



REVIEW

A Review on Global Trends in Inverter Topologies, Controllers, Applications, Challenges and Solutions

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ABSTRACT: Inverters play an essential and indispensable role in energy conversion within modern electrical power systems. Conventional two-level inverters (2LIs) have been widely adopted across industrial applications due to their simple structure and mature control strategies. However, 2LIs exhibit several limitations when interfacing with utility-scale grid systems, including higher harmonic distortion, increased switching stress, and reduced efficiency in high-voltage and high-power operations. Multilevel Inverters (MLIs) have emerged as a transformative solution, enabling high-voltage and high-power applications with improved efficiency and significantly lower harmonic distortion compared to traditional two-level configurations. This review investigates the broad range of applications of 2LIs, along with their operational constraints, and provides a comprehensive overview of major MLI topologies, including neutral-point-clamped (NPC), flying-capacitor (FC), cascaded H-bridge (CHB), hybrid structures, transformer-based converters, and matrix converters. Key modulation and control techniques are also discussed, such as SPWM, SHE, SVPWM and random PWM. Furthermore, this paper highlights the practical deployment of MLIs in industrial motor drives, renewable energy integration, uninterruptible power supplies, and energy storage systems. Beyond technical aspects, global trends in inverter development are examined by comparing efficiencies, capabilities, and challenges among major manufacturers worldwide. Overall, MLIs are presented as scalable, efficient, and reliable converter solutions for the future of industrial and utility-scale power systems, offering valuable insight into current advancements and promising research directions.

KEYWORDS: Inverter; MLIs; topologies; controllers; application; industrial inverters; challenges and solutions

1 Introduction

As modern electrical systems increasingly adopt high-power applications and rely on renewable energy sources, particularly solar-dominated infrastructures, the role of inverters in converting Direct Current (DC) to Alternating Current (AC) is becoming critically important. The MLIs have become the global standard in power electronics, emerging as a solution to the limitations of conventional two-level inverters. While 2LIs remain suitable for low-power tasks due to their simplicity and reliability [1,2] their application in utility-scale grids is hampered by high harmonic distortion, increased switching stress, and low efficiency [3].

MLIs, conversely, excel in medium to high-voltage environments, enabling efficient power conversion by producing smoother voltage waveforms with significantly lower harmonic distortion [4]. Key topological advancements include the development of modular and hybrid MLI architectures [5], such as the Cascaded H-Bridge (CHB), Neutral-Point-Clamped (NPC), and Flying-Capacitor (FC) variants, which aim to reduce component count, complexity, and improve scalability. The future trajectory of MLI technology is centered on the integration of Wide-Bandgap (WBG) semiconductors like Silicon Carbide (SiC) and Gallium Nitride (GaN) to boost efficiency and reduce switching losses, alongside the adoption of AI-enabled control strategies for real-time monitoring and predictive fault detection.

Due to their advantages, MLIs are a foundational technology essential for the modern electric power infrastructure, driven by the global demand for efficient power conversion across diverse applications, including renewable energy, high-power industrial drives, and electric mobility. In renewable energy integration, MLIs are critical for converting vast DC power from solar and wind sources into high-quality, grid-compliant AC power with low Total Harmonic Distortion (THD), ensuring stable grid injection. Furthermore, they optimize high-power industrial drives by providing precise voltage and frequency control, which reduces torque ripple, improves motor efficiency, and extends the operational lifespan of machinery like pumps and compressors. Lastly, MLIs are vital for electric mobility, enabling efficient power conversion within Electric Vehicle (EV) powertrains, and for Battery Energy Storage Systems (BESS), where they facilitate the necessary bidirectional power flow for grid stabilization and integrating intermittent renewable energy sources [6].

Thus, this review thoroughly examines the constraints of 2LIs and provides an extensive overview of major MLI topologies, including NPC, FC, CHB, hybrid, transformer-based, and matrix converters. We also analyze crucial modulation and control techniques such as SPWM, SVPWM, and SHE and their impact on performance metrics like THD, DC bus utilization, and switching losses. By evaluating current global trends and comparing products from leading manufacturers, this study offers critical insights into recent advancements and promising research paths, positioning MLIs as scalable, efficient, and reliable converter solutions for future power systems.

2 Methodology

A systematic review methodology was employed to analyze the current state of inverter technologies. Relevant literature, including peer-reviewed journal articles, conference proceedings, technical reports, and product specifications from leading global manufacturers, was thoroughly examined. Conventional two-level and MLI topologies including neutral-point-clamped (NPC), flying-capacitor (FC), cascaded H-bridge (CHB), hybrid, transformer-based, and matrix converters were categorized and their operational principles, advantages, and limitations were critically assessed. Modulation techniques such as SPWM, SVPWM, SHE and their variants were evaluated in terms of THD, DC bus utilization, switching losses, and implementation complexity. Applications across industrial motor drives, RES, uninterruptible power supplies (UPS), and high-voltage utility grids were analyzed to identify practical deployment challenges, including harmonic distortion, switching stress, Electromagnetic Interference (EMI), cost, and reliability. Comparative analysis was performed to assess efficiency, scalability, and adaptability of different inverter topologies and modulation strategies, while emerging trends and future research directions were highlighted.

3 Conventional Two-Level Inverter

The conventional Voltage Source Inverter (VSI) topology is the most common 2LI configuration as shown in Fig. 1. The three-phase bridge inverter, consisting of six switches, is widely used to generate three-phase AC output from a DC supply.

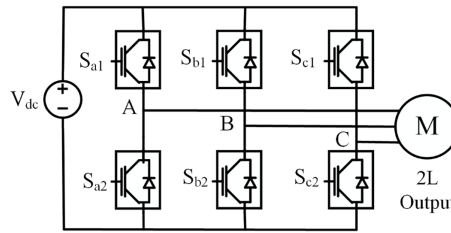


Figure 1: Typical three-phase two-level inverter.

Two-level inverters provide a robust solution for DC-AC conversion in various applications. There are few popular modulation techniques which are widely used in industries such as sine PWM, SVPWM, third harmonic injection PWM, and overmodulation. The SPWM is preferred for simplicity and low complexity, whereas SVPWM offers superior voltage utilization and lower harmonic distortion at higher computational cost. Advanced techniques like third-harmonic injection and overmodulation further improve performance. A comparative summary has been given in [Table 1](#).

Table 1: Modulation techniques and performance.

Technique/ Feature	Switching Method/ Description	THD	DC Bus Utilization	Switching Losses	Complexity/ Notes
SPWM	Carrier comparison (sinusoidal reference vs. triangular carrier)	Low	Moderate	Moderate	Low; simple to implement [7]
SVPWM	Space vector optimization of switching sequence	Lower than SPWM	High	Moderate	High; requires DSP/ computations [8]
Third-Harmonic Injection	Adds third harmonic to reference waveform	Lower than SPWM	High	Moderate	Simple and effective
Overmodulation	Modulation index beyond linear range; flat-topped SPWM	Higher than SPWM	High	Higher	Moderate; boosts voltage at expense of THD [9]

The selection modulation techniques are considered based on THD, DC bus utilization, and switching efficiency which are plotted in [Fig. 2](#).

