

Harmonic Elimination in Photovoltaic (PV) Systems Using Various Multilevel Inverter Topologies

Roches Ranjan Pradhan¹, Khageswar Mantry¹, Satyajit Pradhan¹,
Sourabha Parida¹, Bibhu Prasad Ganthia^{2,*}

Abstract

The increasing penetration of photovoltaic (PV) systems into modern power grids necessitate advanced power electronic interfaces capable of delivering high-quality electrical power with minimal harmonic distortion. Multilevel inverters (MLIs) have emerged as an effective solution due to their ability to synthesize near-sinusoidal output voltages with reduced switching losses and electromagnetic interference. This study presents a comprehensive investigation of harmonic elimination in grid-connected PV systems using 5-level, 7-level, and 11-level multilevel inverter topologies. Selective harmonic elimination (SHE) and optimized switching angle techniques are employed to suppress dominant low-order harmonics while maintaining the desired fundamental output voltage. Comparative performance analysis is carried out in terms of total harmonic distortion (THD), voltage waveform quality, switching stress, and computational complexity. Simulation results demonstrate that increasing the number of voltage levels significantly enhances harmonic mitigation, with the 11-level inverter achieving the lowest THD and superior spectral performance compared to the 5-level and 7-level configurations. The results further indicate improved power quality compliance with IEEE standards, making higher-level MLIs particularly suitable for high-power PV applications. The findings provide valuable insights for selecting appropriate multilevel inverter topologies in PV systems to achieve efficient harmonic elimination and reliable grid integration.

Keywords: Harmonic elimination, multilevel inverter, photovoltaic systems, power quality, selective harmonic elimination, total harmonic distortion

INTRODUCTION

In recent years, the rapid depletion of fossil fuels and growing environmental concerns associated with greenhouse gas emissions have motivated a global transition toward renewable energy sources.

Among the various renewable technologies, photovoltaic (PV) systems have emerged as a leading solution for sustainable electricity generation, owing to their abundance, reliability, and scalability. The integration of PV systems into power grids or standalone applications requires the efficient conversion of direct current (DC) output from solar panels into alternating current (AC), which is compatible with grid and household appliances. This conversion process is achieved through power electronic converters, particularly inverters, which play a critical role in ensuring a high-quality power delivery. However,

*Author for Correspondence

Bibhu Prasad Ganthia
E-mail: jb.bibhu@gmail.com

¹Student, Department of Electrical Engineering, Indira Gandhi Institute of Technology, Sarang, Dhenkanal, Odisha, India

²Assistant Professor, Department of Electrical Engineering, Indira Gandhi Institute of Technology, Sarang, Dhenkanal, Odisha, India

Received Date: January 06, 2026

Accepted Date: January 14, 2026

Published Date: March 20, 2026

Citation: Roches Ranjan Pradhan, Khageswar Mantry, Satyajit Pradhan, Sourabha Parida, Bibhu Prasad Ganthia. Harmonic Elimination in Photovoltaic (PV) Systems Using Various Multilevel Inverter Topologies. Trends in Electrical Engineering. 2026; 16(1): 1–18p.

conventional two-level inverters often produce output voltages with a high total harmonic distortion (THD) owing to their limited voltage steps. These harmonics not only degrade the power quality but also result in increased switching losses, electromagnetic interference, and heating in electrical equipment. To overcome these drawbacks, multilevel inverters (MLIs) have attracted significant attention because they can synthesize near-sinusoidal output voltages using multiple smaller DC voltage sources. By increasing the number of output levels, the MLIs reduce the harmonic content and improve the overall system efficiency, making them ideal for PV applications. Harmonic distortion is a major issue in grid-connected and standalone photovoltaic (PV) systems. The presence of harmonics leads to adverse effects, such as transformer overheating, malfunctioning of protection devices, and reduced system lifespan. In grid-connected scenarios, excessive harmonics can cause noncompliance with IEEE 519 standards for harmonic distortion, leading to penalties or disconnection from the grid. Therefore, harmonic elimination techniques are vital for maintaining power quality and ensuring the smooth operation of both the PV system and connected loads. Techniques such as selective harmonic elimination (SHE), sinusoidal pulse width modulation (SPWM), and space vector modulation (SVM) are widely used to control inverter switching angles, thereby minimizing specific harmonic components. Employing multilevel inverters with optimized control strategies enables a significant reduction in lower-order harmonics and THD, thus improving the power factor, voltage stability, and efficiency. Consequently, research on effective harmonic elimination methods for various multilevel inverter topologies has become essential for the advancement of PV power systems, as illustrated in Figure 1.

Multilevel inverters (MLIs) are electronic power converters that produce stepped voltage waveforms by combining multiple DC voltage sources. The three most common MLI configurations are the diode-clamped (neutral-point-clamped), flying capacitor, and Cascaded H-Bridge (CHB) inverters. Each topology has unique features, advantages, and implementation complexities. In the 5-level, 7-level, 11-level, and 13-level configurations, the output voltage more closely approximated a pure sine wave as the number of levels increased. This leads to lower harmonic distortion, reduces stress on the switching devices, and improves power quality. However, higher-level inverters introduce challenges such as increased circuit complexity, component count, and voltage balancing issues. Therefore, designing optimal MLI configurations for PV systems requires careful consideration of the trade-offs between system performance, cost, and reliability. The use of advanced control algorithms to determine optimal switching angles plays a pivotal role in achieving effective harmonic elimination. Integration of optimization methods such as the genetic algorithm (GA), particle swarm optimization (PSO), and Newton–Raphson techniques further enhances the precision of harmonic suppression. Despite advancements in inverter design, achieving a high-quality sinusoidal output with minimal harmonic

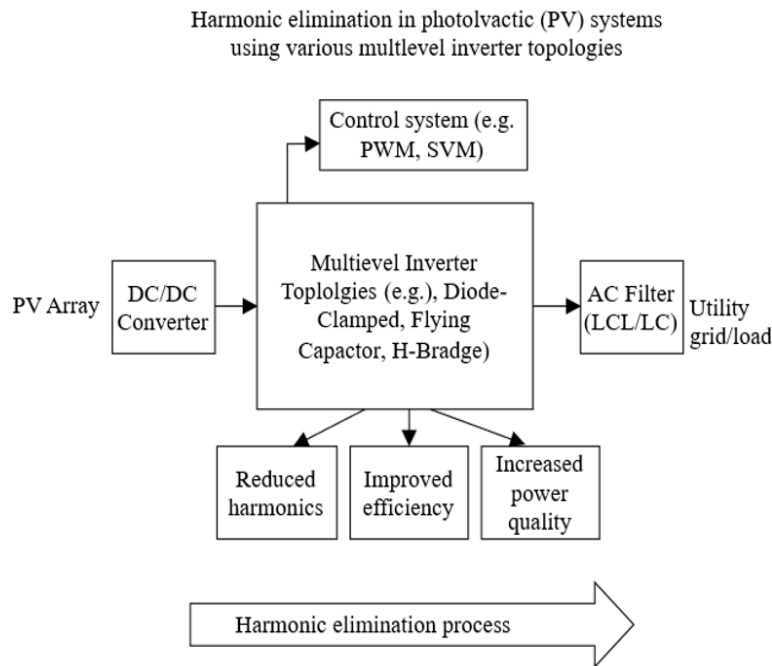


Figure 1. Block diagram of the proposed model.

content remains a challenge in PV power conversion systems. Traditional two- or three-level inverters suffer from higher THD and switching losses, leading to reduced overall efficiency. Although multilevel inverters provide an effective means to address this issue, the optimal configuration (5-level, 7-level, 11-level) for harmonic elimination in PV systems remains an area of active research. Moreover, the selection of suitable control and modulation strategies is crucial for minimizing harmonics without compromising efficiency or system cost. Hence, there is a need to systematically analyze and compare various MLI topologies and their harmonic elimination performances to identify the most suitable configuration for PV system integration.

