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# Comparative analysis of different types of pulse width modulation techniques for multilevel inverters

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**ABSTRACT**

Multilevel inverters have gained significant attention in recent years due to their ability to achieve higher voltage and lower harmonic distortion compared to conventional two-level inverters. Pulse width modulation (PWM) techniques play a crucial role in controlling multilevel inverters by generating the required switching signals for their power electronic devices. This paper presents a comprehensive comparative analysis of various PWM techniques employed in multilevel inverters, including sinusoidal pulse width modulation (SPWM), space vector pulse width modulation (SVPWM), carrier-based pulse width modulation (CBPWM), and selective harmonic elimination (SHEPWM). Each PWM technique's advantages, limitations, and suitability for different multilevel inverter topologies are discussed. Furthermore, recent advancements and hybrid PWM techniques are also examined to explore potential improvements in performance and efficiency. This paper aims to provide researchers, engineers, and practitioners with valuable insights into selecting the most appropriate PWM technique for their specific multilevel inverter applications, considering factors such as performance requirements, cost constraints, and ease of implementation.

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## 1. INTRODUCTION

Multilevel inverters represent a significant advancement in power electronics technology, offering several advantages over traditional two-level inverters in various applications such as renewable energy systems, motor drives, and high-voltage power transmission [1]-[2]. Unlike conventional inverters that generate output voltages by switching between two voltage levels, multilevel inverters produce output voltages by synthesizing several voltage levels using multiple power semiconductor switches and capacitor voltage sources [3]. The concept of multilevel inverters is rooted in the ability to approximate sinusoidal output waveforms with stepped voltage levels, thereby reducing harmonic distortion and improving overall power quality. By distributing the voltage stress across multiple semiconductor devices, multilevel inverters can operate at lower voltage ratings for individual devices compared to their two-level counterparts, leading to enhanced reliability and efficiency [4]-[5]. One of the key advantages of multilevel inverters is their ability

to generate higher output voltage levels without requiring excessively high voltage ratings for individual power switches. This characteristic makes them particularly suitable for high-power applications where voltage scalability is crucial. Additionally, multilevel inverters offer improved efficiency and lower electromagnetic interference (EMI) due to reduced switching losses and harmonic content in the output waveform [6].

Pulse width modulation (PWM) is a widely used technique in power electronics for controlling the power supplied to electrical devices by adjusting the width of the pulses in a square wave signal. PWM methods are essential in applications such as motor control, power inverters, and voltage regulation, offering precise control over the output voltage or current [7]. The basic principle of PWM involves rapidly switching a power switch between fully on and fully off states at a high frequency. By varying the width of the on-time within each switching period, the effective voltage or current delivered to the load can be controlled. This modulation technique allows for the generation of analog-like waveforms using digital control signals, enabling efficient power delivery and precise regulation [8]-[10].

Sinusoidal pulse width modulation (SPWM) is a basic PWM technique where the width of each pulse is adjusted according to a reference signal to generate a modulated waveform. SPWM is simple to implement but may produce significant harmonic distortion [11]. Space vector pulse width modulation (SVPWM) is an advanced PWM technique that aims to synthesize a sinusoidal output voltage waveform by dynamically adjusting the switching times of the PWM pulses. By approximating the reference sinusoidal waveform, SVPWM can achieve lower harmonic distortion and better output waveform quality compared to SPWM [12]. SVPWM is a sophisticated PWM method commonly used in three-phase voltage source inverters. It involves dividing the space vector representation of the reference signal into smaller voltage vectors and dynamically selecting the appropriate voltage vectors to approximate the desired output waveform. SVPWM offers higher efficiency and lower harmonic distortion compared to other PWM techniques [13]-[14]. Carrier-based pulse width modulation (CBPWM) is a straightforward PWM technique where the width of the PWM pulses is modulated based on a carrier signal and a reference signal. CBPWM is widely used in voltage source inverters and motor drives due to its simplicity and effectiveness [15].

These PWM methods vary in complexity, computational requirements, and performance characteristics, making them suitable for different applications based on specific requirements such as harmonic distortion, efficiency, and switching frequency. In practice, the choice of PWM method depends on factors such as the application, desired output waveform quality, hardware constraints, and control system requirements, Figure 1 shows the circuit of three phase VSI circuit.

