A Review on Performance Enhancement of Multilevel Inverters in Renewable Energy Systems Through Advanced Modulation Techniques

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Abstract

Optimised power conversion technologies are in high demand as a result of the introduction of renewable energy sources (RES) including solar, wind, and hydro to the electrical grid. Multilevel inverters (MLIs) have emerged as practical solutions that outperform the conventional two-level inverter in terms of power quality, advantages, efficiency, and harmonic distortion reduction. MLIs transform the RES's fluctuating output from DC to AC so that it may be fed into the grid. The MLI's performance becomes better as the number of voltage levels rises. Because they produce more sinusoidal voltage (better) waveforms, inverter topologies including 5-level, 7-level, and 9-level inverters have received attention for reducing total harmonic distortion (THD) and enhancing system dependability. This study will discuss how sophisticated modulation strategies might increase MLI performance for renewable energy systems. The decrease of switching losses, voltage control, and system efficiency are examined in relation to the key modulation methods of concern here, which include Sinusoidal Pulse Width Modulation (SPWM), Space Vector Modulation (SVM), and Selective Harmonic Elimination (SHE). The study also addresses issues that need intricate solutions for large-scale renewable energy systems, such as sophisticated control algorithms, voltage balancing, and thermal management for higher-level inverters. Along with potential dynamic environment applications, it also explores the potential role of AI-based modulation strategies to further realise performance increase in MLI. For potential future applications in intelligent and adaptive power conversion technologies for renewable energy, the research concludes with a comparative analysis of a few MLI topologies and modulation techniques.

Keywords: Multilevel Inverter (MLI), Modulation Techniques, Total Harmonic Distortion (THD), Renewable Energy Systems, Artificial Intelligence (AI)

1. Introduction

A major shift to renewable energy sources (RES), such as solar, wind, prospective hydropower supplies, etc., has been brought about by the pressing need for energy on a worldwide scale as well as growing environmental discomfort with fossil fuels[1]. In order to achieve long-term energy security and lower greenhouse gas emissions, these sustainable energy solutions are essential[2]. However, since RES are intermittent and variable, integrating them into the electrical grid presents a number of difficulties that need for advanced power electronics for effective energy conversion and management[3]. Multilevel inverters (MLIs), one of the primary power conversion technologies, have become very well-suited interfaces for renewable energy systems because to their capacity to provide high-quality voltage waveforms with decreased electromagnetic interference and switching losses[4] [5]. MLIs change the DC power that comes from green sources into AC power that can be used in the grid. Multilevel inverters, unlike two-level inverters, make a stepped AC voltage waveform by mixing several lower voltage DC sources[6]. This makes the output waveform better and lowers the Total Harmonic Distortion (THD)[7]. Because of this, MLIs work best in medium- and high-voltage situations, like grid-connected PV systems, wind turbine converters, electric cars, and energy storage systems. Diode-Clamped Multilevel Inverter (DCMLI), Flying Capacitor Multilevel Inverter (FCMLI), and Cascaded H-Bridge Multilevel Inverter (CHBMLI) are the most popular MLI designs. Each has its own structure pros and cons[8]. MLIs are made with different voltage levels, like 5-level, 7-level, and 9-level inverters, to make them work even better. The output pattern becomes more like a linear signal as the number of levels goes up[9]. This leads to lower THD and better power quality[10]. On the other hand, raising the stages makes control, moving, and gear needs more complicated. The modulation technique used has a big effect on how well and how efficiently multiple inverters work[11].

Modulation techniques govern the switching pattern of power devices and directly impact the inverter's output voltage quality, switching losses, and dynamic performance[12]. Conventional techniques like Sinusoidal Pulse Width Modulation (SPWM) and Selective Harmonic Elimination (SHE-PWM) have been widely applied due to their simplicity and effectiveness in reducing harmonics. However, they often fall short in high-level inverter applications where more precise control is necessary[13]. These methods offer improved spectral quality, dynamic response, and control flexibility, especially in applications with rapidly changing loads and grid conditions[14]. These intelligent control schemes enhance voltage regulation, fault tolerance, and grid synchronization, particularly in highly dynamic renewable environments[15]. This review paper aims to provide a detailed exploration of multilevel inverter performance improvements through advanced modulation techniques in renewable energy systems. It presents a comparative analysis of 5-level, 7-level, and 9-level MLIs and their respective modulation approaches[16]. Furthermore, it critically reviews traditional and emerging modulation methods, highlighting their operational principles, benefits, and limitations[17]. The paper also discusses key performance indicators such as THD, voltage balancing, power factor, switching frequency, and efficiency, along with the implementation challenges of deploying MLIs in grid-connected renewable energy applications[18]. Lastly, the paper identifies future research directions for developing intelligent, adaptive, and energy-efficient modulation strategies for next-generation power electronics[19].