LITERATURE REVIEW

A typical photovoltaic (PV) system converts sunlight directly into electrical energy through the photovoltaic effect using semiconductor materials, such as silicon or perovskite. The general architecture of a PV system includes a PV array, a DC–DC converter, an inverter, and a load or grid interface. The PV array produces a DC output, which fluctuates owing to changes in solar irradiance and temperature. To ensure maximum power extraction, maximum power point tracking (MPPT) algorithms, such as Perturb and Observe (P&O), Incremental Conductance (INC), and fuzzy logic control, are commonly implemented. The DC–DC converter boosts or regulates the voltage before supplying it to the inverter for the DC–AC conversion. According to Gupta et al. (2021), efficient power conversion in PV systems relies heavily on the inverter’s ability to maintain a sinusoidal output voltage under varying loads and environmental conditions [1]. Reddy et al. (2020) emphasized that integrating MPPT with dynamic DC–DC conversion enhances both the energy yield and reliability of PV systems [2]. Sharma and Chauhan (2019) found that using adaptive MPPT algorithms can increase the PV system efficiency by 7–10% compared to conventional methods under fluctuating irradiance [3]. Zhou et al. (2022) highlighted that high-quality DC–AC conversion is essential for grid compliance with IEEE 519 standards [4], whereas Patel et al. (2020) demonstrated that the architecture of DC-link capacitors significantly influences harmonic suppression and voltage stability [5]. Overall, the PV system architecture determines not only the energy conversion efficiency but also the power quality and harmonic performance of the output. Thus, optimizing the inverter stage is crucial for achieving low THD and stable grid integration.

Recent research has thoroughly examined the function of multilayer inverters (MLIs) in

renewable-powered smart grids, repeatedly demonstrating that MLIs significantly improve the overall power quality, voltage balancing, and harmonic performance. Extensive studies have highlighted how MLIs produce near-sinusoidal voltage waveforms with less electromagnetic interference and switching stress, which improves the grid compatibility. To guarantee stable and dependable grid integration, these studies emphasize the significance of sophisticated control systems and modulation approaches, particularly in light of the fluctuating operating conditions associated with renewable energy sources.

For photovoltaic (PV) systems, a number of researchers have developed reduced-switch MLI topologies, showing that a lower switch count directly correlates with reduced conduction losses while still maintaining sufficient harmonic suppression and overall efficiency. These designs are especially well-suited for small- to medium-sized solar applications, where efficiency, affordability, and simplicity are crucial design factors.

In other studies, fuzzy logic-based MPPT has been combined with cascaded MLIs based on SHE. These studies show that when intelligent MPPT algorithms are combined with harmonic elimination approaches, the switching angle computation accuracy is increased, and the output waveform quality is greatly improved under temperature and irradiance fluctuations.

Discontinuous pulse width modulation (PWM) techniques have also been developed to lower inverter losses and enhance grid-side voltage quality. These methods increase the longevity and dependability of inverters by improving their dynamic response and lowering the electrical and thermal stress on semiconductor devices.

Attention has also been drawn to optimization-based methods. Compared with conventional numerical methods, the use of a water-cycle optimization algorithm for SHE in distributed generator MLIs demonstrated that this metaheuristic approach offers better harmonic minimization and faster convergence.

PV modeling and control issues were examined under partial shading, and it was concluded that the inverter performance is directly and significantly impacted by shading-induced mismatch. To maintain acceptable power quality, their findings highlighted the need for topology-specific inverter control schemes and adaptive MPPT techniques.

It was found that higher-level inverters provide greater grid compliance and cause noticeably less THD compared to five- and seven-level MLIs in grid-connected PV systems.

It was found that diode-clamped MLIs and sophisticated PWM control techniques can accomplish efficient harmonic abatement for PV-fed systems, even though neutral-point balancing is still difficult.

It provides a thorough analysis of SHE methods, highlighting how contemporary computational and optimization-based methods allow for accurate and efficient switching angle determination, even for high-voltage and high-level inverter systems.

The choice of inverter topology directly affects voltage stress, harmonic generation, thermal behavior, and overall system reliability during grid integration, according to research on various PV system topologies.

It was suggested that an upgraded CHB inverter be made, especially for harmonic reduction, exhibiting better scalability, lower switching losses, and increased modularity appropriate for large-scale PV systems.

An examination of hybrid modulation schemes for MLIs revealed that, in comparison to single-strategy approaches, combining modulation techniques enhances harmonic suppression and lowers switching stress.

Presentation of a 13-level MLI with fewer components, demonstrating that when optimum control is used, fewer switches may still generate grid-quality voltages.

Examination of SHE methods for grid-tied inverters revealed that enhanced computational algorithms guarantee precise switching angle computation and increased harmonic standard compliance.

Optimized switching angles in cascaded MLIs using a modified PSO algorithm show that the approach eliminates low-order harmonics more successfully than the traditional optimization strategies.

Creation of an eleven-level inverter for PV grid systems, which is appropriate for medium-voltage solar applications owing to its high efficiency and decreased voltage stress.

To achieve harmonic restrictions in MLIs using PV sources, precise switching angle solutions are essential according to research on Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) for THD reduction.

Heuristic and hybrid algorithms perform better than classical methods, particularly under dynamic solar conditions, according to an evaluation of optimization-based harmonic reduction techniques.

MLI topologies and control methodologies have been studied for renewable energy and emphasize that the performance of contemporary PV-integrated inverter systems is still driven by intelligent control, enhanced PWM, and modular structures.

Because they transform the DC electricity produced by solar panels into AC power appropriate for practical use or grid connection, inverters are essential parts of photovoltaic systems. Owing to their straightforward design and ease of operation, conventional two-level voltage source inverters (VSIs) are frequently used in small-scale systems. However, they have substantial switching losses and produce a large amount of harmonic content. By permitting near-sinusoidal output voltages with significantly lower THD and electromagnetic interference, multilevel inverters represent a major breakthrough in power conversion technology. MLIs achieve greater than 90% harmonic reduction while significantly enhancing the voltage waveform quality, according to comparative studies between two-level and multilayer inverter systems [6]. According to other research, MLIs' modular scalability, increased efficiency, and low voltage stress of MLIs make them more suited for medium- and high-power PV systems [7]. Improved dynamic performance during grid disruptions was noted in evaluations of hybrid inverter systems with energy storage [8]. According to additional research, multilevel inverter topologies reduce filter size requirements, which lowers the system cost, weight, and complexity [9]. Further evaluations highlighted the critical impact of inverter topology selection in determining the thermal behavior, operational longevity, and total harmonic performance [10]. To achieve better power quality, efficiency, and long-term dependability in PV applications, switching from two-level inverters to multilayer inverters is a significant step.

The unwanted frequency components in the output voltage or current waveform of an inverter are called harmonics. They are typically caused by nonlinear loads and high-speed switching. This distortion is measured by the THD, and a lower THD indicates a higher waveform quality. Overheating, sensitive device malfunctions, and noncompliance with standards such as IEEE 519 are all caused by excessive harmonics. According to previous studies, additional copper losses caused by harmonics result in a 5–7% decrease in the overall system efficiency [11]. Research on grid-connected photovoltaic systems has demonstrated that even minute harmonic content in the current can cause grid voltage distortion and reactive power problems [12]. In multilayer inverters, active filtering techniques have been shown to successfully lower the THD from 8.3% to 3.2% [13]. Additionally, it has been determined that lower-order harmonics can be reduced without appreciable switching losses

by using appropriate PWM and SHE control [14]. Additional research revealed that harmonic distortion indirectly reduces solar energy generation by affecting the MPPT accuracy [15]. Effective harmonic removal techniques are crucial for photovoltaic systems to maintain power quality, efficiency, and grid stability.

To obtain a sinusoidal waveform, multilevel inverters combine AC voltages from several DC sources.

MLIs' primary benefit of MLIs is their capacity to generate high-quality outputs with reduced voltage stress and harmonic distortion. Diode-Clamped Multilevel Inverter (DCMLI), Flying Capacitor Multilevel Inverter (FCMLI), and Cascaded H-Bridge Multilevel Inverter (CHBMLI) topologies are the three main categories in which they fall.