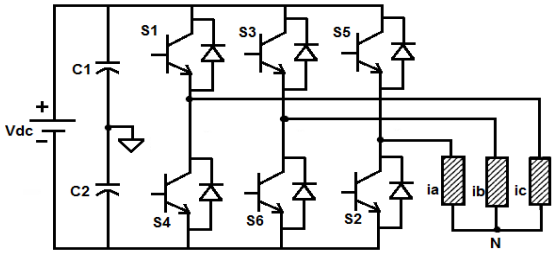


Figure 1. Circuit of three phase VSI circuit

## 2. MULTILEVEL INVERTER TOPOLOGIES

Multilevel inverters are power electronic devices that synthesize a desired voltage waveform using multiple levels of DC voltages. They are employed in various applications such as renewable energy systems, motor drives, and high-voltage power transmission due to their ability to produce high-quality output waveforms with reduced harmonic distortion [16], [17].

### 2.1. Diode-clamped multilevel inverter

The diode-clamped multilevel inverter consists of several power semiconductor switches arranged in a bridge configuration. Capacitors are connected between each phase output and a common neutral point. In this topology, each phase leg is clamped to the neutral point through diodes, allowing the synthesis of multiple voltage levels [18], [19]. By selectively turning on and off the switches, different voltage levels can be generated at the output terminals. The diode clamping ensures that the voltage across each semiconductor device remains within a safe operating range. The Figure 2 is multilevel inverter topologies. The power structure of neutral point clamped inverter is shown in Figure 2(a).

### 2.2. Capacitor-clamped multilevel inverter

The capacitor-clamped multilevel inverter utilizes flying capacitors connected between each phase output and the DC voltage source. Multiple switches control the connection of capacitors to achieve different voltage levels. By charging and discharging the flying capacitors, this inverter topology can synthesize multiple voltage levels at the output terminals [20]. The switches control the connection of capacitors to the DC source and the load, thereby regulating the output voltage. Voltage balancing across capacitors is crucial to maintain the desired output waveform, which is shown in Figure 2(b).

### 2.3. Cascaded H-bridge multilevel inverter

The cascaded H-bridge multilevel inverter consists of multiple H-bridge converter cells connected in series. Each H-bridge cell generates a fraction of the total output voltage. By independently controlling the switching states of each H-bridge cell, this topology can synthesize multiple voltage levels at the output terminals [21]. The H-bridge cells operate in a staircase manner, with each cell adding a voltage increment to the previous cell's output. This modular structure allows for scalability and flexibility in achieving desired voltage levels, which is shown in Figure 2(c).

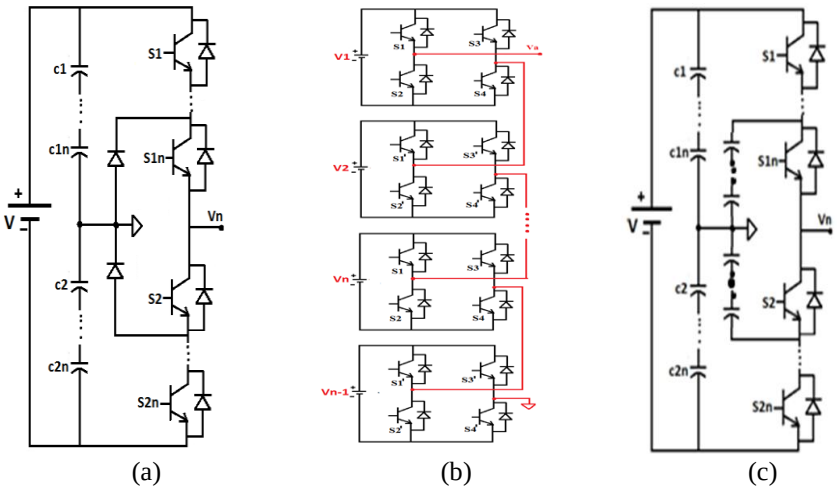


Figure 2. Multilevel inverter topologies (a) neutral point clamped inverter, (b) capacitor clamping inverter, and (c) cascaded H-bridge inverter

### 2.4. Reduced switches based portable multilevel inverter

In general, the working principle of multilevel inverters involves the selective switching of power semiconductor devices to synthesize the desired output voltage waveform [22]. By carefully controlling the switching patterns and duty cycles, multilevel inverters can minimize harmonic distortion, improve power quality, and achieve efficient power conversion. Additionally, voltage balancing among the different levels and phases is essential to ensure proper operation and reliability of the inverter system, which is shown in Figure 3.