2. Multilevel Inverter Topologies

MLIs are used in power systems these days because they can meet the needs for power quality and power rate, and they also have a lower amount of electromagnetic interference and harmonic distortion[20]. An MLI is better than standard two-level inverters in a number of ways[21]. High switching frequency PWM is used in MLIs[22]. MLIs are being thought about as an industrial option for systems that need high power quality and dynamic performance. These systems can have anywhere from 1 to 30 MW of power[23]. Because of this, MLIs are perfect for high voltage uses since they can produce low THD output voltage patterns and higher voltages with a limited device rating[24]. A multiple converter system can work with a lot of different types of renewable energy, like PV cells, fuel cells, and wind[25]. Mostly, the way MLIs work, how efficient they are, how much power they can handle, and what they can be used for depend on the type of control method that is used in their PWM[26]. Over the last few decades, a number of studies have suggested different MLI designs.[27],

https://www.researchgate.net/profile/Gaddafi-Shehu/publication/283350933_A_Review_of_Multilevel_Inverter_Topology_and_Control_Techniques/links/5660447708ae4988a7bf1097/A-Review-of-Multilevel-Inverter-Topology-and-Control-Techniques.pdf,]. In Figure 2, the MLIs are split into two main groups based on how many DC sources are used in their structure. So far, the neutral point clamped (NPC) or diode clamped, the flying capacitor (FC), and the cascaded H-bridge (CHB) designs have been the ones most often used in business. [[28],[29]].

Figure 1: Classification of Multilevel Inverter Topologies

2.1 Diode-Clamped Multilevel Inverter (DCMLI)

Nabae et al. came up with this kind of inverter, which is also known as a neutral point clamped inverter (NPC), in 1981The DCMLI structure, shown in Figure 5, is used to make an output voltage with three levels[30]. Four one-way power switches, two diodes, and two capacitors make up this topology's arrangement. The clamping diodes are linked together in a series so that they can share the blocking voltage. Three voltage values are available at the output of this design: Vdc/2, 0, and −Vdc/2. To make Vdc/2, keep S1 and S2 switches on, and turn on S3 and S4 to make −Vdc/2. To make the 0 level voltage, switches S2 and S3 are turned on. As the corresponding voltage flows through the DC link capacitors, each active switching device should have voltage stress that is held in check by the voltage of each capacitor. This is done by diode clamping[31]. In real life, the stopping voltage is shared by connecting the clamping diodes one after the other. In that case, each active device only needs to block a voltage level of $V/(m-1)$ dc. For clamping diodes to stop reverse voltage, their voltage grades need to be different. It is important to note that the diode reverse recovery of these clamping diodes is a big problem when using the DCMLI with the PWM method in high voltage situations.

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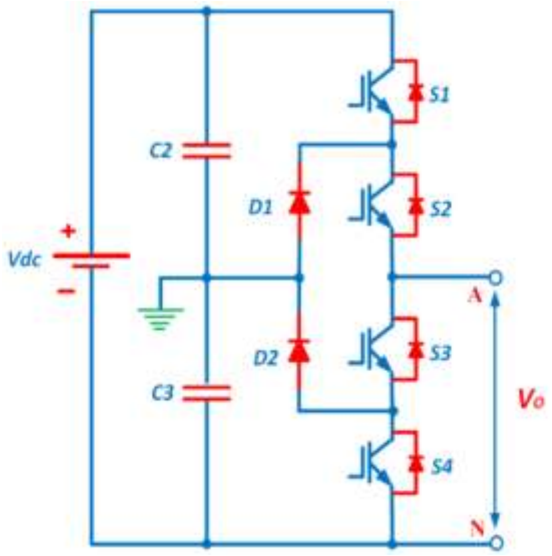

Figure 2. Three-level diode-clamped MLI topology

Compared to the other multilevel converter designs, the DCMLI is more useful in industry because it can give more power, is easier to use, and works more efficiently. It can be used in Static VAR Compensators (SVC) and high voltage system interfaces[32], and motor drives with varying speeds. In the DCMLI converter, there is no need for a capacitance because all the parts share the same DC bus. Because of this, it can be used in back-to-back systems with high power, drives with variable speeds, and others. However, this converter has problems, such as real power flow problems in a single inverter because the DC level can drop or rise without proper control.

https://www.researchgate.net/profile/C-Balamurugan-3/publication/312341557_A_Review_on_Various_Multilevel_Inverter_Topologies/links/587db4a008aed3826af03299/A-Review-on-Various-Multilevel-Inverter-Topologies.pdf, as well as the problem of making sure the DC voltage in the capacitor is stable and balanced in the DC link.

2.2 Flying Capacitor Multilevel Inverter (FCMLI)

The building that this is now stands since 1992. The only thing that makes FC-MLI different from DC-MLI is that it uses floating capacitors instead of clamping diodes. FC-MLI can switch reliably within a phase, which can be used to level out the FC voltages and spread out the losses that happen when switches are on and off. [33]·[34]. Figure 1 shows how the circuit is set up for a five-level FCMLC to be used in GCPV. The output voltage of this MLI can be set to a number of different amounts by using a single dc source (RES). This structure has a lot of benefits, such as being able to be put together in different ways, having a lot of capacitors that can handle power outages better, being able to design more flexible switching patterns, and the voltages of the capacitors naturally balancing themselves. For high voltage levels, however, they need a lot of big storage capacitors, which makes them harder to package, more expensive, and with more complicated control circuits. Also, the capacitors' voltages have to be pre-charged at startup to a value that is close to their standard values.