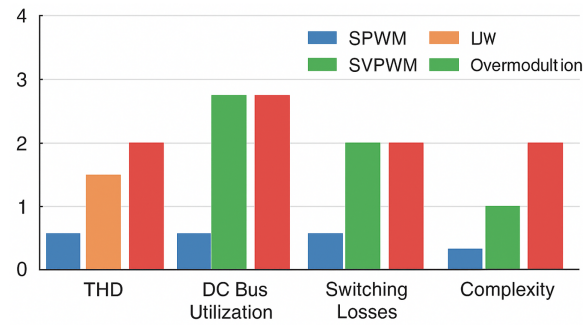


Figure 2: Comparative modulation techniques.

4 Industrial Inverters: Literature Review and Global Landscape

Industrial inverters are vital for DC-AC power conversion in renewable and industrial energy systems. Conventional two-level inverters, however, are constrained by switching losses, harmonic distortion, and device stress. This section provides a global review of inverter technologies and applications, examining products from major manufacturers such as Victron Energy, Selectronic, SMA Solar Technology, Sungrow, Huawei, ABB/FIMER, Siemens, and Ingeteam. A classification has been constructed in [Fig. 3](#). The analysis covers power capacities from 1.2 kW microinverters to central inverters exceeding 7 MW, with efficiencies approaching 99%. A brief comparative summary is given in [Table 2](#). Key challenges related to thermal management, EMI, and cost are addressed. Emerging trends including SiC/GaN devices, modular hybrid architectures, and AI-enabled grid integration are also discussed, offering a comprehensive perspective on the current and future landscape of industrial inverter deployment.

Larger inverters (>500 kW) achieve up to 99% efficiency, while smaller units average 95%–97% as depicted in [Fig. 4a](#). Global industrial market share has been presented in [Fig. 4b](#). Asia leads with ~40% market share, followed by Europe (25%) and North America (20%). Africa, South America, and Australia account for smaller shares. Sungrow, Ingeteam, and SolarEdge demonstrate peak efficiencies up to 99%, whereas microinverter producers like Enphase average 97% as shown in [Fig. 5](#). Challenges in modern inverter systems include several critical technical and economic factors. Thermal management remains a major concern, as inadequate heat dissipation can significantly reduce inverter lifetime and reliability. EMI is another challenge, since high-frequency switching operations generate electrical noise that may affect nearby equipment and grid compliance. In addition, the high initial cost of advanced inverter technologies limits widespread adoption, particularly in large-scale deployments. Maintenance is also increasingly important, especially for utility-scale inverters rated above the megawatt level, where continuous operation demands predictive monitoring and fault-prevention strategies.

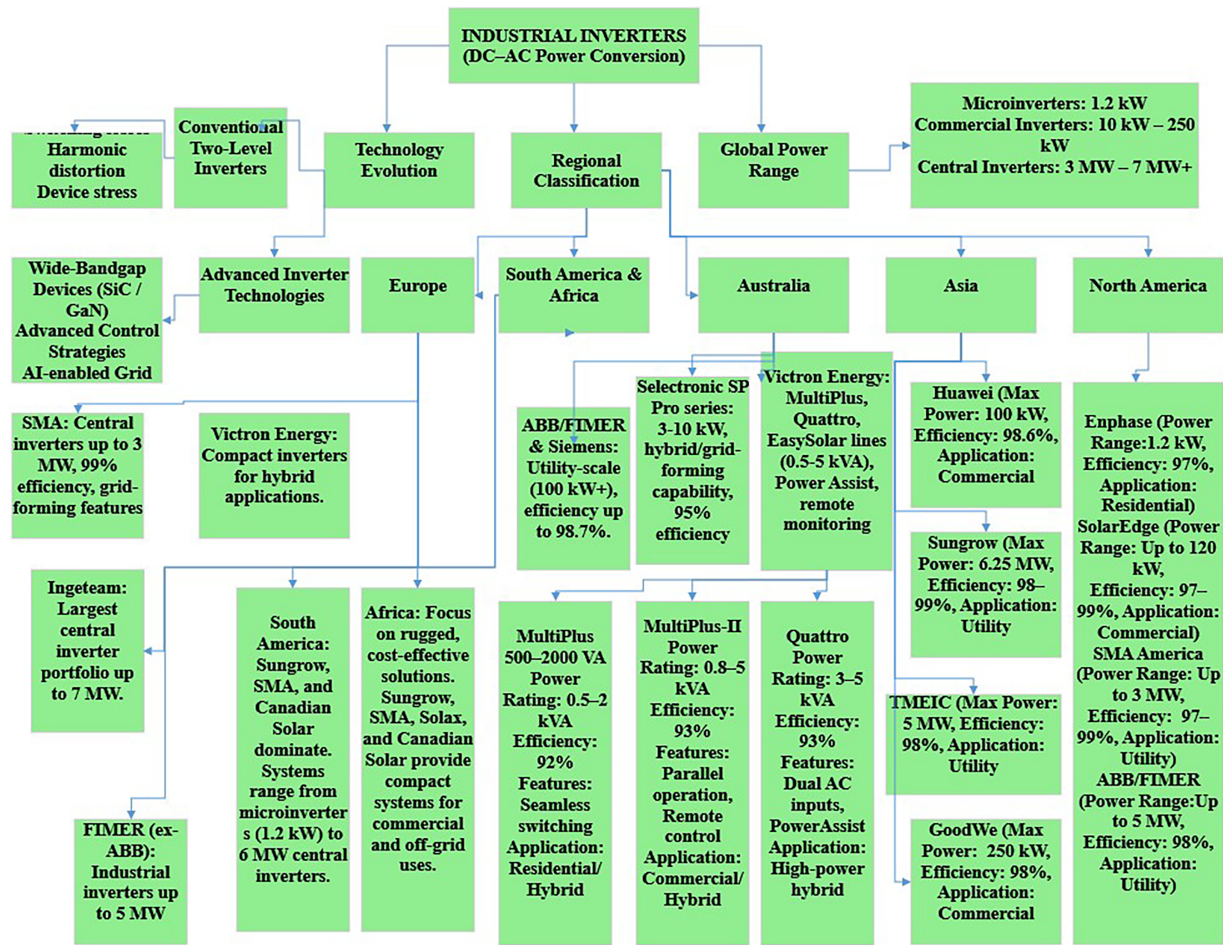


Figure 3: Classification of industrial inverters with global landscape.

Table 2: Comparative summary on industrial inverter.