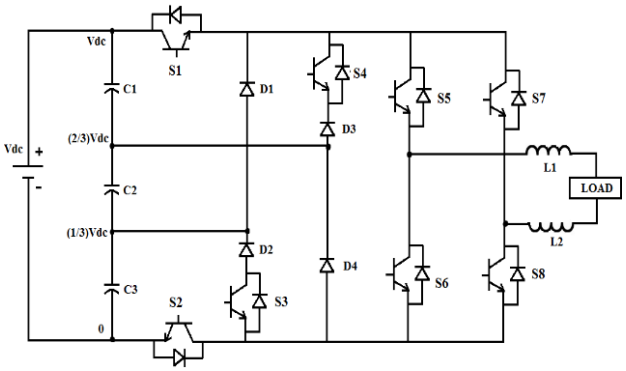


Figure 3. The 5-level reduced switches-based inverter

## 3. PULSE WIDTH MODULATION TECHNIQUES

PWM is a fundamental technique used in power electronics to control the power delivered to electrical devices by adjusting the width of the pulses in a square wave signal. PWM methods are essential in various applications such as motor drives, power inverters, and voltage regulation, providing precise control over voltage or current levels [23]. These PWM methods vary in complexity, performance characteristics, and applications. The choice of PWM method depends on factors such as the desired output waveform quality, harmonic distortion requirements, hardware constraints, and control system specifications. Each PWM method offers unique advantages and is tailored to specific applications to achieve optimal performance and efficiency.

### 3.1. Sinusoidal pulse width modulation

SPWM is a technique used in power electronics to generate a modulated waveform that closely resembles a sinusoidal waveform. It's commonly employed in voltage source inverters for applications such as motor drives and grid-tied power converters. The basic idea behind SPWM is to compare a reference sinusoidal waveform with a high-frequency triangular carrier waveform to generate PWM signals. A sinusoidal reference signal, typically representing the desired output voltage or current waveform, is generated. This reference signal defines the amplitude, frequency, and phase angle of the desired output A high-frequency triangular carrier signal is generated. This carrier signal serves as the basis for generating PWM pulses. The frequency of the carrier signal is much higher than the frequency of the reference signal to ensure smooth modulation. The sinusoidal reference signal is compared with the triangular carrier signal. This comparison is usually performed using a comparator or a similar circuit. Sinusoidal Pulse Width Modulation Technique is shown in Figure 4.

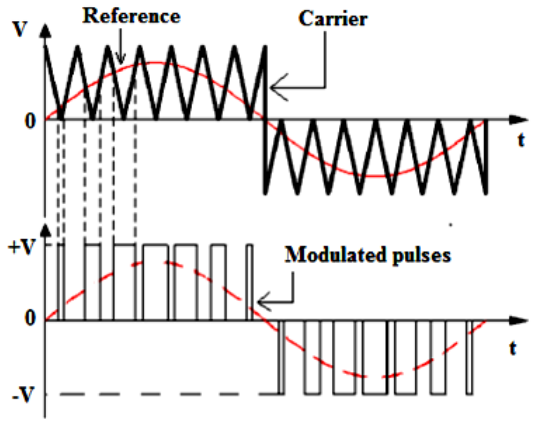


Figure 4. Sinusoidal pulse width modulation technique

Based on the comparison result, PWM pulses are generated. When the amplitude of the sinusoidal reference signal is greater than the amplitude of the carrier signal, the PWM output is high (1); otherwise, it is low (0). The width of each PWM pulse is determined by the duration during which the reference signal is greater than the carrier signal. This width varies continuously based on the instantaneous amplitude of the reference signal. The PWM pulses generated are applied to the power switches (typically transistors or IGBTs) of the voltage source inverter. By switching the power switches on and off according to the PWM pulses, the inverter generates an output waveform that follows the shape of the reference sinusoid. The output voltage or current is effectively modulated by adjusting the duty cycle of the PWM pulses, thereby controlling the power delivered to the load. The sinusoidal PWM provides a means to generate high-quality output waveforms with low harmonic distortion, making it suitable for applications requiring precise control and high-power quality.

## 4. CARRIER-BASED PULSE WIDTH MODULATION

CBPWM is a widely used technique in power electronics for generating pulse-width modulated signals. It's commonly employed in applications such as voltage source inverters for motor drives, uninterruptible power supplies (UPS), and grid-tied converters. The basic principle of CBPWM involves

comparing a reference signal (typically a sinusoidal waveform) with a high-frequency triangular carrier waveform to generate PWM signals.

