.

$$P = \frac{f_C}{f_S} \quad \textbf{(3)}$$

where f_c is the carrier frequency, and f_s is the voltage reference frequency. Radan and Shahirinia [24] proposed three novel carrier-based approaches:

1- The initial approach, known as "New," involves introducing carriers positioned above the reference zero-line. These carriers are shifted in phase by (90°) compared to their neighboring carrier; however, they are out of phase by (180°) with carriers located below the zero-line, as demonstrated in Fig. 14.

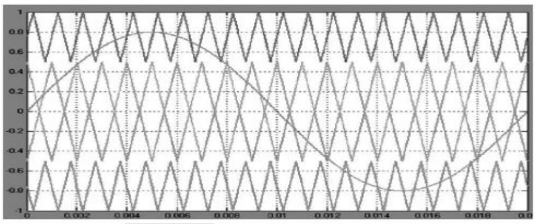

Fig. 14 New-PWM [24].

2- The second suggested approach, SPD, shifts every carrier 180° toward the adjacent one. Unlike other approaches, the amplitude and carrier distribution here are not equal and symmetric, as shown in Fig. 15.

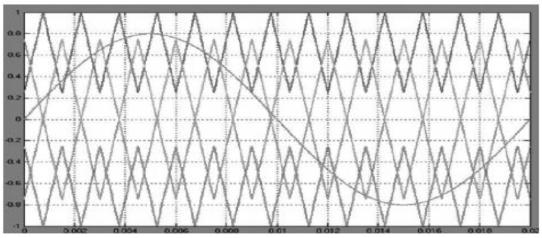

Fig. 15 New-PWM [24].

3- In the third novel approach that has been suggested, called PDS, the carriers of the reference voltage's above-zero line are 180° out of phase and have an amplitude that is the same, but the size of the carrier in this method is double that of the PD method. Each carrier occupies the entire frequency band above the zero line. The carriers positioned both above and below the zero-line exhibit symmetry. Additionally, the carrier frequency in this approach is half the frequency of the carrier used in the (PD) method, as shown in Fig. 16.

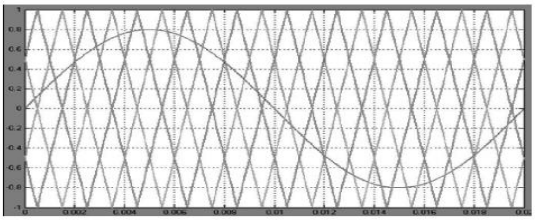

Fig. 16 PDS-PWM [24].

Bang et al. [35] proposed a simple and flexible *PS-PWM* that can be implemented by incorporating an offset voltage to produce the reduced common-mode voltage to reduce the loss caused by switching actions because of the minimization of the commutations. Like the traditional phase-shifted carrier PWM, the suggested technique still uniformly distributed the cell powers and balanced the capacitor voltages. An improved PWM technique was proposed using a single carrier to create five levels of the inverter output terminal. The enhanced PWM approach reduced THD in the current injected into the grid and the filter size required at the output of the inverter terminals, adjusting the harmonics to frequencies that are even multiples of the carrier frequency [32]. The more advanced PWM method reduced the amount of leakage current flowing through the solar panels. A new modulation strategy in [36] is based on dedicated logic functions combined with a sine triangle pulse width modulation technique. Using these specific logic operations, all switch gate pulses were delivered. All inverter switches were controlled by switching pulses from dedicated logic functions, ensuring that the common-mode voltage (CMV) fluctuation was constant while the inverter operated. Sonti et al. [37] proposed a PWM approach for grid-connected PV inverters without transformers to reduce leakage current. Compared to the traditional SPWM technique, the proposed PWM technique used fewer carrier waveforms. For the functioning of two PV sources close to the maximum power point (MPP), the proposed PWM technique was integrated with the maximum power point tracking (MPPT) approach. A PWM method was suggested to suppress the leakage current [38]. In contrast to most existing solutions, the proposed method was easily generalized through the series connection of 5-level CHB blocks. The phase-shifting (PS) approach was widely employed in cascade inverters, while carrier-based modulation schemes were frequently established for diode-clamped inverters based on carrier disposition techniques [22, 24, 39]. Boonmee and Wajanatepin [26] and Maaroof et al. [40] proved that the THD of output voltage waveforms controlled with four PWM techniques (PS, PD, POD, APOD) had almost the same level; however, the output current waveform of CHB-MLI controlled with PS generated the lowest THD.