Manufacturer	Power Range	Efficiency	Application	Notable Features
Enphase (NA)	1.2 kW	97%	Residential	Microinverter, modular
Victron (AU)	0.5–15 kW	95%–98%	Off-grid/Hybrid	PowerAssist, remote monitoring
SMA (EU)	Up to 3 MW	97%–99%	Utility	Grid-forming, MPPT
Sungrow (AS)	Up to 6.25 MW	98%–99%	Utility	Smart cooling, high fault curr.
Ingeteam (EU)	Up to 7 MW	98%–99%	Utility	Robust scalability
Siemens (EU)	10–500 kW	98%	Industrial	Smart grid ready

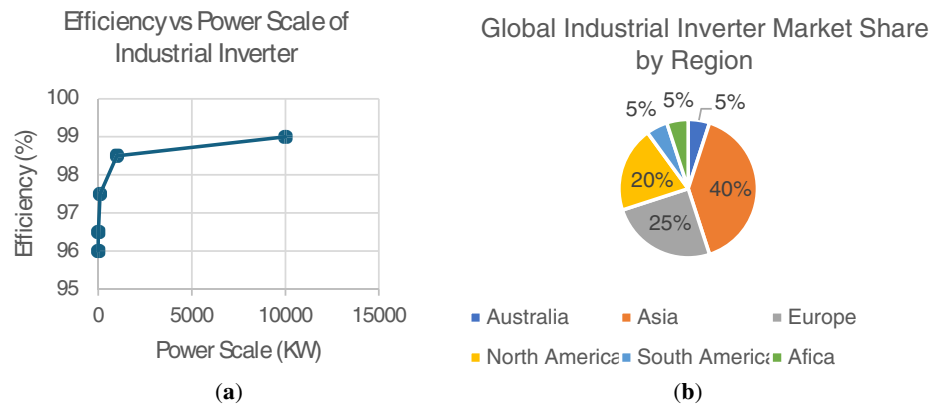


Figure 4: (a): Efficiency vs. power scale of industrial inverters, (b) global industrial inverter market share by region.

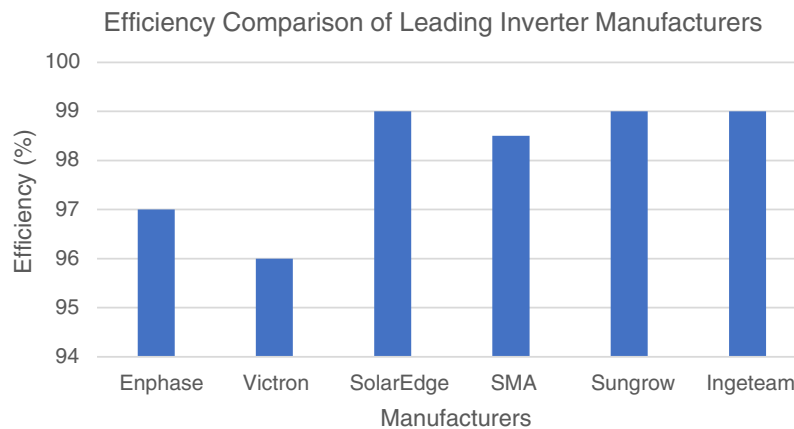


Figure 5: Efficiency comparison of leading inverter manufacturers.

Despite these challenges, significant opportunities are emerging to enhance inverter performance and scalability. The adoption of wide-bandgap semiconductor devices such as SiC and GaN offers higher efficiency, reduced switching losses, and improved thermal capability. AI-enabled diagnostics are gaining attention for real-time health monitoring and predictive fault detection, enabling smarter maintenance frameworks. Furthermore, smart-grid integration and grid-forming inverter support are becoming essential for renewable-dominated power systems. Finally, hybrid modular inverter designs present a promising pathway to reduce system costs while improving scalability, flexibility, and reliability for future industrial and utility-scale applications.

5 Multilevel Inverters

The MLIs have established themselves as a cornerstone of high-power industrial applications, offering significant advantages over conventional two-level designs. By generating more refined voltage waveforms with reduced harmonic distortion, MLIs alleviate mechanical and electrical stress on components, dampen EMI, and enhance both the efficiency and quality of power delivery.

The basic idea behind an MLI is to generate a near-sinusoidal output by combining several voltage levels from multiple DC sources. An n -level inverter produces n distinct voltage steps relative to the DC source's negative terminal as shown in Fig. 6, and increasing the number of levels requires optimizing the inverter's structure [10].

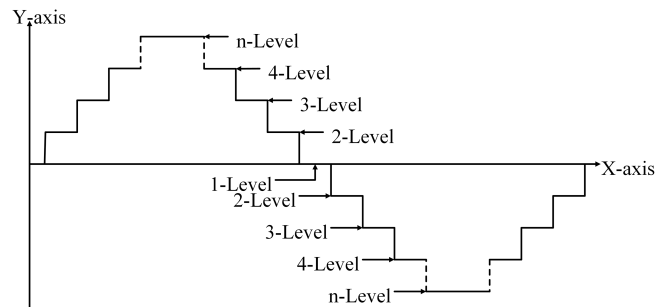


Figure 6: Staircase waveform for an n -level inverter.

A classification of converter topologies is constructed in Fig. 7. In general, AC power can be converted in two ways directly or indirectly [11]. Direct converters, like cycloconverters and matrix converters, link the supply and load directly, but they struggle with poor dynamic performance in high-power settings [12,13]. Indirect conversion, on the other hand, uses storage elements such as capacitors along with converters like voltage source converters (VSCs) or Current Source Inverters (CSIs), resulting in smoother and more stable operation. While CSIs often face issues like low power factor and input current distortion, VSCs overcome these drawbacks and come in two main types: conventional two-level and multilevel converters [14].

Conventional two-level voltage source converters (VSCs) come with several drawbacks they can shorten the lifespan of connected machines, cause grid synchronization issues, and produce lower output voltage with higher harmonic distortion and switching losses [15–17]. To reduce these harmonics, large output filters are needed, but they make the system bulkier and more expensive. This has led to the development of multilevel VSCs, which can generate higher voltages, deliver cleaner power, and significantly reduce THD.

That said, traditional MLI designs like matrix converters and both transformer-based and transformer-less types often require many semiconductor switches and components. This increases circuit complexity and can lower reliability compared to simpler two-level systems [18]. To overcome these challenges, researchers have introduced new inverter designs, such as reduced-switch MLIs [19], cascaded transformer-based converter [20], neutral-point clamped (NPC) [21], flying-capacitor (FC) [16], cascaded (CMI) [10], and hybrid MLIs (HMI) [22].

6 MLI Topologies

The topologies of multilevel VSIs are mainly classified into three categories such as transformer-less MIs, transformer-based MIs and matrix MIs. Despite these three MLI categories, a few other MLIs topologies have recently been developed by modifying the infrastructure of the three basic structures. The main MLIs' topologies have been presented below, along with current trends and advanced features.