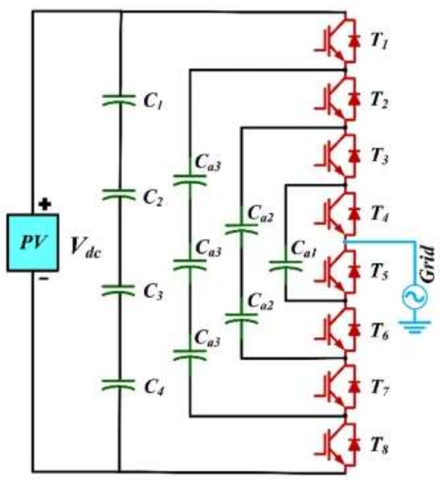

Fig 1: Flying capacitor (FC)-MLI **https://www.nature.com/articles/s41598-024-84296-1**

2.3 Cascaded H-Bridge Multilevel Inverter (CHBMLI)

The CHB-MLIs are made by connecting many single-phase H-bridge inverters with their own DC sources in a series. Figure 3 shows that each H-bridge has one DC source and four power switches that only work in one way [35]. When the DC source is connected to the AC output, each inverter level is set to make three voltage outputs (+Vdc, 0, and −Vdc). The four switches (S1–S4) are connected in different ways to get the desired output. The +Vdc output is made when S1 and S4 are switched to the ON position. The −Vdc output is made when S2 and S3 are switched to the ON position. Either S1 and S2 or S3 and S4 must be on for the 0 output voltage to be made. One way to connect the AC outputs of the full-bridge inverter is in series. This makes the voltage pattern that is made reflect the sum of all the outputs from the inverters. The number of output phase voltage levels in a cascade inverter is shown by $m = 2s + 1$. The number of DC sources is shown by s https://www.scielo.org.mx/pdf/jart/v11n1/v11n1a11.pdf. The number of parts needed for this design is lower than for DCMLI and FCMLI because it doesn't need binding diodes and capacitors. Besides that, it doesn't have the voltage balance problem because it doesn't have any DC link capacitors[36],[37]. If voltage balance is the most important thing, the multiple DC sources can be switched out for either separate renewable energy sources with separate converters or a single renewable energy source with multiple output converters.

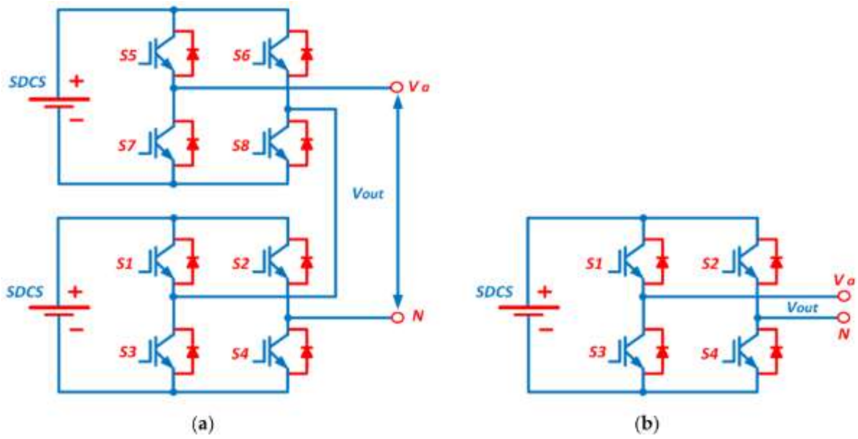

Figure 3. (a) Five-level CHBMLI topology, (b) three-level CHBMLI topology

Different ideas have been put forward for how multiple cascaded inverters could be used to create static variables and connect to RES [38]They have also been suggested for use in situations that need batteries. Another way to use a cascade inverter for static var adjustment is to connect it directly to the power source and connect it in series. Because they need different DC sources for fuel cells and photovoltaics, they can be used to connect RES to the AC grid[39] They Another idea is to use them as the main traction drive in electric cars, since several batteries or ultra-capacitors can work as SDCSs in those cases.

It is easy to change the structure of this design so that it can be used with different numbers of inverter levels. It is possible to make different output voltages by using different DC source ratios and cutting down on the switching duplication caused by inner voltage levels. Transformer-dependent CHBMLIs are being made to cut down on the need for separate DC sources. They have the same structure as CHBMLIs, but the output voltage of the isolation transformer is connected in series instead of parallel[40].

Comparison between CHB-MLI, FC-MLI, and DC-MLI Topologies

As shown in Table 1, this part compares the three main MLI topologies, which are called "classical topologies," in terms of their pros and cons.

Table 1. Advantages and disadvantages of the classical topologies (DC-MLI, FC-MLI, and CHB-MLI)

Types of MLI	Advantages	Disadvantages
DC-MLI [[41],[42],[43]]	• A good option for industrial applications. • Exhibits high fundamental frequency switching efficiency. • Can precharge the capacitors as a group. • Control method is simple. • Reduces the number of required DC sources. • Appropriate for fault-tolerant application. • The use of neutral clamping switches can solve the issue of voltage balancing and uneven loss sharing between the switching devices in neutral point clamped (NPC) converters.	• The complexity of voltage balancing circuit. • The unequal share of losses between inner and outer switches. • Increased number of clamping diode as the level increased.
FC-MLI [[44],[45],[46]]	• Reduces the number of required DC sources.	• The complexity of voltage balancing circuit.