5.2.Hybrid-PWM Method

The combination of modulation of the fundamental frequency and multilevel sinusoidal pulse width modulation (MSPWM) is employed in the hybrid-modulation approach. It was created with the performance of the well-known carrier-based space-vector modulation, the phase-shifted carrier, the single-carrier sinusoidal modulation, and the alternative phase opposition disposition. These modulations' primary characteristics include equal distribution of the devices' power loss inside a cell and among the series-connected devices and a reduction in switching losses with good harmonic performance cells [41]. Another hybrid-PWM approach was introduced to reduce leakage current [42]. Ambhore et al. [43] proposed two hybrid PWMs based on a sinusoidal pulse width modulation (SPWM).

5.3.SVM- PWM

Space vector modulation can be described as an alternative strategy for operating PWM switches regarding efficiency, ease of usage, low current ripple, and highest transfer ratio. SVM asserts several benefits. These advantages make SVM more appropriate for applications requiring high voltage due to the complexity states and redundant switching states significantly increasing as the number of levels increases. The SVM is used to make the output voltages of the inverter identical to the appropriate values during any switching time [31]. For AC driving applications, the SVM method is widely accepted due to various benefits, such as [44]:

1- Increased output voltage.
2- Reduced THD.
3- High levels of flexibility and efficiency can be used in vector control systems.
4- Raise the ratio of output magnitude voltage by optimizing the use of DC voltage links.
5- Digital signal processing boards are used in the SVM implementation.

Because each triangle has a different number of switching states, conventional SVPWM requires a different number of logical computations for on-time calculations and a varied number of lookup tables. A simple SVPWM that uses just four logical computations for each triangle's on-time calculation, four active switching states, and four lookup tables [45]. The space vector modulation (SVM) technique has recently become popular in NPC-MLI because it minimizes switching loss, self-neutral point balance, almost zero CMV reduction, and DC-link voltage balancing. As a result, it is a preferred option for most applications involving electrical conversion, including grid-connected inverters, high-power industrial drives, renewable energy production, and electric traction [46].

5.4.The Nearest Level Modulation (NLM)

Using NLM as a modulation technique is highly intriguing when the number of submodules (SMs) is very large. Given that there are modular multilevel converters (MMCs) today that easily exceed 200 SMs. Due to the extremely high number of carriers required to generate pulses in such MLIs, NLM is considered a more appropriate PWM technique over PD-PWM or PS-PWM, e.g., 100 carrier signals with phase angle are needed for PS-PWM. The reference voltage for the NLM method is created by combining two different voltage levels. It is possible to create a signal whose mean value equals the desired value by progressively applying each voltage level over a set period [47].

5.5.Selective Harmonic Elimination (SHE) PWM

SHE was proposed when it was discovered in the early 1960s. Integrating multiple switching angles into a square-wave voltage was introduced to reduce the presence of low-order harmonics. Subsequently, a set of transcendental and nonlinear equations were employed in later years to expand upon this concept. The harmonic components of a PWM waveform are mathematically represented by a Fourier series, where the number of equations equals the quantity of harmonics that can be eliminated. The low-order harmonics of the transitions were then adjusted to zero while maintaining the fundamental component. The idea behind SHE-PWM techniques is built upon the foundation of Fourier theory breakdown of the PWM waveform of the voltage/current, and it is contingent upon the formulation or structure of the provided waveform and its characteristics [48,49]. There are two methods to apply the SHE techniques to cascaded multilevel inverters: The first method considers one commutation angle per inverter; as a result, (N -1) harmonics can be removed (N is the number of levels). A similar group of equations to those for two-level (SHE) can be used to determine the switching arrangement of the multilevel SHE. These equations are solved numerically using Newton's method, resultant theory, and genetic algorithms. The second technique combines the multilevel version with the original SHE. There are multiple angles of switching for each voltage level. In this approach, the fundamental frequency is smaller than the switching frequency, and the number of eliminated harmonics remains unaffected by the number of output voltage levels [22]. The development of SHE-PWM for various applications, particularly high power, high-voltage converters, where switching losses are considerable, and their reduction holds significant importance. SHE-PWM exhibits several characteristics, including [48]:

1- Achieve exceptional efficiency while maintaining a minimal ratio between the switching and fundamental frequencies.
2- A wide range of converter frequency response and substantial voltage amplification.
3- Reduce the size of filtering requirements.
4- Eliminating lower-order harmonics, often used in inverter power supply, preventing harmonic interference, including potential resonance with external line filtering networks.
5- Reduced switching losses, tight harmonic control, and the capacity to leave triple harmonics unregulated so that the three-phase system circuit design can benefit.