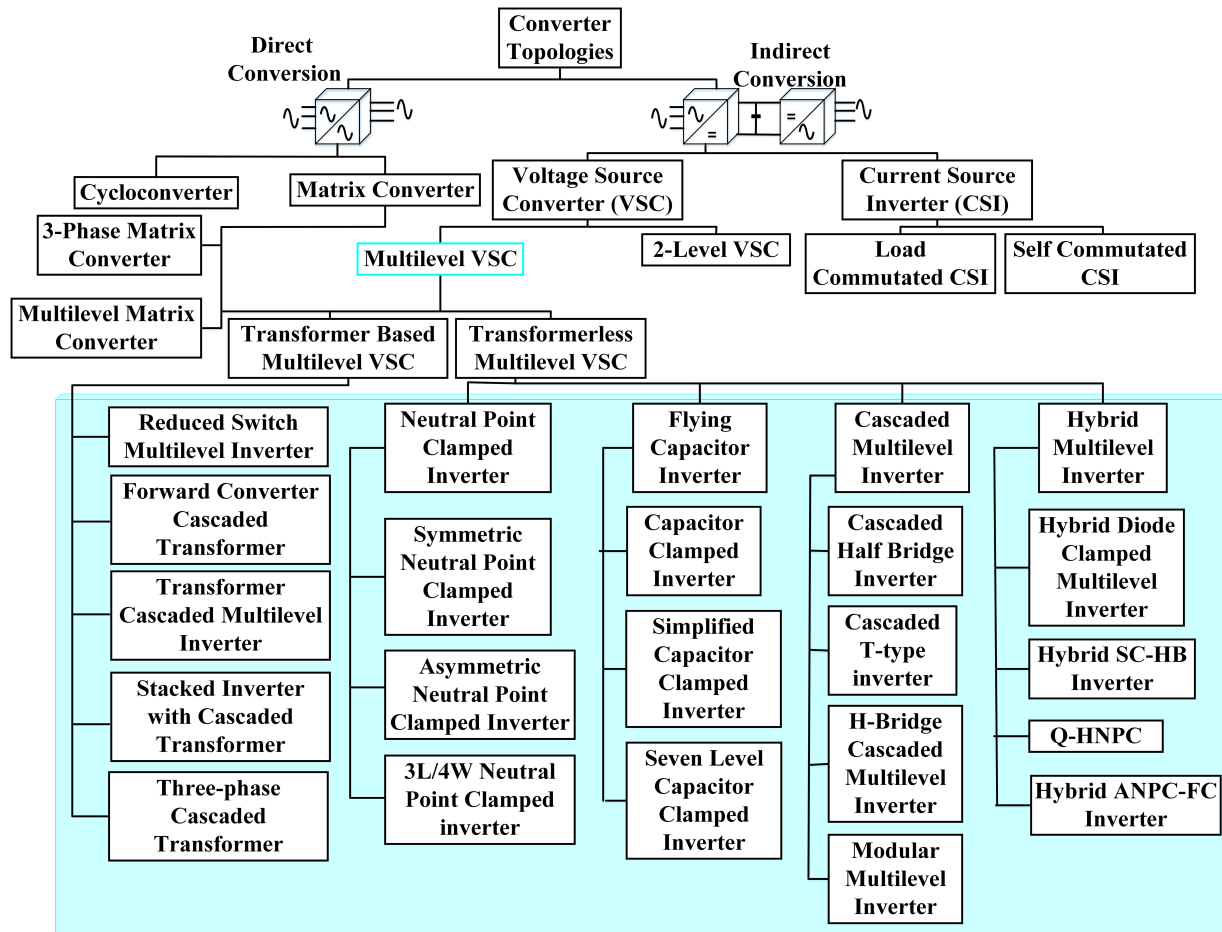


Figure 7: Classification of MLIs topologies.

6.1 Transformerless MLI

Transformer-less MLI topologies can be sorted into four categories including neutral point clamped inverter (NPCI), cascaded MLI (CMI), flying capacitor clamped MLI (FCMLI), and hybrid MLI (HMI).

6.1.1 Neutral Point Clamped Inverter

The neutral point clamped inverter (NPCI) was first introduced as a 3-level topology in 1981 as shown in Fig. 8a and has since evolved for high-power applications. An m -level, three-phase NPCI typically uses $6(m-1)$ switches, $6(m-2)$ clamping diodes, and $(m-1)$ series dc-link capacitors. Increasing the number of levels improves the output waveform, making it closer to a pure sine wave. In a 3-level NPCI, the dc-bus voltage is shared across series capacitors, while specific switch combinations generate zero, half, or full dc-link voltage. The clamping diodes, key to NPCI operation, limit the switching voltage to half the dc-bus voltage [16].

Variants include asymmetrical NPCIs with two dc sources, allowing bidirectional power flow and flexible active/reactive power control [23], and three-phase four-wire NPCIs, which handle unbalanced loads, improve efficiency, and stabilize the neutral point [24]. The main limitation of NPCIs is their complexity, requiring many clamping diodes, making implementation bulky and control challenging [25].

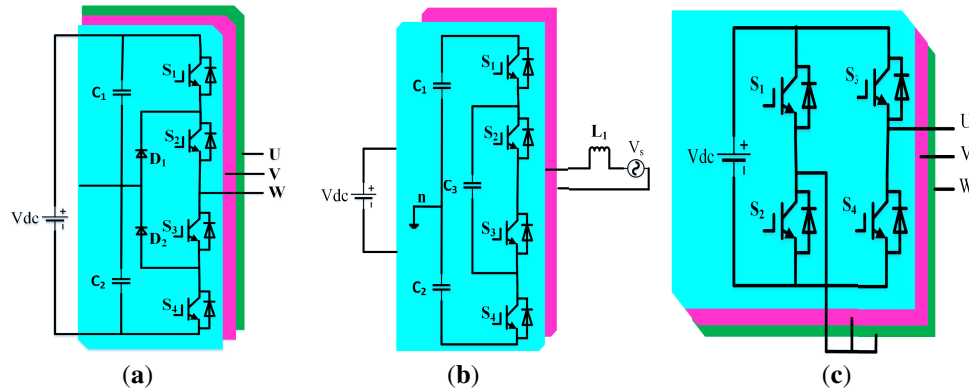


Figure 8: (a) 3-level NPCI, (b) 3-level FCMLI, (c) CHBI.

6.1.2 Flying Capacitor Clamped MLI

The flying capacitor clamped MLI (FCMLI) has emerged as an alternative to the diode-clamped inverter (DCLI), replacing clamping diodes with capacitors [26] as shown in Fig. 8b. Structurally similar to the NPCI, FCMLI uses ladder-formed dc-side capacitors to balance voltage levels via phase redundancies. Its voltage synthesis is more reliable, with the voltage step between adjacent capacitors defining the output increment. To generate an m -level waveform, FCMLI requires $3(m-2)$ clamping capacitors—about half the clamping devices of NPCI—while using the same number of switches and only two dc-bus capacitors. Output voltage levels are produced similarly to NPCI: zero level occurs when S_3 and S_4 are on while S_1 and S_2 are off, half dc-link voltage ($V_{dc}/2$) occurs with toggle operation of S_2 and S_3 with S_1 and S_4 , and full dc-link voltage (V_{dc}) occurs when S_1 and S_2 are on and S_3 and S_4 are off.