	• Phase redundancies are available for balancing the voltage levels of the capacitors. • Appropriate for fault-tolerant application. • Real and reactive power flow can be controlled • No need for filters to reduce harmonics.	• Requires numerous capacitors for high levels. • High losses and switching frequency for real power transmission. • High installation cost.
CHB-MLI [[47],[48],[48]]	• Modular and simple structure. • Easy to extend to higher levels. • Requires only unidirectional switches. • Appropriate for fault-tolerant application. • Potential of electric shock is reduced due to the separate DC sources. • Asymmetric source configuration can be employed. • Can be implemented as a single DC source configuration.	• Less number of output voltage levels. • Requires more number of gate driver circuits. • Requires several DC sources to increase the output voltage. • Limited to certain applications where separate DC sources are available. • Switches have to bear blocking voltage equal to the input voltage value. • Loss of modularity (asymmetric source configuration). • Implement cost is high (asymmetric source configuration). • Switches are differently voltage rated (asymmetric source configuration).

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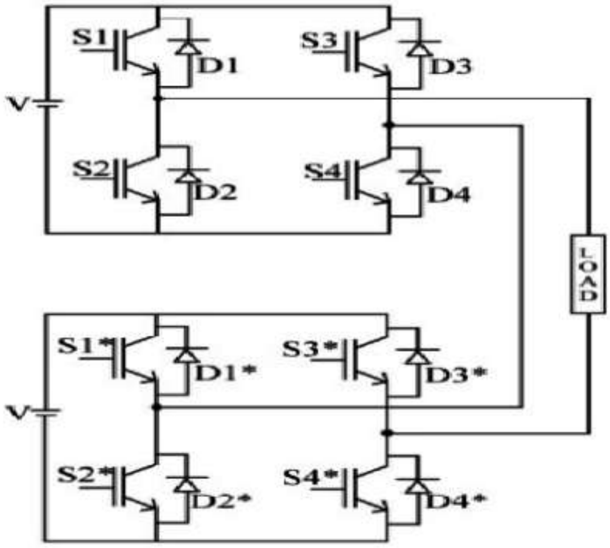
3. Types of Multilevel Inverters Based on Number of Levels

There is a big difference between the output quality and harmonic distortion depending on how many voltage levels are in a multilayer inverter (MLI). Total Harmonic Distortion (THD) goes down as the number of levels goes up because the inverter makes the output pattern more symmetrical. This is important for power quality in situations where accurate waveform creation is needed, like in green energy systems that are connected to the power grid. Higher voltage levels also mean that each semiconductor device is under less voltage stress, that makes the inverter more efficient and reliable overall.

More levels in an MLI make the output pattern closer to the ideal sine wave by lowering low-order harmonics. This leads to better performance, especially in green energy systems like solar power and wind energy. By lowering harmonics, the technology cuts down on the need for heavy filters and makes the grid more compliant.

3.1 5-Level Inverter

Most 5-level inverters use a cascaded H-bridge setup with two H-bridge cells. This lets the inverter make five different voltage output levels. Most of the time, the five levels are +V_dc, +V_dc/2, 0, -V_dc/2, and -V_dc. Two DC sources are used for each H-bridge, and a switching process creates voltage steps that are close to what is wanted at the output. Compared to regular two-level inverter setups, this one makes less harmonic content as well.

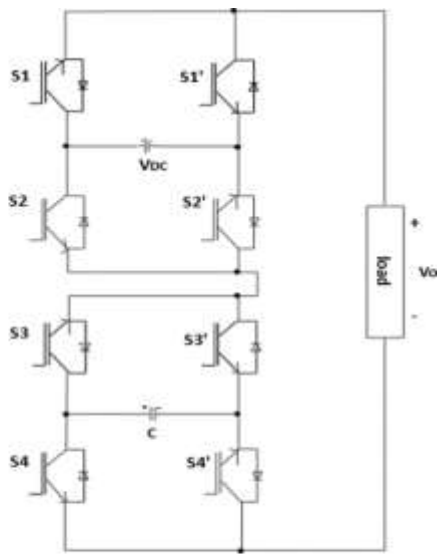


In practice, 5-level inverters tend to operate in medium-power applications such as small scale solar systems, uninterruptable power supplies (UPS), and deforming DC-AC conversion for electrical grid applications. 5-level inverters tend to represent a midpoint of complexity and performance, generating lower THD levels than two-level inverters; about the same power quality as they directly correlate with the number of output voltage levels; however, they are less optimized for a higher level inverter common in high-power applications.

3.2 7-Level Inverter

The 7-level inverter uses a total of three H-bridge cells (for three additional voltage levels) to create 7 distinct voltage levels. The levels typically include +V_dc, +2V_dc/3, +V_dc/3, 0, -V_dc/3, -2V_dc/3, and -V_dc. The design allows us to add an improved voltage waveform by taking advantage of the additional switching states.