Performance indices can be improved in many areas of quality, such as THD of current/voltage. The optimization techniques of (SHE) PWM are shown in Fig. 17.

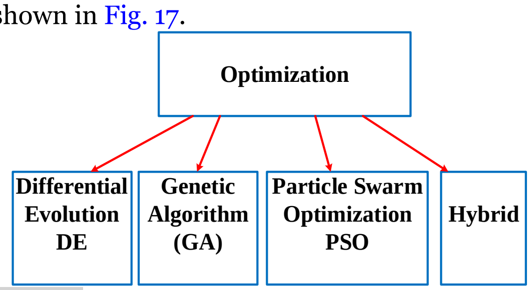

Fig. 17 Optimization Techniques of SHE [48].

SHE-PWM can be converted into an optimization challenge using the following cost function to represent the trigonometric equations for each harmonic [48]. To identify every conceivable collection of solutions, contemporary stochastic search techniques are used to minimize the cost function with the constraint. The DE approach is used to calculate the ideal switching angles after converting the SHE-PWM transcendental equations into a constraint optimization problem. Another method started using two- and three-level waveforms before being expanded to various multilevel waveforms. It is based on a minimization strategy coupled with an arbitrary search. The set of transcendental equations is the object of direct application of the method, yielding all solutions to the SHE problem in a single rather straightforward step even when several harmonics need to be removed. The SHE-PWM problem has also been addressed using genetic GAs. Although GAs were first developed as an optimization method to find the best switching angles in a PWM AC-DC rectifier that minimizes the line current harmonic. They were later expanded to various (SHE-PWM) output waveforms, such as two-, three-, and multilevel, for either THD minimization or selected harmonic elimination. Another possible optimization approach for the (SHE-PWM) problem is PSO, recently used for different waveforms. In addition, for both equal and nonequal DC source instances, instead of removing all low-order harmonics from the multilevel waveform, (PSO) was used to calculate the angles of switching that reduce (THD). Table 2 presents various injected current values and their corresponding THD measurements obtained through fast Fourier transform (FFT) analysis. These measurements were conducted on the line current and voltage of three-phase 5-level cascaded H-bridge grid-connected inverters using carrier-based modulation techniques.

Table 2 The behavior of CHBMLI under various types of carriers-based PWM approaches [40].

Injected current (A)	PS-PWM		PD-PWM		POD-PWM		APOD-PWM	
	Inverter current THD (%)	Inverter voltage THD (%)	Inverter current THD (%)	Inverter voltage THD (%)	Inverter current THD (%)	Inverter voltage THD (%)	Inverter current THD (%)	Inverter voltage THD (%)
100	1.21	39.60	2.71	39.60	6.44	39.30	4.80	39.46
125	0.97	39.30	2.17	39.56	5.15	39.25	3.86	39.41
150	0.81	39.29	1.81	39.53	4.29	39.25	3.23	39.37
175	0.70	39.26	1.55	39.47	3.68	39.22	2.78	39.34
200	0.61	39.18	1.35	39.44	3.22	39.16	2.44	39.28

According to Table 2, it is clear that PS-PWM has the lowest THD for inverter current, while POD-PWM has the highest THD for all injected current values, and POD-PWM has the lowest THD for inverter voltage, while PD-PWM has the highest THD for all injected current values.

6. SUPPRESSION OF LEAKAGE CURRENT IN TRANSFORMERLESS GRID-CONNECTED SYSTEMS

Without isolation transformers, cascaded inverters are more efficient, lighter, and smaller [50,51]. However, when the isolated transformer is removed, a dangerous leakage current travels through the PV module's parasitic capacitance and the ground is passing [38, 50-53]. The total harmonic distortion of the grid current, electromagnetic interference, and safety issues could be exacerbated by the leakage current. Therefore, it is crucial to decrease the leakage current. There are three basic methods to suppress the leakage current, including topology solutions [54-59], filter solutions [60-62], and modulation solutions [37, 38, 42, 52, 63]. If the RMS value of the leakage current or its peak value increases beyond 30 mA and 300 mA, respectively, the PV system must be disconnected from the grid within 0.3 s, according to the German standard VDE 01261–1. Therefore, the leakage current in single-phase transformerless PV systems has attracted considerable attention [38, 50, 64].