A five-level FCMLI is presented on the basis of bridge modular switched capacitor topology. This topology features reduced semiconductor switching losses and a number of required components when it is compared to the topology shown in Fig. 8b.

A seven-level FCMLI, is designed for medium-voltage, high-power industrial use, featuring fewer switches and components with simpler control [27]. While it's less complex than the NPCI, managing voltage balance across all clamping capacitors remains a major control challenge.

6.1.3 Cascaded MLI

R. H. Baker and L. H. Bannister introduced the cascaded MLI (CMI), later known as the cascaded H-bridge inverter (CHBI) [28], shown in Fig. 8c. This simple, modular topology uses series-connected H-bridge cells without clamping diodes or capacitors. It offers easy voltage scaling, reduced harmonics, and no voltage balancing issues, while requiring fewer components than NPCI and FCMLI.

A self-balanced CHB with a binary ratio is proposed using a single DC source per phase [29]. Several identical hybrid inverter modules have been cascaded to develop a single-phase, m -level grid-tied inverter [30]. This topology needs a small filter to eliminate voltage and current ripples.

6.1.4 Hybrid MLI

Hybrid MLIs have been developed by modifying conventional topologies to combine their advantages. Recent designs include hybrid clamped inverters and hybrid switched-capacitor H-bridge (SC-HB) inverters. The hybrid clamped inverter [31], shown in Fig. 9a, integrates features of the NPCI and FCMLI, enabling balanced voltage levels suitable for both standard and high-power applications.

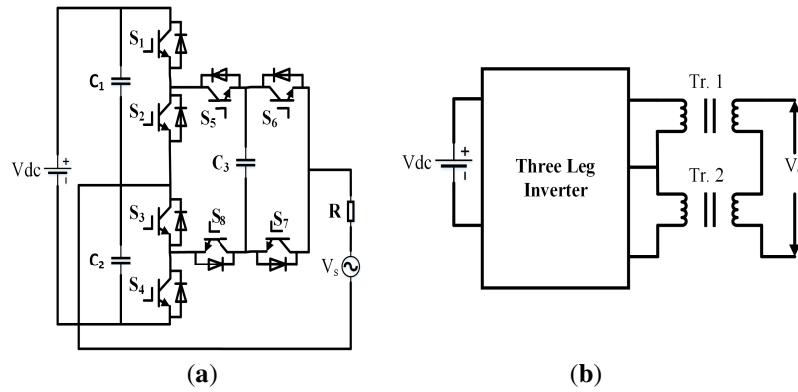


Figure 9: (a) Hybrid clamped inverter, (b) RS MLI.

The hybrid SC-HB inverter [32], combines a series capacitor inverter with switched-capacitor units, significantly reducing the number of switches and isolated dc sources. This design lowers system cost and size while doubling the input voltage without transformers or complex balancing control. Additionally, the quadrupled hybrid neutral point clamped (Q-HNPC) converter [33], enhances the output voltage levels with only a small increase in components.

Several other MLI topologies have been proposed in the literature [34]. A common challenge with these inverters is the large number of semiconductor switches, which increase cost, size, and control complexity while raising the risk of faults. To address this, various simplified structures have been introduced, such as a cascaded H-bridge inverter using only two switches and two freewheeling diodes [35]. The use of bulky phase-shifting transformers also contributes to system weight, prompting the development of high-frequency cascaded H-bridge inverters with galvanic isolation to reduce size and weight [36], though this again increases the number of switches.

Capacitor-clamped topologies offer advantages like reduced voltage stress and high-voltage operation at low switching frequencies, but they are less favored in industry due to the large number of required capacitors [37]. Similarly, diode-clamped inverters have been extended to higher voltage levels, five [38], and beyond [39] but their benefits are offset by the excessive use of diodes and capacitor voltage balancing issues. Although solutions like bidirectional buck-boost dc-dc converters help manage voltage imbalance [40], they add further complexity with extra components and control requirements.

6.2 Transformer-Based MLI

Transformer-based MLIs have been introduced to minimize the number of isolated dc sources. A reduced-switch, cascaded transformer-based 3-level inverter, shown in Fig. 9b, eliminates the need for H-bridges and can produce five levels using equal transformer turn ratios, with potential for higher-level extensions. Another design, the 15-level forward converter cascaded transformer (FCCT) inverter, uses only one dc source along with a forward buck converter, cascaded transformer, and H-bridge to achieve a compact, efficient structure.

The buck converter uses an isolated transformer with primary, tertiary (diode-connected), and secondary windings. However, this design is less suitable for high-power applications due to its many passive components and complex multi-winding transformer. It also requires an advanced compensator to stabilize the output voltage. To improve performance, an asymmetric transformer ratio of 6:7:8:9 was proposed, achieving balanced power distribution and reduced deviation error.

6.3 Multilevel Matrix Converter

The multilevel matrix converter is a promising topology for medium-power, high-voltage industrial drives. Built from direct or indirect multilevel structures like NPC and H-bridge inverters, it can generate multi-level output waveforms and transfer high active power at unity power factor. However, its benefits come at the cost of numerous switching devices, increasing both system cost and complexity.

7 Modulation Techniques

The main purpose of the modulation techniques of MIs is to synthesise the desired output voltage waveform as close as possible to a pure sinusoidal waveform. Several Pulse Width Modulation (PWM) techniques (PWM) have been designed and tested in the past three decades for industrial applications [41]. The quality of those modulated output waveforms, system losses and efficiencies have been greatly affected [42]. A brief discussion on modulation techniques is given in below.

7.1 Sine PWM

SPWM is one of the simplest PWM techniques that bears attractive features in modern industrial applications. The basic principle of the SPWM is to compare a low-frequency (50 Hz) sinusoidal waveform with a high-frequency (few KHz) rectangular waveform to produce control signals [43]. The control signal diagram is depicted in Fig. 10.

In SPWM, the control pulse is high (1) when the instantaneous sinusoidal reference exceeds the triangular carrier, and low (0) otherwise. The ratio of the sinusoidal waveform amplitude to the carrier waveform amplitude, called the modulation index, determines the output voltage of the inverter. Despite its simplicity, conventional SPWM has limitations: it attenuates the fundamental voltage component, increasing THD. Raising the switching frequency can reduce THD but causes higher switching losses, and conventional SPWM is generally limited to two-level inverters [44].