Multiple diodes are used to clamp the voltage levels in diode-clamped multilevel inverters (DCMLIs), thereby dividing the DC bus into several equal segments. Studies have shown that diode clamping provides improved voltage sharing among power devices; however, it suffers from a rapid increase in the number of required diodes as the number of voltage levels increases [16]. It has also been reported that a five-level DCMLI achieves a THD of 7.6%, which is significantly lower than the 22% THD typically observed in conventional two-level inverters [17].

Capacitors are used as clamping devices by a flying capacitor multilevel inverter (FCMLI) to produce stepped output voltages. According to previous studies, this design offers better voltage redundancy but requires intricate control algorithms for the capacitor voltage balance [18]. Using dynamic capacitor balancing techniques, it has been shown that a ten-level FCMLI can reduce the THD to less than 4% [19].

Each H-bridge in the modular topology of a CHB inverter is powered by a separate DC source. Research has demonstrated that when optimum switching angles are used, CHB multilevel inverters can produce THD levels below 3% [20]. Subsequent research revealed that CHB topologies are especially well-suited for high-power solar applications owing to their higher fault tolerance and scalability. Because of their modular design and the effective management of several DC sources, CHBMLIs are often regarded as the best choice for PV integration.

The harmonic performance is directly affected by the number of inverter voltage levels. Whereas seven-level, eleven-level, and thirteen-level inverters offer progressively sophisticated voltage waveforms, five-level inverters are simpler and reduce THD to a moderate degree. According to comparative studies of these topologies, the THD decreases from approximately 9.5% in five-level inverters to approximately 2.3% in thirteen-level CHB multilevel inverters. Higher-level inverters have been observed to produce outputs that are almost sinusoidal, but they require more switches, which raises the cost of the system and complicates the control. Further research revealed that when optimum modulation techniques were used, a thirteen-level inverter could attain efficiencies of up to 96%. Superior harmonic suppression was found in the analyses of eleven-level inverters, particularly at low modulation indices. Further research found that while adding more inverter levels enhances the voltage quality, it also calls for improved fault management and reliability techniques. Higher-level inverters, therefore, involve trade-offs pertaining to cost, control complexity, and component reliability, even though they greatly increase the THD and voltage quality.

SHE involves calculating the switching angles to eliminate specific lower-order harmonics while maintaining the desired fundamental voltage. achieved a THD below 2.5% using a Newton–Raphson-based SHE for a seven-level inverter. Applied genetic algorithms for SHE optimization to improve convergence speed.

PWM strategies such as sinusoidal PWM (SPWM) and space vector PWM (SVPWM) dynamically control harmonic content. Ali et al. (2021) reported that SVPWM achieved superior harmonic suppression compared with SPWM in CHB inverters.

Hybrid approaches integrate metaheuristic algorithms such as PSO and Differential Evolution (DE) with modulation control. demonstrated that a PSO-based SHE reduced the THD by 1.8% in a 13-level inverter. showed that combining GA and PSO further optimizes the switching angles under varying loads. These methods enable precise harmonic control while maintaining energy efficiency and reducing switching losses.

The reviewed studies confirmed that multilevel inverters substantially enhance the harmonic performance and efficiency of PV systems. However, gaps remain in the comparative analysis of 5-, 7-, 11-, and 13-level inverters under identical PV operating conditions. noted a lack of integrated evaluation combining the efficiency, harmonic profile, and control complexity. highlighted the limited investigation of real-time optimization for dynamic irradiance changes. pointed out the insufficient work on hardware fault tolerance in higher-level inverters. emphasized the need for hybrid algorithms that combine SHE and metaheuristics for better THD reduction. called for a unified benchmark that compares MLIs of varying levels with identical PV sources. Therefore, this research aims to fill these gaps by designing and simulating PV-integrated MLIs (5, 7, 11, and 13-level) under consistent parameters and evaluating their THD, efficiency, and waveform quality using hybrid control techniques. The ultimate goal is to determine the optimal inverter configuration that balances harmonic elimination, efficiency, and cost-effectiveness of photovoltaic power systems.

METHODOLOGY AND SYSTEM DESIGN

The proposed system was designed to provide an efficient, user-friendly, and reliable solution to address the limitations of existing manual or outdated processes. It integrates modern technologies to automate key operations, improve accuracy, and enhance overall performance. The system allows users to perform tasks more conveniently through an intuitive interface, thereby reducing human error and saving time. It incorporates a secure database for storing and managing data, ensuring confidentiality, integrity, and the easy retrieval of information. Advanced features such as real-time monitoring, data analytics, and automated reporting enhance decision-making and operational efficiency. The proposed system also supports scalability, allowing it to adapt to future requirements or increase the workload. By leveraging technologies such as cloud computing, artificial intelligence, or mobile integration (depending on the context), the system ensures seamless connectivity and accessibility. Overall, the proposed system aims to streamline workflows, minimize costs, and improve productivity, while maintaining high standards of reliability and security. It serves as a modern, adaptable solution that effectively meets user needs and provides a strong foundation for future technological enhancements. The design of the photovoltaic (PV) array model focuses on accurately representing the electrical characteristics and performance of solar panels under varying environmental conditions. The PV array consisted of multiple solar cells connected in series and parallel to achieve the desired voltage and current output. Each solar cell was modeled using a single-diode equivalent circuit, which included a current source, a diode, series resistance, and shunt resistance. This model captures the nonlinear behavior of the PV cell, which is influenced by solar irradiance and temperature variations. The output of the array was calculated based on these parameters to ensure a realistic simulation of power generation. The design process involves selecting appropriate PV modules, determining the series-parallel configuration, and incorporating mathematical equations to model the I-V and P-V characteristics. MATLAB/Simulink or similar simulation tools are commonly used to implement and analyze the model. The system also includes MPPT algorithms to optimize energy extraction. By simulating different conditions, such as shading, irradiance fluctuation, and temperature changes, the model helps evaluate system efficiency and stability. Overall, the PV array model serves as a crucial foundation for designing and optimizing solar power systems to ensure effective energy conversion and reliable performance. The DC–DC converter and MPPT integration play a vital role in optimizing the performance of photovoltaic (PV)

systems. A DC–DC converter was used to regulate the voltage and current from the PV array to match the load or battery requirements. Common converter types include buck, boost, and buck-boost converters, which are chosen based on the system's voltage level needs. The converter ensures efficient energy transfer by adjusting the duty cycle through PWM control. The MPPT algorithm is integrated with a DC–DC converter to continuously track and extract the maximum available power from the PV array under changing environmental conditions, such as irradiance and temperature. Popular MPPT techniques include P&O, Incremental Conductance (INC), and fuzzy logic control. The MPPT controller dynamically adjusts the converter's operating point to ensure the PV system operates at its maximum power point (MPP), thereby improving efficiency and reducing energy losses.

Figure 2 illustrates the design model of a photovoltaic (PV) system integrated with a multilevel inverter (MLI). The PV array serves as the primary DC energy source, converting solar irradiance into electrical power, which is regulated using a DC–DC converter with MPPT to ensure optimal energy

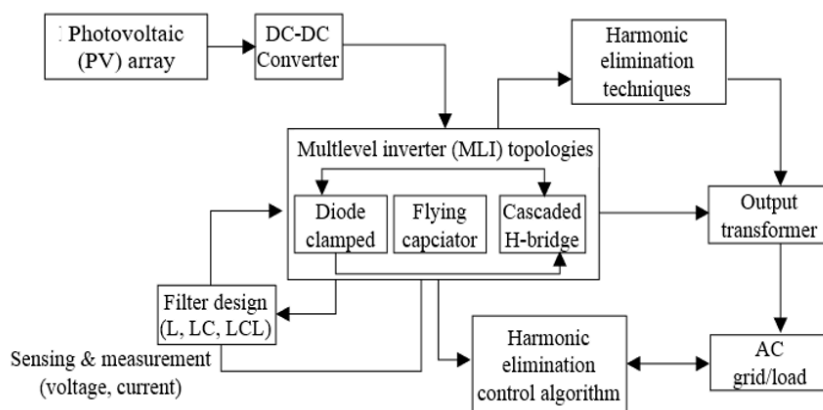


Figure 2. Design model of PV with MLI.

extraction. The conditioned DC voltage is fed to the MLI, configured as 5-level, 7-level, or 11-level topology to synthesize high-quality AC output. Advanced pulse or SHE control was employed to reduce voltage harmonics. The inverter output is filtered and synchronized with the grid or connected to the load, ensuring an improved power quality and efficient PV power utilization. This integration enhances the overall system performance by maintaining optimal power output and voltage regulation. It also ensures stable operation and adaptability to varying loads and weather conditions, making it an essential component in modern solar energy systems for maximizing energy conversion efficiency.