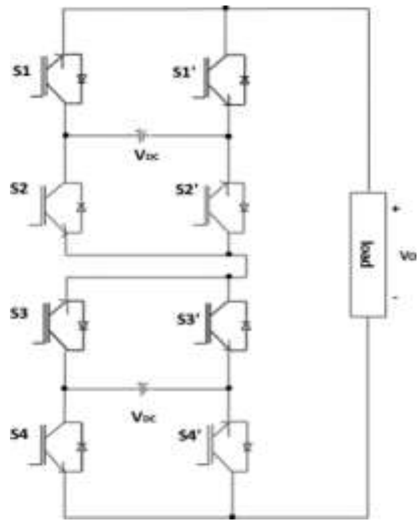
The method uses multiple H-bridges that are synchronized, with modulation such as Space Vector Modulation (SVM) or Selective Harmonic Elimination (SHE), to minimize harmonics and create better overall output quality. The array of voltage levels provided by the 7 Level inverter allows for a much smoother waveform than the 5 level inverter with much less filtering.



7-level inverters are often used in grid-connected photovoltaic systems, wind energy conversion systems, and electric vehicle charging stations, where they offer a substantial efficiency and power quality improvement over 5-level systems. The THD is down to approximately 1.32%, which is much better with regard to how beneficial 7-level inverters are in integrating renewable energy into the grid. The fact that there are more levels reduces harmonics and provides better compliance with the grid.

3.3 9-Level Inverter

A 9-level inverter uses four H-bridge cells in series to generate nine distinct voltage levels. The levels are typically +V_dc, +4V_dc/5, +3V_dc/5, +2V_dc/5, +V_dc/5, 0, -V_dc/5, -2V_dc/5, and -V_dc. With 9 levels, the inverter output becomes even closer to a pure sinusoidal waveform, offering significant improvements in harmonic reduction and voltage utilization.



Incorporating more levels results in improved dynamic performance, higher efficiency, and lower switching losses. A 9-level inverter also ensures reduced voltage stress on individual power semiconductors, thus enhancing their lifespan and system reliability.

The THD for a 9-level inverter is typically 0.76%, a significant reduction compared to 1.35% for 5-level and 1.32% for 7-level inverters. This makes 9-level inverters ideal for high-power applications where power quality is critical, such as large-scale grid-tied renewable systems.

4. Modulation Techniques for Multilevel Inverters

The main goal of a modulation method is to give each switching device in an MLI synchronised pulses[49]. They are also used to lower the amount of harmonics in the output voltage and current waves. This is how modulation methods are usually used with all types of MLIs, not just T-MLIs. Most experts and makers have used the same modulation methods in their MLI designs for many years, as shown in Figur

https://core.ac.uk/download/pdf/186895584.pdf,52,53,54].

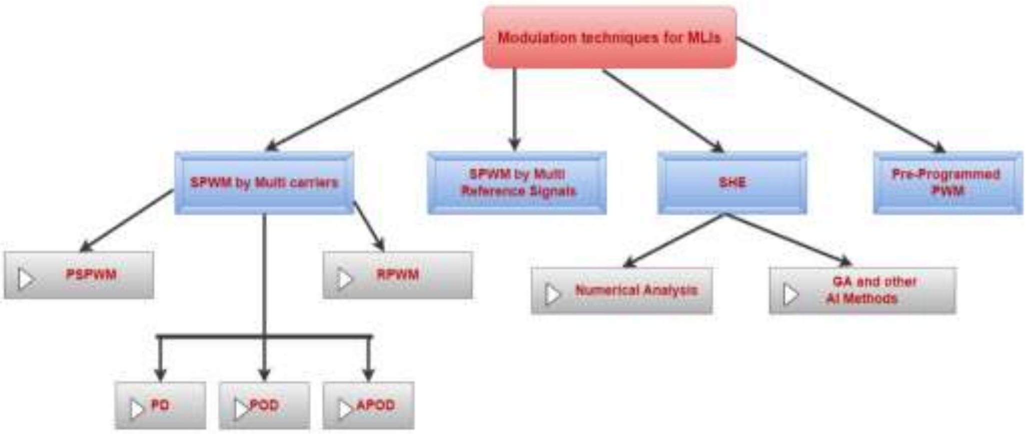


Figure 4. Modulation techniques of single-phase MLIs

4.1 Sinusoidal Pulse Width Modulation (SPWM)

Most single- and three-phase inverters use sinusoidal PWM, also written as SPWM, as their modulation method. There are several ways that SPWM can be used for MLIs. It is used in this part by comparing a number of saw-tooth or triangular carriers at a high frequency with a sine wave that acts as a reference (modulating) signal at a basic frequency. Usually, you need two carriers for a three-level MLI. For a five-level inverter, you need four carriers. For a seven-level inverter, you need six carriers. For an N-level inverter, you need N-1 carriers[50]. If you switch from a sine wave reference signal to its absolute function, that is, a reference signal of |sin(x)|, the number of carriers can be cut down to -12. SPWM with more than one carrier can be put into the following groups.