A reference signal is generated based on the desired output voltage or current waveform. This reference signal determines the amplitude, frequency, and phase angle of the desired output. A high-frequency triangular carrier waveform is generated. This carrier waveform typically has a frequency much higher than the frequency of the reference signal. The carrier waveform serves as the basis for generating the PWM signals. The reference signal is compared with the triangular carrier waveform. This comparison is typically performed using a comparator or a similar circuit. Based on the comparison result, PWM pulses are generated. When the amplitude of the reference signal is greater than the amplitude of the carrier waveform, the PWM output is high (1); otherwise, it is low (0). The width of each PWM pulse is determined by the duration during which the reference signal exceeds the amplitude of the carrier waveform. This width varies continuously based on the instantaneous amplitude of the reference signal. The PWM pulses generated are applied to the power switches (such as transistors or IGBTs) of the voltage source inverter. By switching the power switches on and off according to the PWM pulses, the inverter generates an output waveform that follows the shape of the reference signal. The Figure 5 shows the multicarrier based PWM method.

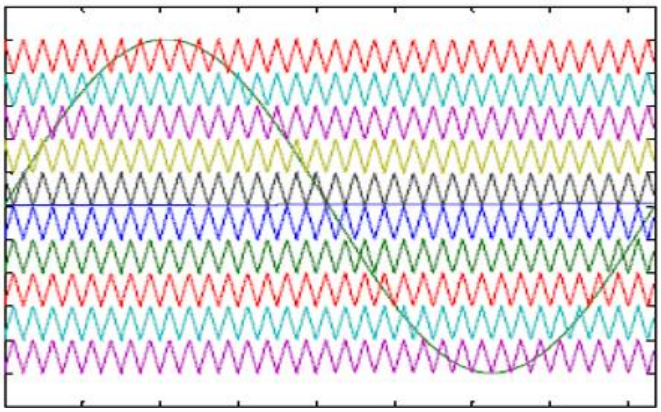

Figure 5. Muticarrier based PWM method

The output voltage or current is effectively modulated by adjusting the duty cycle of the PWM pulses, thereby controlling the power delivered to the load. Depending on the application, the modulated output waveform may be passed through a low-pass filter to remove high-frequency components introduced by the PWM switching. This filter helps smooth out the waveform and reduce harmonic distortion. The CBPWM provides a straightforward and effective method for generating pulse-width modulated signals based on a reference signal and a carrier waveform. It allows for precise control over the output voltage or current, making it suitable for a wide range of power electronics applications.

## 5. SELECTIVE HARMONIC ELIMINATION

SHE is a sophisticated PWM technique used in power electronics to eliminate specific harmonic components from the output voltage waveform. It is commonly employed in multilevel inverters, such as diode-clamped and cascaded H-bridge inverters, to achieve high-quality output waveforms with minimal harmonic distortion. The Figure 6 shows the Selective Harmonic Elimination.

Before applying SHE, the harmonic content of the desired output waveform is analysed. This analysis involves identifying the specific harmonic frequencies present in the output voltage waveform and determining which harmonics need to be eliminated or minimized [24]. Based on the harmonic analysis, an objective function is formulated to specify the desired amplitude of each harmonic component that needs to be eliminated. The objective function typically includes terms representing the amplitudes of the desired fundamental and harmonic frequencies. SHE involves solving a set of nonlinear algebraic equations derived from the objective function. These equations relate the switching angles of the inverter to the desired harmonic content of the output waveform.

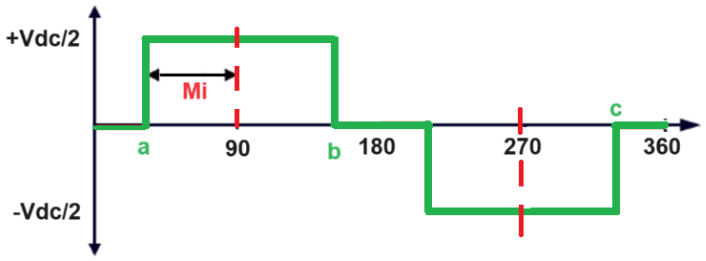


Figure 6. Selective harmonic elimination

The nonlinear equations are typically solved iteratively using numerical optimization techniques such as the Newton-Raphson method or the gradient descent method. The solution to the nonlinear equations provides the optimal switching angles for the inverter to achieve selective harmonic elimination. These switching angles determine when each semiconductor switch in the inverter should be turned on or off to minimize the specified harmonic components in the output voltage waveform. Based on the calculated switching angles, PWM signals are generated to control the operation of the power switches in the inverter. The PWM signals dictate the timing and duration of the switch transitions to produce the desired output voltage waveform with selective harmonic elimination. The PWM signals are applied to the power switches of the inverter to synthesize the output voltage waveform. By precisely controlling the switch transitions according to the calculated switching angles, the inverter generates an output waveform that closely matches the desired harmonic profile specified by the objective function. During operation, the output waveform is monitored to ensure that the specified harmonic components are effectively eliminated or minimized. Adjustments to the PWM signals may be made iteratively to fine-tune the harmonic suppression performance and optimize the output waveform quality [25].