To address these issues, multi-carrier SPWM compares a single sinusoidal reference with multiple triangular carriers, improving voltage waveform quality, reducing harmonics, enhancing dc-bus utilization, and lowering stress on switching devices [45]. Variants include third-harmonic injection SPWM [46], which increases output voltage without appearing in the output waveform, though the optimal harmonic injection is not well established. Another method shifts the first significant harmonic back [47], reducing THD compared to conventional SPWM but at the cost of higher switching stresses and residual input-side distortion. These modified techniques expand SPWM's applicability to MLIs and improve overall performance.

7.2 SHE PWM

SHE is a modulation technique that determines optimal switching angles to control power electronic converters [48]. Unlike carrier-based PWM, SHE calculates the switching angles offline to eliminate up to $m-1$ low-order harmonics from the output voltage, significantly reducing THD. The technique works effectively as long as all switching angles remain below 90° , but becomes impractical if any angle exceeds this limit. A modified SHE method has been proposed for transformer-less static synchronous compensator systems using cascaded H-bridge inverters [49]. This approach achieves low harmonic content in the output while maintaining the inverter's main structure. The primary challenge, however, is the optimization of the switching angles, which adds complexity to its practical implementation.

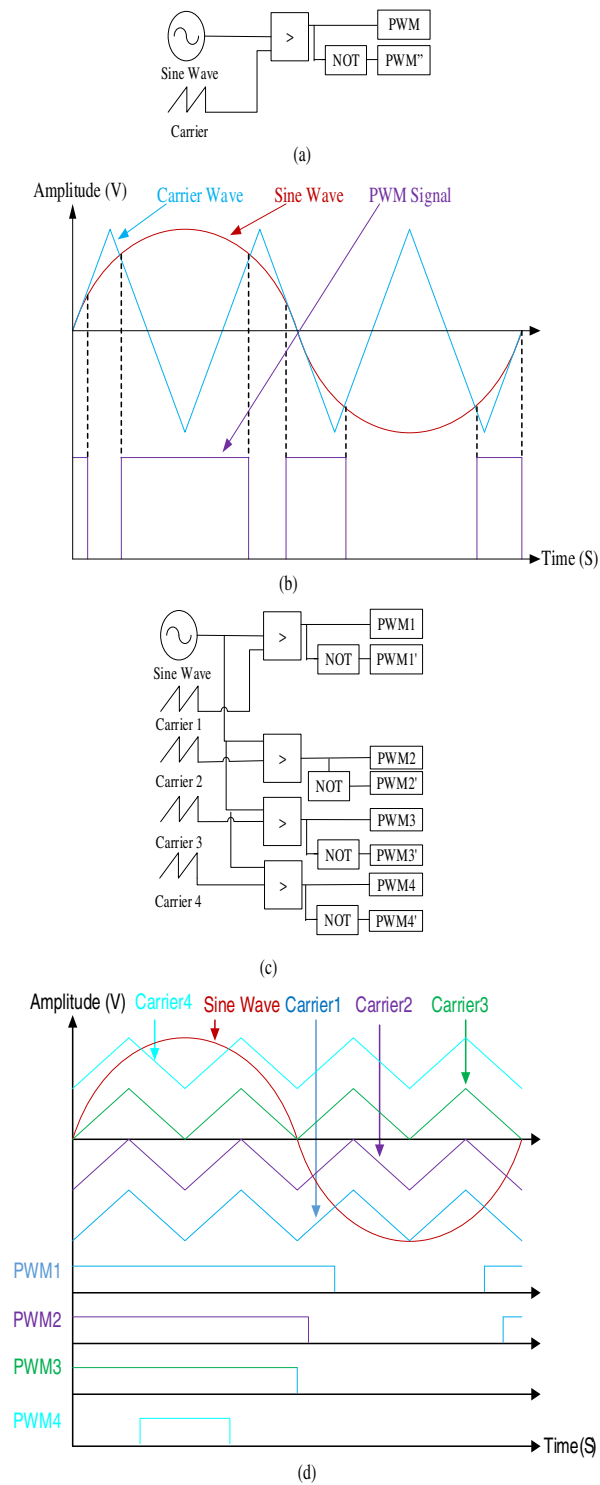


Figure 10: (a) Block diagram of the SPWM control signals generation (b) Control signals generation of the SPWM (c) Block diagram of multi-carrier SPWM control signals generation (d) Control signals generation of the multi-carrier SPWM.

7.3 SVPWM

Recently, SVPWM has brought great advancement to the variable frequencies drive application due to its superior performances [50]. SVPWM provides the lowest harmonic distortion in the output waveforms when it is compared to other modulation techniques and is well suited for hardware implementation. The utilization of dc bus voltage is increased by 15.5% when SVPWM is employed.

A new SVPWM for 3-level inverters has been proposed to significantly reduce execution time [51]. In this approach, the 3-level space vector (SV) diagram is divided into six 2-level SV diagrams. For cascaded H-bridge inverters, a generalized SVPWM method based on dwell-time calculation has been introduced [52], along with a dead-band hysteresis to prevent level jumping in the output voltage. However, this method adds complexity due to the need for separate on-time equations, rotating reference vector calculation, and switching state selection.

Traditionally, the 2-level SV diagram for 3-phase inverters forms a hexagon with six sectors, each an equilateral triangle in which each side length is unity and height is $h = \sqrt{3}/2$, totaling m^3 switching state vectors in the α - β reference frame [53] as shown in Fig. 11. Over the last three decades, this has been extended to multilevel space vector (MSV) diagrams [8], where each sector is divided into $2(m-1)$ triangles with a total of m^3 switching states [44]. For a 3-level inverter, each sector has four triangles and 27 switching states [43], and this approach can be extended to higher-level inverters as needed.

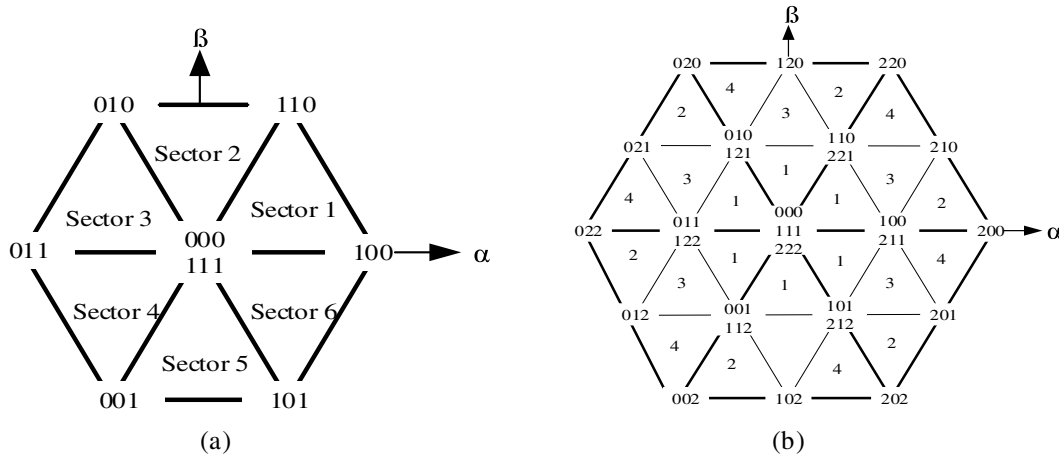


Figure 11: Space vector diagram (a) 2-level (b) 3-level.