4.1.1. PD, POD, and APOD

All three triangle waveform carriers in the phase disposition (PD) method are set in different places, even though they have the same phase, frequency, and amplitude. This is shown in Figure 15a. At the centre frequency, the main harmonic elements are brought in https://d1wqtxts1xzle7.cloudfront.net/71651472/ecij.2015-libre.pdf?1635211807=&response-content-disposition=inline%3B+filename%3DSimulation_of_Cascaded_H_Bridge_Multilev.pdf. Only odd sounds come out of this method [10]. You can use modulation in the PD method for an MLI with an uneven structure as well[51]. All three waveform drivers in the phase opposition disposition (POD) method are 180° out of phase with each other. All of the carriers have the same frequency and pattern intensity, but they are spread out in different places, as seen in Figure 15b. The carrier signal is moved 180° out of phase in the alternative phase opposition disposition (APOD) method, as shown in Figure 15c.

4.1.2. PSPWM

One type of SPWM that uses multicarrier modulation is phase-shifted (PSPWM). Each triangle-shaped carrier wave has the same highest level of amplitude and frequency. However, there is a phase shift of Πcr = 360°−1 between any two neighbouring carrier waves, where N is the voltage level of an MLI [52]. As shown in Figure 15d, a five-level inverter needs four triangular carriers, so there is a phase shift of 90° for any two carriers that are next to each other.

4.1.3. RPWM

RPM stands for random pulse width modulation. It is an SPWM method that has become an important way to reduce the harmonic effects of PWM inverters. There is a lot less electromagnetic and sound noise coming out of RPWM inverters now[53], [54], [55],[56]. The sine wave output or its absolute function is used to compare a random number, as shown in Figure 15e.

4.1.4. SPWM by Multi Reference Signals

There are only one or two triangular carrier waves and multi-reference signals in this modulation method. These have the same frequency and phase, but their position is moved. There must be two sine wave standards for a five-level amplifier. There must be F−12 sine wave reference signals for N-levels of the output voltage, as seen in Figure 15f[57],[58].

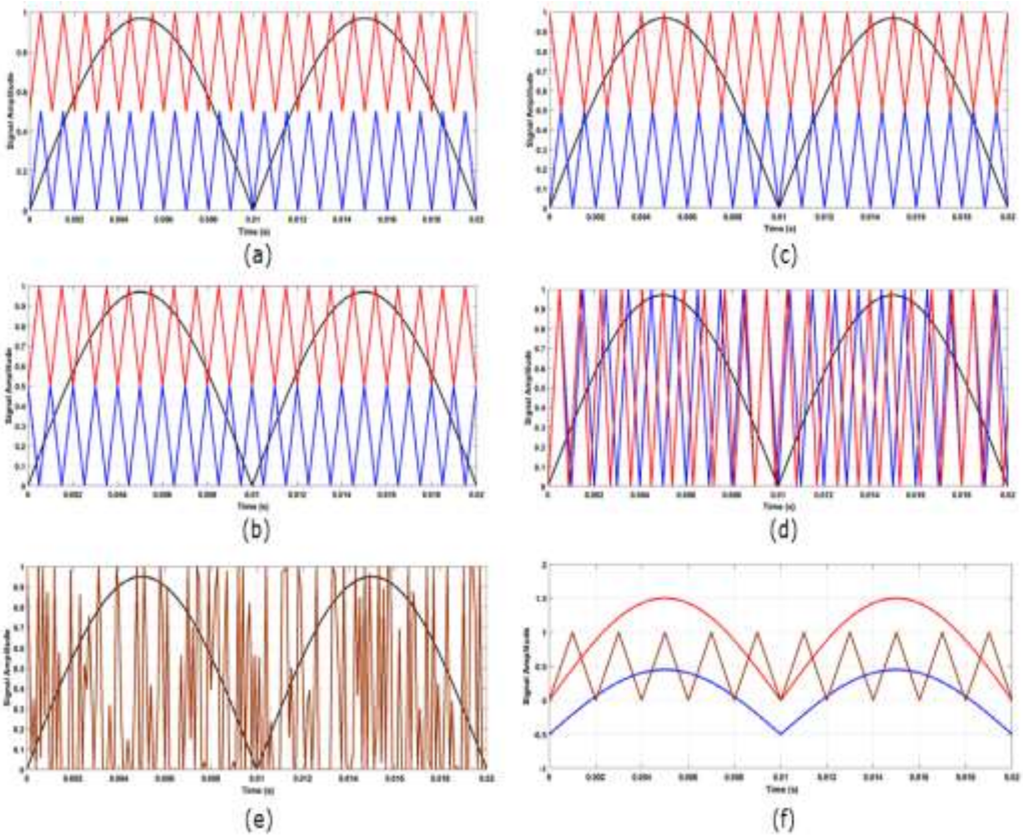


Figure 15. SPWM modulation techniques for five-level inverter: (a) PD, (b) POD, (c) APOD, (d) PSPWM, (e) RPWM, and (f) multi references PWM

4.2 Selective Harmonics Elimination (SHE)

The PWM by SHE method is based on voltage patterns in Fourier analysis and a selected harmonic reduction system. The SHE figures out a part of the switching process that keeps the switching frequency the same while filtering out unwanted output voltage harmonics. The math formula for the harmonics that aren't present in N-level MLIs is $N-32$. To get rid of the 5th and 7th harmonics in a seven-level cascaded HB, for example, set the output phase voltages of each harmonic order to zero. In math, Equations (1) and