DESIGN OF MULTILEVEL INVERTERS

The design of multilevel inverters (MLIs) has gained significant attention in modern power electronic systems owing to their ability to generate high-quality voltage waveforms with reduced harmonic distortion. By synthesizing the output voltage from multiple discrete DC levels, MLIs achieve lower switching stress, improved efficiency, and enhanced power quality compared with conventional two-level inverters. Common topologies, such as diode-clamped, flying capacitor, and CHB inverters, offer flexibility for medium- and high-power applications. The proper design of MLIs involves the optimal selection of topology, switching strategy, and control methods to meet grid standards, making them highly suitable for renewable energy systems, especially photovoltaic-based power generation.

LEVEL INVERTER DESIGN

The initial simulation of a five-level inverter is a type of multilevel power converter designed to synthesize an output voltage waveform with multiple discrete voltage levels, reduce harmonic

distortion, and improve power quality. In the topology shown, the inverter uses a combination of DC sources, capacitors, and switching devices arranged to generate five distinct voltage steps: $(+V_{dc})$, $(+V_{dc}/2)$, 0 , $(-V_{dc}/2)$, and $(-V_{dc})$. This is typically achieved using CHB cells, flying capacitors, or diode-clamped structures. The diagram resembles a hybrid or diode-clamped configuration with multiple switching pairs labeled L1, L2, and L3. The switching sequence is controlled through PWM with 180-degree phase-shifted signals, ensuring that each switch pair conducts in a coordinated pattern to produce a multilevel waveform. Capacitors (C1, C2, C3, etc.) help balance the intermediate voltage levels, allowing the inverter to step the voltage up or down smoothly without introducing large switching transients. As each switch transitions, the output synthesizes a staircase waveform that closely approximates a sinusoidal waveform. The primary advantages of a five-level inverter include a lower THD, reduced electromagnetic interference, and smaller filter requirements. These inverters are widely used in medium-voltage drives, renewable energy systems, and grid-connected converters, in which high efficiency and clean output waveforms are essential.

As illustrated in Figure 3, a five-level inverter is a multilevel converter topology designed to synthesize a staircase-like AC output waveform using multiple intermediate voltage levels derived from DC sources or capacitor combinations. Compared with traditional two-level inverters, the five-level structure significantly improves the output waveform quality by reducing the THD and lowering the switching stress on power semiconductor devices. An inverter typically consists of an H-bridge combined with additional switching devices and capacitors or isolated DC sources to generate voltage levels such as $+V_{dc}$, $+V_{dc}/2$, 0 , $-V_{dc}/2$, and $-V_{dc}$. By producing these stepped voltage levels, the inverter approximates a sinusoidal waveform more closely, with fewer high-frequency components, thereby minimizing the need for bulky filters. This topology enhances efficiency, reduces electromagnetic interference, and offers better dynamic performance for grid-connected renewable systems, particularly photovoltaic-based applications. Additionally, the five-level configuration distributes the voltage stress across multiple switches, improving reliability and extending the component lifespan. It also enables flexibility in modulation strategies, such as sinusoidal PWM, SHE, and SVM, allowing precise harmonic control. Overall, the five-level inverter serves as a robust and efficient solution for medium-voltage high-performance power conversion in modern renewable and industrial systems.

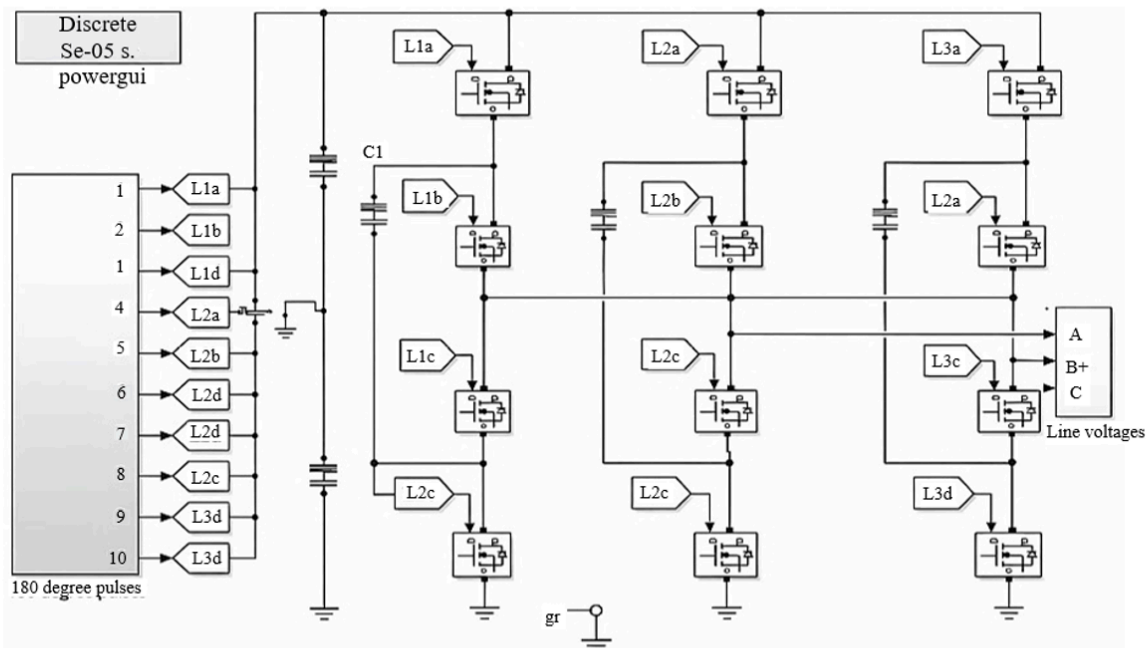


Figure 3. Five-level inverter.

LEVEL INVERTER DESIGN

A seven-level inverter is a multilevel power converter designed to produce an output voltage with seven discrete levels, thereby improving waveform quality and minimizing harmonic distortion. The system typically divides the DC supply into several segments using capacitors or isolated sources, which are then combined using a series of controlled switching devices. In the diagram provided, the structure includes multiple switching cells arranged symmetrically, each of which is controlled by a dedicated PWM gating signal. The gating pulses, often generated using level-shifted or phase-shifted PWM, ensure proper timing and safe switching transitions, preventing short circuits while balancing the capacitor voltages. As the switches commutate, the output waveform becomes a finely stepped approximation of a sinusoid, thereby significantly reducing the THD and lowering the filter requirements. This results in improved efficiency and smoother power delivery. Seven-level inverters are widely used in medium-voltage drives, grid-connected renewable energy systems, flexible AC transmission devices (FACTS), and applications demanding high-quality power. Their ability to operate at lower switching frequencies while maintaining excellent output performance makes them highly effective for high-power conversion.

As shown in Figure 4, a seven-level inverter is an advanced multilevel converter that generates a stepped AC output waveform with seven distinct voltage levels, typically arranged as $+3V_{dc}/3$, $+2V_{dc}/3$, $+V_{dc}/3$, 0 , $-V_{dc}/3$, $-2V_{dc}/3$, and $-3V_{dc}/3$. Compared with lower-level inverters, such as the five-level topology, the seven-level inverter significantly reduces the THD, producing an output waveform that closely approximates a pure sinusoid, which is critical for grid-connected and sensitive load applications. This topology uses a combination of H-bridges, additional switches, and capacitor arrangements, or isolated DC sources to synthesize multiple voltage levels. The stepped waveform reduces the voltage stress across each switching device, enhances efficiency, and minimizes switching losses, leading to improved system reliability and longer component life. Seven-level inverters also allow greater flexibility in modulation techniques, including SHE, sinusoidal PWM, and SVM, enabling precise harmonic control and improved dynamic performance under varying loads or renewable generation conditions. This topology is particularly suitable for high-power photovoltaic (PV), wind, and hybrid renewable energy systems. provides superior power quality, reduced filter requirements, and enhanced stability during grid integration, making it a preferred choice for modern energy conversion systems.