7.4 Random PWM

The main purpose of the random PWM is to reduce the harmonic distortion from the inverter output voltage [54]. However, it reduces the amplitude of the fundamental frequency component and shows a rapid deterioration of the quality of operation at low values of the modulation index. Also, it produces additional switching losses and stresses to the semiconductor devices due to the random carrier frequency.

7.5 Other Recent PWM

Apart from the above mentioned three techniques, other modulation techniques have been presented in the recent literature during the last few years. SHE PWM is an offline computation technique that restricts the dynamic performance of the converter. Authors of [55] proposed a new PWM technique based on space vector control (SVC) and nearest vector control (NVC) without a modulator which significantly reduces the computation complexity and provides high dynamic performance. A nearest voltage level control (NLC)

instead of nearest vector control is proposed to obtain the desired output voltage reference [56] which is able to detect a close voltage level easily.

8 Applications of Topologies and Modulation Controllers

Recent developments including multilevel topologies, wide-bandgap semiconductors, and advanced control strategies have been introduced to mitigate these limitations. MLIs (MIs) have become widely used in modern industry due to their superior performance [43]. Initially developed to reduce harmonic ripple in conventional 2-level inverters, MIs now offer features such as inherent voltage boosting, continuous input current, power factor correction, and significant reduction of line current harmonics, making them suitable for a wide range of industrial applications. Today, MIs are applied in industrial control, power quality improvement devices, traction loads, renewable energy integration, uninterruptible power systems, and marine and mining electric power sectors [57].

Among the topologies, cascaded H-bridge inverters (CHBIs) are popular for high-voltage, high-power applications (up to 13.8 kV, 30 MVA) and are used in FACTS, active filters, reactive power compensation, PV conversion, static synchronous compensators, wireless power transformers and UPS systems [58,59]. Diode-clamped inverters are common in high-power AC motor drives, regenerative applications, and chemical or mining industries [60], while flying capacitor inverters (FCMLIs) serve high-bandwidth, high-switching-frequency applications like traction drives. Hybrid topologies find use in industrial drives, flexible AC transmission systems, and high-voltage DC transmission [61]. MIs are also critical in RES, including wind, solar, and fuel cells [62]. Innovations such as CoolMOSFET-based diode-clamped inverters for transformerless solar systems [63] and simplified capacitor-clamped DC-DC boost converters [64] enhance efficiency, reduce cost, and improve reliability in PV-grid interfacing. An application summary is listed in Table 3.

Table 3: Industrial applications of MLIs.

Application Area	Description	Common Topologies	Key Ref.
Medium-Voltage Motor Drives	Control speed and torque of large motors in pumps, fans, compressors, and conveyors	Diode-Clamped (DCMC), Cascaded H-Bridge (CHB)	[65,66]
Static Compensators (STATCOMs)	Provides reactive power compensation and voltage regulation; enhances grid power stability	NPC, FC, CHB	[67]
Uninterruptible Power Supplies (UPS)	Ensures continuous, high-quality AC supply during outages; critical industrial/commercial loads	DCMC, CHB	[68]
High-Power Industrial Motor Drives	Enhances torque control, reduces vibrations, and improves efficiency; used in automotive, marine, and metal processing industries	CHB, NPC	[69]

(Continued)

Table 3 (continued)

Application Area	Description	Common Topologies	Key Ref.
EV (EV) Powertrains	Supports bidirectional power flow, regenerative braking, and efficient energy conversion	Modular Multilevel Converter (MMC), CHB	[70]
Battery Energy Storage Systems (BESS)	Manages energy storage and distribution; integrates renewables and provides backup power	CHB, FC	[71]
Medium-Voltage Industrial Power Conversion	Evaluates performance, control strategies, and reliability	NPC, Flying Capacitor (FC), CHB	[72]
Renewable Energy Integration	Converts DC from PV and wind systems to high-quality AC; facilitates efficient grid integration	CHB, NPC	[73]

9 Challenges, Solutions of Conventional, MLIs and Future Research Directions

The increasing penetration of power electronic converters in industrial and utility-scale applications has intensified the debate between the use of conventional two-level inverters and MLI technologies. While MLIs provide superior waveform quality, efficiency, and scalability, both inverter types face significant challenges in terms of efficiency, control, reliability, and cost over 2LI. A comparative performance is also listed in [Table 4](#). The following discussion highlights these issues and the strategies proposed in literature to overcome them as shown in [Table 5](#).

Table 4: Comparison: industrial inverters vs. 2-Level and MLI.

Criteria/Aspect	2-Level Inverter	MLI	Industrial Inverter	Reference
Voltage/Power	<690 V, <1 MW	>11 kV, >7 MW	100 kW–8.8 MW, >11 kV	
Topology	Half-bridge/full-bridge	CHB, NPC, FC, MMC	Central, string, hybrid	
Efficiency	92%–97%	97%–99%	98%–99% (high efficiency)	
THD	5%–10%	<3%	<3% (high quality)	
Switching Frequency	10–20 kHz	1–5 kHz	1–5 kHz (lower EMI)	
Thermal Stress	High per switch	Lower (modular design)	Lower (modular design)	

(Continued)

Table 4 (continued)

Criteria/Aspect	2-Level Inverter	MLI	Industrial Inverter	Reference
Cost	Low	High CAPEX, lower O&M over time	High CAPEX, lower O&M over time	[74–79]
Complexity	Simple PWM control	Complex (SPWM, SVPWM, MPC, neural)	Complex (AI-based, smart grid integration)	
Reliability	High (fewer devices, simple)	High (modular redundancy)	High (modular redundancy, distributed stress)	
Applications	Residential, small commercial	Smart homes, mini-grids, EV + solar	Solar/wind farms, HVDC, FACTS, railway traction	
Scalability	~1 MW max	Modular, highly scalable (>7 MW)	Modular, highly scalable (>7 MW)	
Future Outlook	Residential, commercial system	Industrial and grid-scale power electronics	Industrial and grid-scale power electronics	

Table 5: A summary of challenges and proposed solution of MLIs.