(2) show a normal odd harmonic component and output phase voltage. The following table shows the odd harmonics and switching angles[59]:

For general output voltage,

$$V(\omega t) = \sum \infty n = 1,3,5, \ldots Vnsin(n\omega t)$$

The odd harmonic components,

$$Vn = 4\, Vdcn\, \pi \sum ni = 1cos(n\, \vartheta i)$$

For a seven-level inverter, the PWM by conventional SHE includes three switching angles. So, the nonlinear mathematical expressions are as follows:

$$\begin{cases} \cos\alpha_1 + \cos\alpha_2 + \cos\alpha_3 - \dfrac{3\pi}{4} M = 0 \\ \cos 5\alpha_1 + \cos 5\alpha_2 + \cos 5\alpha_3 = 0 \\ \cos 7\alpha_1 + \cos 7\alpha_2 + \cos 7\alpha_3 = 0 \end{cases}$$

Also, the condition that the switching angles must fulfill is as follows:

$$0 < \alpha 1 < \alpha 2 < \alpha 3 < \pi 2$$

The optimal solutions of Equation (3) are found by taking into the consideration the constraints of Equation (4) through minimization of the objective function $F1$ as follows:

$$F_1 = \frac{\sqrt{V_5^2 + V_7^2}}{V_1}$$

where $\alpha 1, \ldots, \alpha 3$ are the switching angles, $V1$, $V5$, and $V7$ represent the fundamental component, fifth component, and seventh component of the output voltage, respectively.

When SHEPWM technology is used in MLIs, the output voltage is better than when other modulation methods are used. It is possible to get tight control and a high output harmonic voltage while keeping the frequency of the switching devices as low as possible in the output voltage pattern. The high intensity of the first set of unwanted harmonics is seen as a problem with SHE[60], [61]. The usage of numerical analysis for SHE for MLIs with a high number of levels is inefficient [62],[63]. These issues have been solved directly with optimisation methods that use artificial intelligence (AI) techniques. These methods are mostly used because they don't have long ranges and don't depend on any starting assumptions. This means they can do less computing. These methods for optimisation also work well with cheap DSPs. There are many bioinspired algorithms, such as the genetic algorithm (GA), the bee algorithm (BA), particle swarm optimisation (PSO), and differential evolution (DE). Using objective functions can cause nonlinearities in low-order harmonic equations. To lower harmonics, experts usually use a number of different target functions. Many ideas have been put forward to solve harmonic reduction problems

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5. Performance Enhancement Analysis

Modulation methods have a big effect on how well multilevel inverters (MLIs) work. They change several important parameters, including Total Harmonic Distortion (THD), switching losses, power quality, voltage balance, and fault tolerance. Each modulation method tries to find the best settings for these factors so that MLIs work well, with few loses and better total performance.

Total Harmonic Distortion (THD):

THD measures the amount of harmonics in the inverter's output and is an important way to judge the quality of the output pattern. Advanced modulation methods like Space Vector Modulation (SVM) and Selective Harmonic Elimination (SHE) lower THD by getting rid of low-order harmonics and making the switching process of the inverter's power devices work better. THD goes down as the number of voltage levels goes up (for example, from 5 levels to 9 levels), and the output pattern gets closer to a pure sine wave. This is especially important for uses that need high power quality.

Switching Losses:

The switching losses of multilevel inverters (MLIs) depend on the switching frequency and number of switching devices used. The use of phase-shifted PWM (PSPWM) and hybrid modulation strategies can minimize switching loss. By increasing the number of devices and optimizing switching sequences, in this application, hybridity helps reduce losses for the switching device(s). Hybrid modulation consists of two or more modulation methods to modify switching to minimize switching losses while delivering performance needs.

Power Quality:

It is very important to have good power when working with green energy systems because the inverter output needs to be in sync with the grid. Simple modulation methods, such as Level-Shifted PWM (LSPWM) and Phase-Shifted PWM (PSPWM), make the power better by creating a good voltage pattern with fewer harmonics. Both modulation methods work to make the inverter produce more like a sine wave with less distortion. This makes the connection to the grid more stable and reliable. In general, power from high-level inverters (9-level) is better than power from 5-level or 7-level inverters because they make less noise.

Voltage Balancing:

In MLIs, particularly those that have many levels, maintaining voltage balance across the DC link capacitors throughout operation is a critical aspect for efficient operation of an MLI. Methods that process voltage balancing for MLIs, for example Phase-Shifted PWM methods, ensure balanced voltage distribution across the capacitors at all times so that the voltage never gets unbalanced and potentially ruin the inverter or its efficiency. In addition to reliability, with voltage balancing all capacitors are charged and discharged equally which can extend the life of inverter.

Fault Tolerance:

Using a modulation strategy such as Artificial Intelligence (AI)-based modulation, can enable the inverter with increased fault tolerance by adjusting the switching sequence in real time relative to the operating states. Example scenarios where system faults may be persistent in an environment prone to faults, can enable the AI-based system to adjust based on the fault and still perform in a stable way while minimizing human intervention. These modulation strategies can enhance the reliability of the inverter and system fault tolerance, especially in renewable energy systems, where a failure of the overall system may take place where power to a specific area is lost.