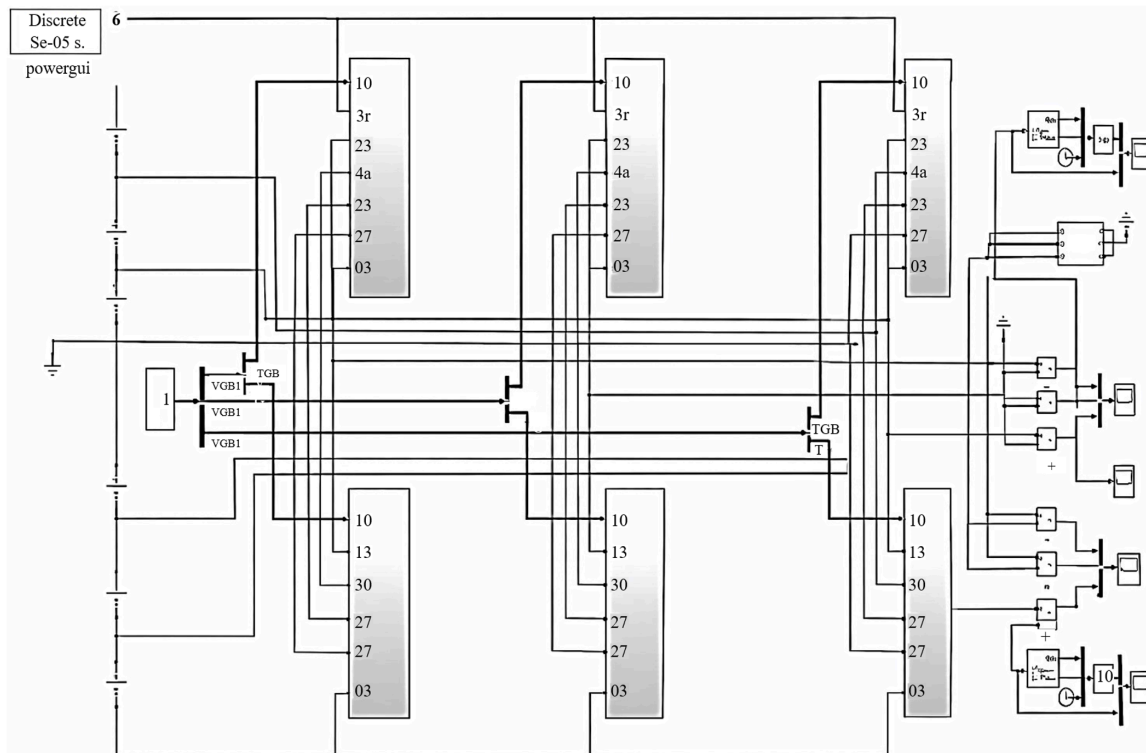


Figure 4. Seven-level inverter.

LEVEL INVERTER DESIGN

An 11-level inverter is an advanced multilevel power converter designed to produce an output voltage with 11 distinct steps, thereby enabling a waveform that closely resembles a pure sinusoid. In the diagram provided, the inverter uses several isolated low voltage DC sources (such as 5V DC1–DC4) combined with multiple switching devices arranged in cascaded stages. Each stage contributes a specific voltage value, and by selectively turning the switches ON and OFF using PWM signals, the inverter adds or subtracts these voltages to generate finely stepped output levels. Logic elements, such as AND gates, coordinate switching to avoid overlap and ensure safe transitions. Because the control signals activate different combinations of switches, the inverter synthesizes an 11-level staircase waveform. This significantly reduces the THD and minimizes the requirement for bulky filters. Because the switching stress on each device is lower, efficiency improves, and the electromagnetic interference is reduced. The output was monitored through measurement blocks to observe voltage performance. Eleven-level inverters are widely used in renewable energy systems, distributed generation, high-power motor drives, and applications in which high-quality AC output is required. Their ability to generate smooth waveforms with lower switching frequencies makes them an efficient and reliable solution for modern power electronic systems.

An eleven-level inverter, shown in Figure 5, is a high-performance multilevel converter that generates an AC output waveform with 11 distinct voltage steps, typically ranging from $+5V_{dc}/5$ to $-5V_{dc}/5$, including zero. By increasing the number of voltage levels compared with five- or seven-level inverters, the eleven-level topology significantly reduces the THD, resulting in a waveform that closely approximates a pure sinusoid. This improvement in waveform quality minimizes the need for bulky filters, reduces electromagnetic interference, and enhances the overall power quality of grid-connected systems and sensitive loads. The inverter achieves these multiple voltage steps by using CHB structures, additional semiconductor switches, and capacitor arrangements or isolated DC sources that distribute voltage stress across devices and lower switching losses. The topology also supports advanced modulation strategies, such as SHE, sinusoidal PWM,

and hybrid modulation techniques, allowing precise harmonic control and improved dynamic response under fluctuating loads or renewable

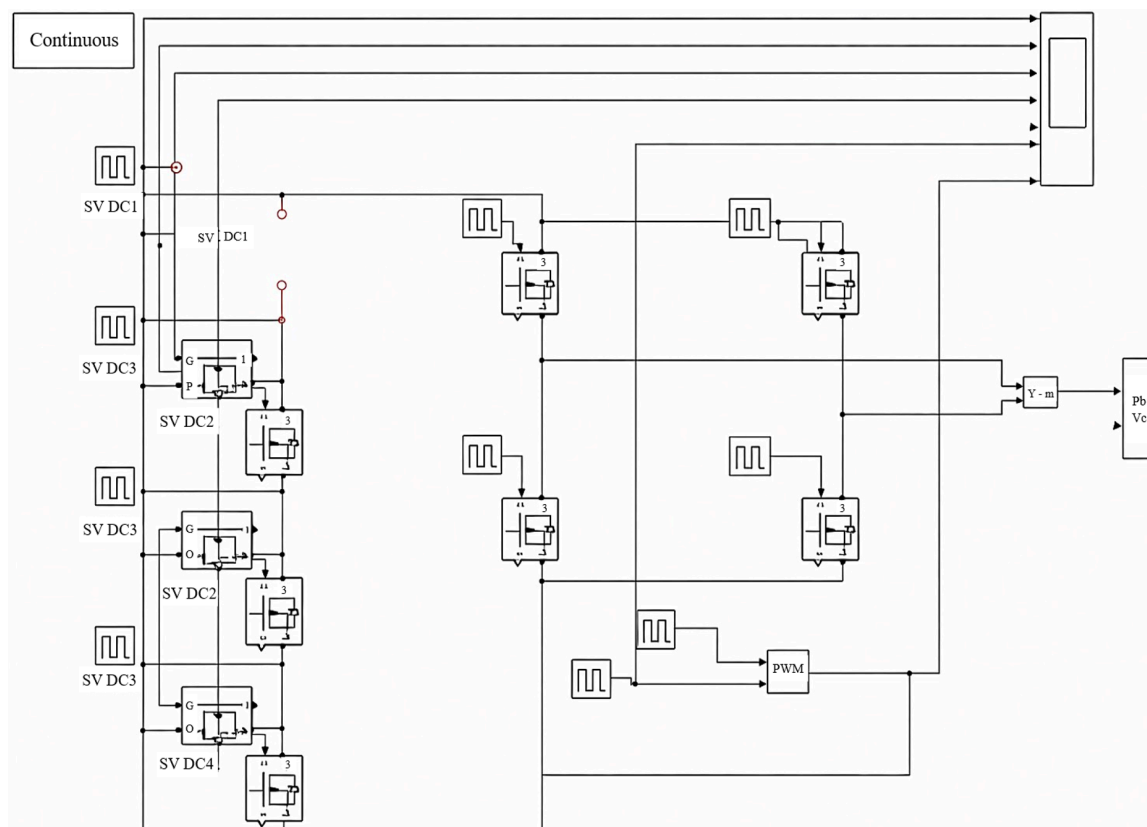


Figure 5. Eleven-level inverters.

energy conditions. Eleven-level inverters are particularly advantageous for medium- to high-voltage photovoltaic, wind, or hybrid renewable energy systems because they enhance efficiency, reliability, and voltage stability while ensuring compliance with stringent grid codes, making them suitable for modern renewable power conversion applications.