Challenge	Description	Proposed Solutions (Literature)
Control Complexity & High Component Count (MLIs)	MLIs require many switches, capacitors, and isolated DC sources, complicating gate driving, modulation, and voltage balancing. Advanced modulation increases computational burden [80].	- Topology optimization (hybrid/asymmetric MLIs) to reduce switch count [81] - AI/ML-based and predictive control for switching and balancing [82]
Switching Losses & Voltage Stress (2-Level Inverters)	Two-level inverters suffer from high switching losses and large dv/dt stress, causing EMI and limiting high-power applications [82].	- Soft-switching and wide-bandgap (SiC/GaN) devices [83] - Use of MLIs to reduce voltage stress and dv/dt [84]
Harmonic Distortion & Grid Compatibility	Two-level inverters produce high THD, while MLIs improve waveform quality but may face imbalance issues [85].	- Advanced PWM (SHE, SVPWM) techniques [86] - MMC-based solutions for grid compliance (HVDC) [87]

(Continued)

Table 5 (continued)

Challenge	Description	Proposed Solutions (Literature)
Reliability & Maintenance (MLIs)	High component count increases failure probability; imbalance and semiconductor faults are major concerns [88].	- Fault-tolerant modular topologies with redundancy [89] - AI-based and signal-processing-based fault diagnosis
EMI	Both inverter types generate EMI; more severe in two-level inverters due to high dv/dt switching [90].	- Randomized PWM and EMI-aware control strategies [91] - Improved filtering and switching techniques [92].

Despite significant advancements, several challenges remain in inverter technologies. Conventional systems often struggle with harmonic distortion, while advanced configurations such as MLIs introduce increased complexity due to a higher number of components and sophisticated control requirements. Additional concerns include EMI, thermal management, switching losses, long-term reliability, and overall system cost.

Future research is increasingly focused on improving efficiency, reducing complexity, and enhancing system intelligence. Wide-bandgap semiconductor devices, such as SiC and GaN, enable higher efficiency and faster switching performance. At the same time, AI (AI) techniques are being explored for advanced control, fault detection, and performance optimization.

There is also growing interest in modular and scalable inverter architectures to improve flexibility and ease of implementation. Overall, future developments aim to achieve an optimal balance between performance, cost, and complexity, particularly for applications in RES, EVs, and smart grid infrastructures.

10 Research Gaps and Contributions

Existing studies on inverter technologies often focus on individual aspects such as topology design, modulation techniques, or application domains, without providing a comprehensive perspective. Moreover, many studies rely primarily on simulation-based analysis, with limited validation using real industrial data.

Comparative evaluations between two-level and MLIs are often incomplete, particularly in terms of key performance metrics such as efficiency, THD, cost, and scalability. Additionally, practical challenges including EMI, thermal effects, and control complexity are typically addressed independently rather than within an integrated framework.

To address these limitations, this study presents a comprehensive analysis that integrates inverter topologies, modulation strategies, application domains, and real-world industrial data. The key contributions include a systematic comparison of inverter technologies, identification of major challenges along with their potential solutions, and incorporation of emerging trends such as AI-based control and wide-bandgap semiconductor devices. This integrated approach enhances both the theoretical understanding and practical applicability of inverter technologies.

11 Discussion

The results demonstrate that MLIs outperform conventional two-level inverters in terms of efficiency, output waveform quality, and reduced THD, which is consistent with existing literature. However, these advantages are achieved at the cost of increased system complexity, as MLIs require more components and advanced control strategies, making them less suitable for low-cost or simple applications.

The analysis of modulation techniques indicates that while advanced approaches such as SVPWM provide superior performance, simpler methods like SPWM remain widely used due to their ease of implementation. This suggests that the selection of modulation techniques is highly dependent on application requirements and design constraints.

The inclusion of real industrial inverter data enhances the practical relevance of this study by highlighting key considerations such as cost, thermal performance, and system reliability, which are often overlooked in purely theoretical or simulation-based studies. In addition, issues such as EMI and thermal stress remain important concerns across all inverter types.

Emerging technologies, including AI (AI)-based control and wide-bandgap semiconductor devices such as SiC and GaN, are expected to further improve the efficiency and functionality of inverter systems.

12 Policy and Regulatory Implications

The adoption of MLI technologies is strongly influenced by regulatory standards and policy frameworks that ensure grid stability, safety, and power quality. Standards such as IEEE 519, which specifies harmonic limits, and IEEE 1547, which governs the interconnection of distributed energy resources, play a critical role in shaping inverter design and operation.

Policy measures, including renewable energy incentives, subsidies, and net-metering schemes, promote the deployment of advanced inverter technologies across residential, commercial, and industrial sectors. In regions emphasizing smart grid development and electric mobility, regulatory requirements increasingly mandate high efficiency, low THD, and reliable operation.

Recent policy trends also encourage the adoption of wide-bandgap semiconductor technologies, integration of energy storage systems, and implementation of advanced control techniques, including AI-based methods, to improve overall system performance. These regulatory developments support the transition toward more efficient and sustainable power systems.

13 SDG Alignment and Sustainability Impact

This study contributes to several United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

By improving efficiency, scalability, and power quality, the study supports the integration of renewable energy sources and promotes sustainable energy systems. Advanced MLI technologies enable reliable operation in industrial applications, smart grids, and electric mobility systems.

Furthermore, enhanced energy conversion efficiency and reduced harmonic distortion contribute to improved energy utilization and reduced environmental impact. Overall, the proposed advancements support sustainable infrastructure development and contribute to the reduction of carbon emissions in modern power systems.

14 Conclusion

MLI technology has evolved into a mature and indispensable element of modern power conversion systems, particularly in renewable, industrial, and utility-scale applications. Conventional two-level inverters remain attractive for low- and medium-power systems due to their structural simplicity and cost efficiency, yet their high switching stress and harmonic distortion limit their scalability. In contrast, MLIs deliver superior efficiency, enhanced voltage scalability, and improved power quality, positioning them as the preferred option for medium- to high-voltage applications. Despite these advantages, challenges such as control complexity, increased component count, harmonic management, and long-term reliability continue to drive active research. Minimizing switching and conduction losses, as well as THD, necessitates optimized circuit configurations and precise voltage-balancing strategies. Emerging advances in modulation techniques, hybrid converter architectures, and AI-enabled fault detection are further improving performance and operational stability. Looking ahead, future research is expected to emphasize wide-bandgap semiconductor devices such as SiC and GaN, alongside intelligent, adaptive, and fault-tolerant control frameworks. Globally, inverter technologies now range from compact 1.2 kW microinverters to central inverters exceeding 7 MW, reflecting regional specializations: Asia's dominance in scalable designs, Europe's excellence in utility-grade precision, and North America's leadership in modular innovation. Continued efforts to reduce losses, mitigate harmonics, and enhance reliability will be pivotal to sustaining technological progress and ensuring seamless renewable-energy integration in next-generation power networks.

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Abbreviation

2LI	Two-Level Inverter
MLI	Multilevel Inverter
VSI	Voltage Source Inverter
CSI	Current Source Inverter
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
SHE	Selective Harmonic Elimination

THD	Total Harmonic Distortion
EMI	Electromagnetic Interference
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
SiC	Silicon Carbide
GaN	Gallium Nitride
DC	Direct Current
AC	Alternating Current
HVDC	High Voltage Direct Current
VFD	Variable Frequency Drive
EV	Electric Vehicle
RES	Renewable Energy Systems
MPPT	Maximum Power Point Tracking
AI	Artificial Intelligence

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