Selective Harmonic Elimination offers a powerful method for achieving high-quality output waveforms with minimal harmonic distortion in multilevel inverters. By precisely controlling the switching angles of the inverter, SHE allows for the targeted elimination of specific harmonic components, resulting in improved power quality and reduced electromagnetic interference.

## 6. SPACE VECTOR PULSE WIDTH MODULATION

SVPWM is a sophisticated pulse-width modulation technique used in three-phase voltage source inverters. It provides precise control over the output voltage magnitude and phase angle while minimizing harmonic distortion. SVPWM is particularly popular in applications such as motor drives, renewable energy systems, and grid-tied inverters. SVPWM represents the three-phase output voltage as a vector in a two-dimensional space known as the space vector diagram. This representation allows for a geometric interpretation of the output voltage and simplifies the modulation process.

A reference signal is generated based on the desired output voltage waveform. This reference signal specifies the magnitude and phase angle of the desired output voltage vector. The space vector diagram is divided into six sectors, each corresponding to a particular combination of active voltage vectors. Based on the reference signal, the sector in which the reference voltage vector lies is identified. Within the identified sector, two adjacent active voltage vectors are selected to approximate the reference voltage vector. These two voltage vectors form the basis for modulating the output voltage waveform. The reference voltage vector is decomposed into its components along the selected active voltage vectors. This decomposition determines the magnitudes of the two active voltage vectors required to approximate the reference voltage vector. PWM signals are generated to control the switching of the power semiconductor devices in the inverter. The PWM signals dictate the timing and duration of the switch transitions to produce the desired output voltage vector. By dynamically adjusting the duty cycles of the PWM signals, the inverter generates a series of voltage vectors that follow a trajectory in the space vector diagram. Figure 7 shows the representation of SVPWM. This trajectory approximates the reference voltage vector while minimizing distortion. During modulation, if the reference voltage vector crosses the boundary between two sectors, the modulation strategy is adjusted to ensure smooth transition and continuity of the output voltage waveform. In addition to the active voltage vectors, zero voltage vectors are employed to maintain the desired modulation index and ensure the inverter operates within its voltage and current limits.

The modulated PWM signals are applied to the inverter's power switches to synthesize the three-phase output voltage waveform. By controlling the switching patterns according to the SVPWM algorithm, the inverter generates a high-quality output voltage with reduced harmonic distortion. SVPWM offers several

advantages over conventional PWM techniques, including improved voltage utilization, reduced switching losses, and lower harmonic distortion. Its ability to precisely control both the magnitude and phase angle of the output voltage makes it suitable for demanding applications requiring high-performance motor control and grid integration.

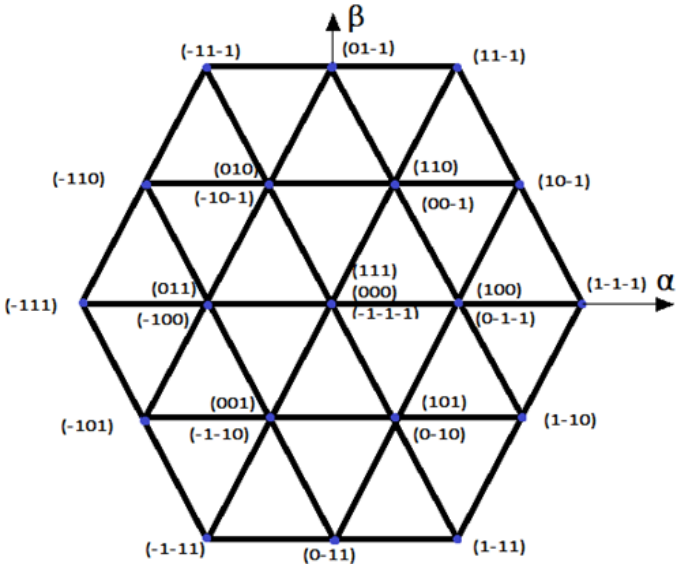


Figure 7. Representation of space vector pulse width modulation

## 7. CONCLUSION

The comparative analysis of different PWM techniques for multilevel inverters highlights their diverse characteristics, advantages, and limitations. Each PWM technique offers unique benefits and trade-offs, making it crucial to consider specific application requirements when selecting the most appropriate modulation strategy. The choice of PWM technique for multilevel inverters depends on several factors, including harmonic requirements, efficiency considerations, computational complexity, and implementation constraints. By understanding the strengths and limitations of each PWM method, engineers can make informed decisions to optimize the performance and reliability of multilevel inverter systems for a wide range of applications.

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