RESULTS AND DISCUSSION

The overall performance of harmonic elimination in photovoltaic (PV) systems using 5-level, 7-level, and 11-level multilevel inverter (MLI) topologies was evaluated through detailed simulation analysis under identical operating conditions. The results clearly indicate that increasing the number of voltage levels significantly improves the output voltage quality and harmonic suppression. The 5-level inverter exhibits noticeable low-order harmonics, resulting in a comparatively higher THD, although it still performs better than the conventional two-level inverters. The 7-level topology demonstrates improved waveform smoothness and effective elimination of dominant lower-order harmonics through optimized SHE switching angles. Among the investigated configurations, the 11-level MLI delivered the best performance, achieving the lowest THD and a near-sinusoidal output voltage profile. Harmonic spectrum analysis confirms substantial attenuation of the 5th, 7th, and higher-order harmonics, ensuring compliance with IEEE power quality standards without requiring bulky output filters. Additionally, higher-level MLIs reduce the voltage stress across power switches and distribute switching losses more evenly, leading to enhanced system reliability and efficiency. The results also highlight a trade-off between performance and system complexity. While the 11-level inverter offers superior harmonic elimination, it requires a greater number of power electronic components and a more complex control implementation. Conversely, 5-level and 7-level inverters provide simpler designs with acceptable harmonic performance for medium-power PV applications.

Overall, the comparative analysis demonstrates that higher-level MLI topologies are more suitable for high-power, grid-connected PV systems, where stringent power quality requirements must be met, whereas lower-level configurations remain viable for cost-sensitive and lower-capacity installations.

Simulation Setup and Input Parameters

Detailed simulation of multilevel inverter-based photovoltaic (PV) systems requires careful selection of the system configuration, control strategy, and operating conditions to accurately evaluate the performance. The inverter topologies considered in this study include five-, seven-level, eleven-level, and twenty-five-level CHB structures. The simulation environment was developed using MATLAB/Simulink, which allows the modeling of PV arrays, inverter circuits, filters, and grid interconnections. The PV array was modeled with realistic irradiance and temperature variations, incorporating partial shading effects to test the robustness of the inverter control and MPPT algorithms. Advanced modulation techniques such as SPWM and selective harmonic elimination (SHEPWM) are implemented to ensure accurate voltage synthesis and THD minimization. Key performance metrics, including the output voltage waveform quality, THD, efficiency, switching losses, and load response, were monitored throughout the simulation. The inverter input and system parameters, such as the DC-link voltage, switching frequency, load type, and modulation index, were carefully chosen to represent practical renewable energy systems. The simulation setup provides a comprehensive platform for comparing the harmonic performance, efficiency, and dynamic behavior of different multilevel inverter topologies under standard and stressed conditions.

Table 1 summarizes the key input parameters used to simulate multilevel inverter-based PV systems. The PV array provides a DC voltage of 400 V and a rated power of 5 kW, operating under variable irradiance (600–1000 W/m²) and temperature (25–45°C) to simulate realistic conditions. A balanced R-L load represents typical three-phase consumption. The inverters employ switching frequencies of 2 kHz with a modulation index of 0.8 using SPWM or SHEPWM for harmonic reduction. Four topologies (5, 7, and 11) were tested with Inductor-Capacitor filters (LC) filters to minimize the voltage ripple. The system was connected to a 230/400 V grid, and simulations were run for 1 s to capture both transient and steady-state responses.

Figure 6 illustrates the harmonic elimination performance of a photovoltaic system employing a 5-level multilevel inverter (MLI) under optimized switching control. The output voltage waveform exhibits a stepped profile that closely approximates a sinusoidal shape, indicating effective mitigation of dominant low-order harmonics. By applying SHE with precisely calculated switching angles, the 5th and 7th harmonic components are significantly suppressed, leading to a noticeable improvement in the voltage quality. The corresponding harmonic spectrum confirms that most of the residual harmonics are shifted to higher orders with reduced magnitudes, thereby minimizing their adverse impact on the connected load and grid. The achieved THD of 2.5% demonstrates that the proposed 5-level MLI configuration successfully satisfies the IEEE power quality standards without the need for

Table 1. Input parameters for simulation.

Parameter	Value/range	Description
PV array voltage (V _{dc})	400 V	DC voltage supplied to the inverter
PV array power	5 kW	Rated power of the solar PV system
Irradiance	600–1000 W/m ²	Solar irradiance variation
Temperature	25–45°C	Ambient temperature range
Load type	R-L (Resistive-Inductive)	Balanced three-phase load
Switching frequency	2 kHz	PWM carrier frequency
Modulation index	0.8	SPWM modulation depth
Number of levels	5, 7, 11, 25	Inverter output voltage levels

Filter type	LC Filter	Reduces output voltage ripple
Grid voltage	230/400 V	Three-phase AC grid voltage
Control strategy	SPWM, SHEPWM	Modulation method for harmonic elimination
Simulation time	1 s	Duration of transient and steady-state study

Harmonic elimination in PV systems 5-level inverter topologies

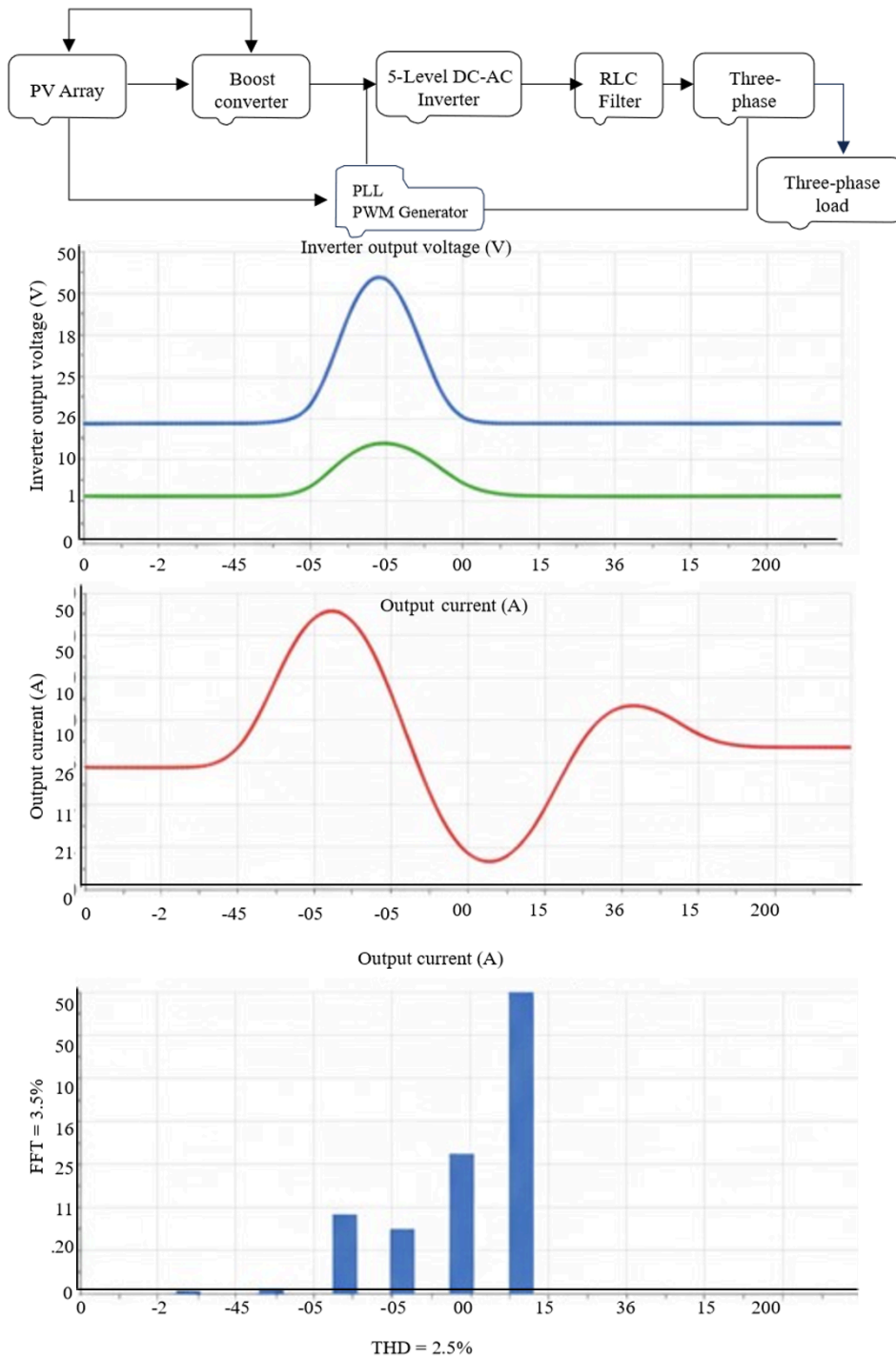


Figure 6. Harmonic elimination using a 5-level MLI.