7. MLIS Applications

Successful usages of multilevel inverters are highlighted in this section.

7.1.CHBMLI Applications

The actual applications of cascaded H-bridge multilevel inverters include [22]:

a. Pumps and Fans: Almost all industries heavily rely on pumps and fans. Pumps and fans with high voltage and high power are used in boilers, furnaces, nuclear power plants, geothermal energy, cooling systems, underground mines, and other equipment. Because they often operate with variable speed at the partial load, using CHBMLI to drive these devices could significantly improve efficiency.

b. STATCOM*:* Power-quality appliances such as STATCOMs and power-quality conditioners applicable universally are some of the best uses for CHBMLI. These devices are directly linked to networks operating at medium voltage and do not need active power injection to operate normally.

c.Traction*:* To feed the traction motors, traction systems should rectify the low-frequency, high-voltage AC power from the catenary. It has been suggested that (MMCs) can be employed as an interface between low-voltage motor drives and catenary voltage motor drives.

d.Liquefied Natural Gas (LNG) Plant The LNG plant exhibits cyclical behavior throughout the year. In the summer, the turbine is propelled by the power generated from the power station. In the winter, when there is greater energy demand, the power direction is reversed. Due to the poor efficiency of the gas turbine (about 30%), using a compressor directly coupled to one result in an efficiency of only 25%. The efficiency was raised to 36% employing the system. The gas turbine was substituted in this setup with a synchronous motor and a regenerative converter based on CHB topology.

***e. Electric Vehicles**:* Both Dell'Aquila et al. [65] proposed a back-to-back CHBMLI architecture, and Du et al. [66] employed CHBMLI with a floating DC link, functioning as an inductorless boost inverter, are examples of applications of CHBMLI on electric vehicles.

f. Renewable Energy: The CHB multilevel inverter has drawn more attention among various multilevel inverter topologies due to its distinctive construction, capacity to extend to higher voltage levels, number of parts, modularity, and reliability. Integrating with renewable energy sources, it can also be used for several applications requiring high voltage [67]. In the CHB, each H-Bridge has a separate DC voltage source which can be replaced by solar cells in PV applications [68].

7.2.NPCMLI Applications

The actual applications of neutral point clamped multilevel inverter include [69]:

a. Static var compensation-SVC.
b. Variable speed motor drives.
c. Interconnections of high-voltage systems.
d. Integration with high voltage AC/DC transmission systems.

7.3.FCMLI Applications

The actual applications of flying capacitor multilevel inverter include [69]:

a. static-var generation (SVG).
b. AC motor drives.
c. Active filter operations.
d. switched converters.
e. sinusoidal current rectifier.
f. converters with THD-reducing capacities.

8. CONCLUSIONS

This paper reviews topologies and pulse width modulation (PWM) approaches based on cascaded H bridge MLI. Some of the most existing cascaded multilevel converter topologies derived from the standard H–Bridge inverter are explored. A summary of the advantages and disadvantages of each topology is also presented in this paper. Various PWM multilevel approaches are highlighted, focusing on the most appropriate method for cascaded H bridge MLI. Strategies for fundamental switching frequency and higher switching frequencies are included. The main differences between using various PWM approaches, such as carrier-based PWM, which includes PD, POD, APOD, and PS; SVM; and SHE are explored in addition to the suitability of each PWM method to the application. SHE-PWM can be used in various applications, particularly high-voltage and high-power converters, where switching losses pose a significant challenge. While SVM is more suited for high voltage applications since an increase in the number of levels results in additional redundant switching states and increased complexity, the SVM method is widely accepted for AC driving applications. NLM is preferable when the number of submodules (SMs) is very large. Multilevel carrier-based PWM employs multiple triangular carrier signals that can be adjusted in phase and/or vertical position to minimize the presence of harmonics of the output voltage. The PS-PWM approach is widely employed in cascade inverters because it provides equal distributions of power between CHBMLI cells. Several applications employing CHB-MLI are also reviewed. Renewable energy is considered one of the significant applications of this converter.

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