6. Challenges and Limitations

multilevel inverters (MLIs) have several advantages that include better power quality and lower harmonic distortion, and have significant challenges and limitations that will need to be addressed for efficient and reliable work. The most prominent challenge is the complexity in control algorithms for inverters of higher levels. The control strategy of an inverter which has many voltage levels will have to manage many switching devices as well, leading to considerable higher computational complexity. If we look further to advanced modulation techniques that need to go beyond traditional switching strategies like Space Time Vector Modulation (STVM) or variable multilevel approaches like that of Artificial Intelligence (AI) to arrive at a switching decision and successfully manage the inverter voltage levels. These higher control algorithms are providing challenges for implementation as they require significantly more computational power making real time application problematic and can create lags in dynamic systems that make the inverter less functional or powerful when controlling physical systems. Additionally, there is an increase in costs and size considerations in MLI of higher level. The requirement of additional components, such as more capacitors, voltage sources and more power semiconductor devices lead to an increase in both cost and the physical criteria of the inverter to be larger in size and volume than lower level counterparts. This may ultimately limit the overall scalability of multilevel inverters, especially in types of implementations where cost and the size will ultimately limit their deployment and implementation like residential or Small-scale approaches in renewable energy sectors.

Other important challenges include capacitor voltage balancing and thermal management. As the number of levels increases, balancing capacitor voltages is complicated, requiring sufficient control to minimize voltage imbalances and prevent system inefficiency or failure. Also, higher levels produce more heat and thermal management is important to avoid exceeding temperature limits and maintain reliability. Finally, real-time implementation issues with AI-based modulation techniques will always remain a barrier. Although AI-based modulation techniques improve performance, their real-time implementation on hardware requires high processing capabilities and results in delays. These issues affect their use in renewable energy systems that are dynamic and constantly changing.

7. Future Scope

The multilevel inverter's (MLI) future within renewable energy systems appears to be very bright, with a number of exciting advancements and developments possible. As renewable energy sources — particularly solar and wind — dominate the energy market globally, the requirement for high efficiency and high-performance power electronics will only increase. A major area of future development for MLIs will be in intelligent modulation methods. The usage of AI (Artificial Intelligence) and ML (Machine Learning) in modulation methods and strategies will improve performance by allowing MOD to keep turning the switches optimally when generating real-time switching patterns. AI can help improve efficiency further by dynamically adjusting the control strategies associated with switching and modulation according to power demands from real-time sensing, where the modulation changes appropriately, and almost immediately, according to the power input, especially in grid-tied renewable applications, say for a wind and PV generated power plant when generation fluctuates depending on weather conditions (clouds, wind). In addition to AI and ML, improvements in technology through semiconductor devices, such as wide-bandgap negative (e.g., SiC, GaN) will lead to next-generation MLI technologies for semiconductor devices. Wide-bandgap devices will permit operation at higher switching frequencies by producing higher modulation frequencies, reducing switching loss, and providing better overall inverter performance. Meeting demand side management and market conditions for the grid will also require methods based on smart grid technologies and communicate interfaces to enable real-time management, distribution, and communications while using the IoT (Internet of Things) and cloud computing structures. An another significant area of development is modular multilevel converters (MMC). MMC has higher power ratings and scalability and fault tolerance, and designs for the MMC are being considered with large-scale grid connections and renewable energy to the grid, with benefits ranging from improved voltage balancing to more flexible control schemes. In addition, the work currently in development on high-level inverter topologies (15-level, 21-level, etc.) and hybrid inverter systems will lead to advancements in performance, harmonic reduction, and energy efficiency. This advancement will ultimately lead to the next generation of modular multilevel inverters (MLIs) that are more compact, cost effective, and being able to support the growing demands of high-power renewable energy systems.

8. Conclusion

To sum up, multilevel inverters (MLIs) are a key part of modern power electronics, especially in systems that use green energy. The MLI can provide good AC power with low harmonic distortion and switching losses. This makes it possible for green energy sources like solar and wind energy to be added to the grid. When you use more voltage levels—5-level, 7-level, and 9-level—you get a clearer pattern and better power quality overall. This drops the Total Harmonic Distortion (THD) level so that the grid can help. Advanced modulation methods like Sinusoidal Pulse Width Modulation (SPWM), Space Vector Modulation (SVM), and Selective Harmonic Elimination (SHE) are used by MLIs to give their users a lot of value. These methods make it possible to fine-tune switching patterns (patterns that lower harmonic content), control voltage, and make the system work better. In addition, AI modulation techniques will provide further advantages on the basis of a quick/real-time adaptive switching assessment component for operation in dynamic renewable energy environments with improved efficiency.

Even with these advantages, MLIs will continue to face obstacles such as complex control algorithms, cost, size, voltage balancing, and thermal management. Several components and higher switching frequencies associated with higher-level inverters create both economic and technical barriers to expanding the use of modular multilevel inverter technology. The future of MLI technology will involve more modular systems, intelligent control, and the implementation of wide-bandgap semiconductors to reduce losses and improve thermal management. With greater investment, research, and advancement, MLIs will allow more reliable, efficient and scalable renewable systems that are critical for sustainable management of global energy needs.

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