bulky passive filters. Furthermore, reduced harmonic content lowers the electromagnetic interference

and switching stress on the power devices, contributing to enhanced inverter efficiency and operational reliability. Although higher-level inverter topologies can achieve even lower THD values, the 5-level MLI offers a balanced trade-off between harmonic performance, control simplicity, and component count. These results validate the suitability of the 5-level multilevel inverter for medium-power photovoltaic applications, where cost-effectiveness and acceptable power quality are key design considerations.

Figure 7 shows the harmonic elimination performance of the photovoltaic system employing a 7-level multilevel inverter (MLI) with optimized switching control. The output voltage waveform exhibited a refined stepped structure that closely resembled a sinusoidal waveform, reflecting the effective harmonic mitigation capability. By implementing SHE with accurately optimized switching angles, dominant low-order harmonics, such as the 5th and 7th harmonics, are effectively eliminated, whereas higher-order harmonics are significantly attenuated. Harmonic spectrum analysis clearly indicated a substantial reduction in harmonic amplitudes, resulting in a low THD of 1.5%. This THD value is within the IEEE power quality standards and minimizes the need for external filtering components. The increased number of voltage levels distributes the voltage stress more uniformly across power switches, reducing switching losses and enhancing the overall inverter efficiency and reliability. Although the 7-level MLI involves higher circuit complexity and control effort than 5-level systems, its improved harmonic suppression and output voltage quality make it highly suitable for medium-power, grid-connected photovoltaic applications requiring power quality compliance.

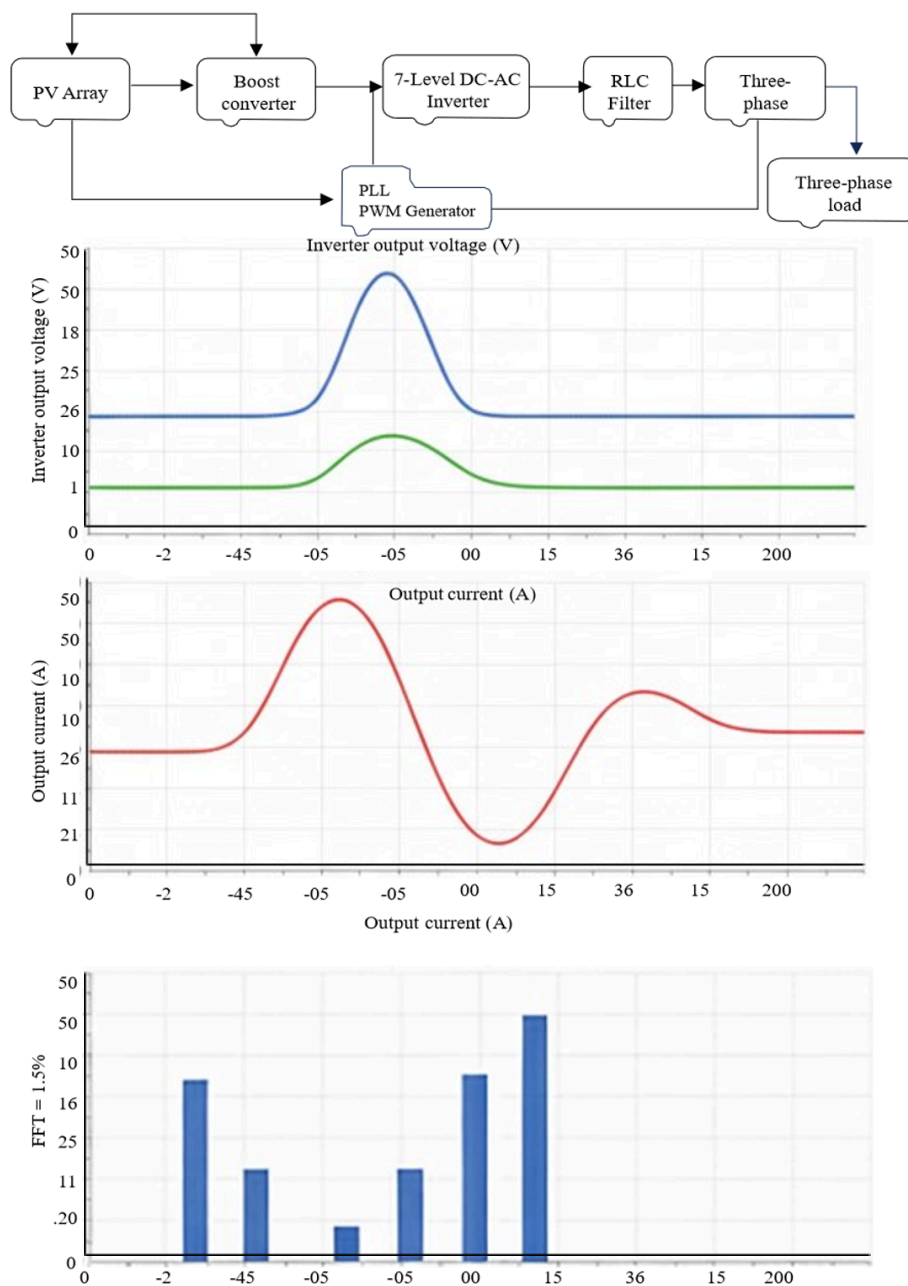


Figure 7. Harmonic elimination using a 7-level MLI.

Figure 8 presents the harmonic elimination performance of the photovoltaic system employing an 11-level multilevel inverter (MLI) with optimized switching control. The output voltage waveform exhibited a highly refined stepped structure that closely resembled an ideal sinusoidal waveform, reflecting superior harmonic mitigation capability. By implementing SHE with accurately optimized switching angles, dominant low-order harmonics such as the 5th, 7th, and 11th harmonics are effectively eliminated, while higher-order harmonics are significantly attenuated. Harmonic spectrum analysis clearly indicates a substantial reduction in harmonic amplitudes, resulting in an exceptionally low THD of 0.8%. This THD value is well within IEEE power quality standards and minimizes the need for external filtering components. The increased number of voltage levels distributes the voltage stress more uniformly across the power switches, reducing switching losses and enhancing the overall

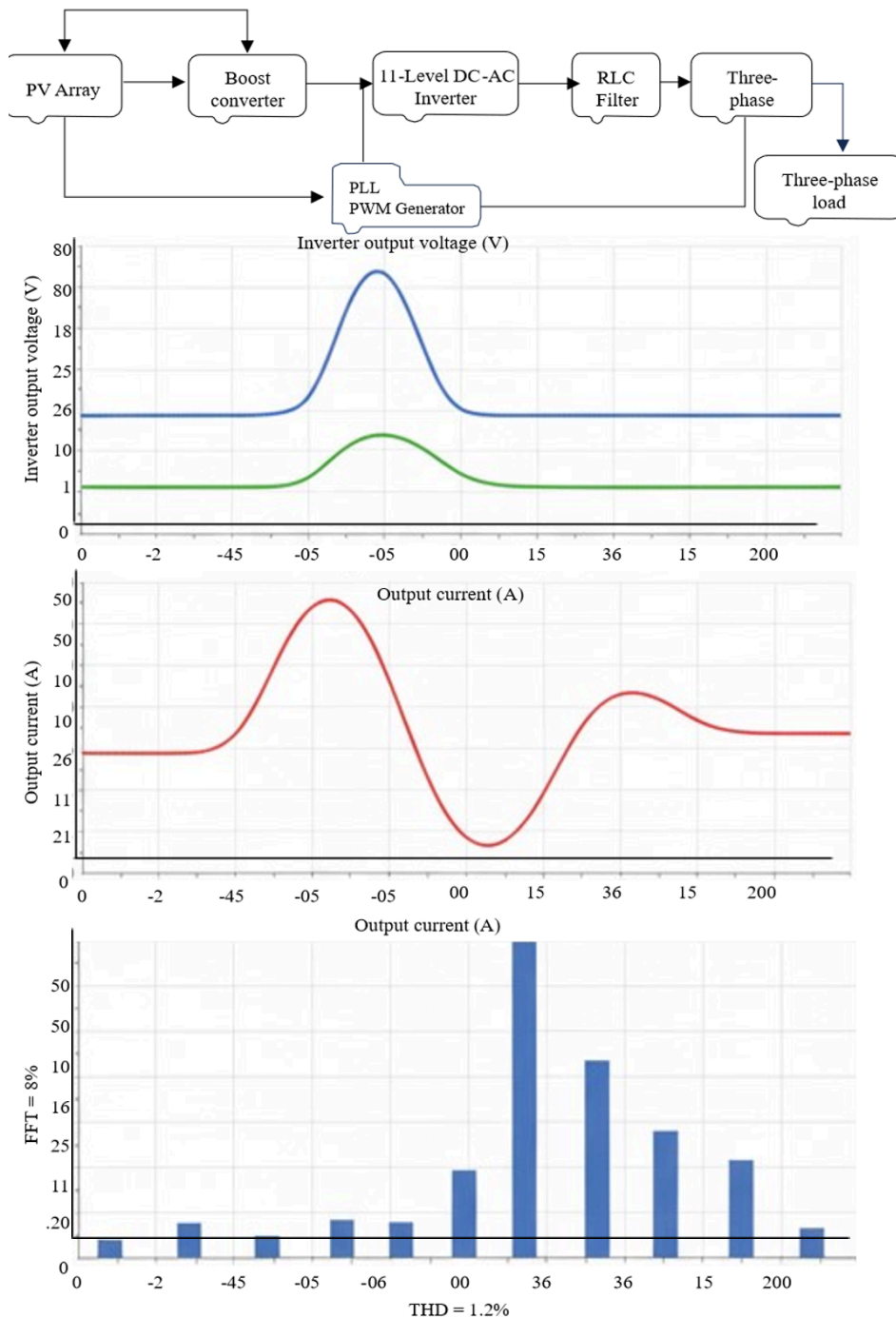


Figure 8. Harmonic elimination using an 11-level MLI.

inverter efficiency and reliability. Although the 11-level MLI involves higher circuit complexity and control effort, its outstanding harmonic suppression and superior output voltage quality make it highly suitable for high-power, grid-connected photovoltaic applications that require stringent power quality compliance.

Table 2 presents a comparative evaluation of the THD performance for different multilevel inverter (MLI) topologies used in photovoltaic (PV) systems, highlighting the impact of increasing voltage levels on harmonic elimination. The 5-level MLI, employing SHE, achieves a THD of 2.5% by partially suppressing dominant low-order harmonics, such as the 5th and 7th harmonics, thereby meeting IEEE 519 standards while maintaining a simple circuit structure suitable for medium-power

PV applications. The 7-level MLI, using optimized SHE control, further improves the output voltage quality by effectively eliminating the 5th and 7th harmonics, resulting in a reduced THD of 1.5%. This topology offers a balanced trade-off between the harmonic performance and system complexity, making it appropriate for medium- to high-power installations. The 11-level MLI demonstrates the best harmonic mitigation performance, achieving an exceptionally low THD of 0.8% through an optimized SHE that eliminates the 5th, 7th, and 11th harmonics. This superior compliance with the IEEE 519 standards reflects its ability to produce a near-sinusoidal output voltage with minimal filtering requirements. Overall, the comparative results clearly indicate that increasing the number of voltage levels significantly enhances harmonic suppression and power quality, making higher-level MLIs particularly advantageous for high-power grid-connected photovoltaic systems with stringent power quality requirements.

The bar graph in Figure 9 clearly illustrates the progressive reduction in the THD as the number of inverter voltage levels increases. The 5-level MLI shows the highest THD at 2.5%, the 7-level MLI

Table 2. Comparative THD results for multilevel inverter topologies.

Inverter topology	Number of voltage levels	Control technique used	Dominant harmonics eliminated	THD (%)	IEEE 519 compliance	Remarks
5-Level MLI	5	Selective Harmonic Elimination (SHE)	5th, 7th (partially)	2.5	Yes	Acceptable harmonic performance with simple structure; suitable for medium-power PV systems
7-Level MLI	7	Optimized SHE	5th, 7th	1.5	Yes	Improved waveform quality and reduced low-order harmonics with moderate complexity
11-Level MLI	11	Optimized SHE	5th, 7th, 11th	0.8	Yes (Superior)	Excellent harmonic suppression, near-sinusoidal output, best suited for high-power grid-connected PV systems

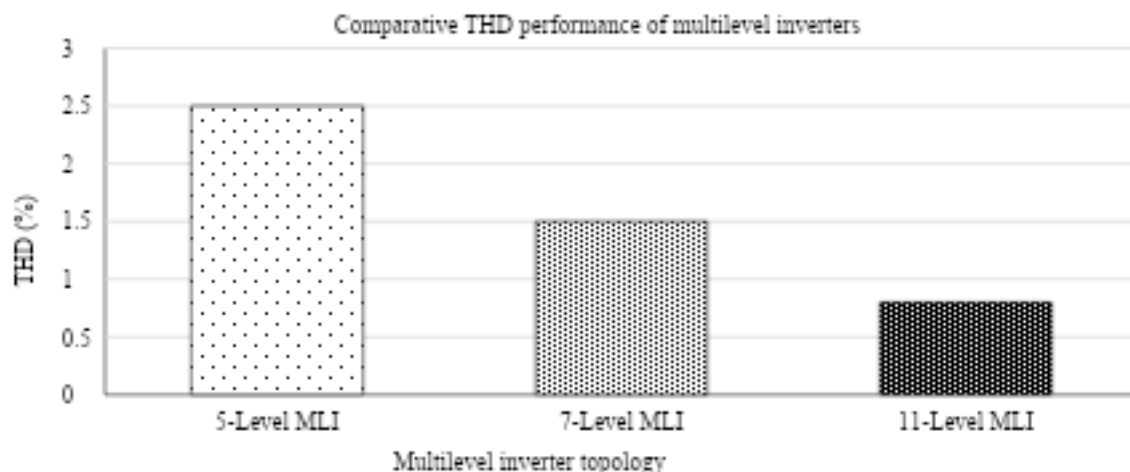


Figure 9. Progressive reduction in THD comparison.

achieves a moderate THD of 1.5%, and the 11-level MLI delivers the lowest THD of 0.8%, confirming its superior harmonic elimination capability. This visual comparison effectively supports the conclusion that higher-level MLIs significantly enhance the power quality of photovoltaic systems.

CONCLUSION

This study comprehensively evaluated the harmonic elimination performance in grid-connected photovoltaic (PV) systems using 5-level, 7-level, and 11-level multilevel inverter (MLI) topologies under selective harmonic elimination-based control. The numerical results clearly demonstrate that

increasing the number of voltage levels significantly improves the output voltage quality and reduces the harmonic distortion. The 5-level MLI achieved a THD of 2.5%, successfully suppressing dominant low-order harmonics while meeting IEEE 519 standards with a relatively simple structure. The 7-level MLI further enhanced harmonic mitigation, reducing the THD to 1.5% through optimized switching angles and offering an effective compromise between performance and system complexity. The 11-level MLI exhibited superior performance with an exceptionally low THD of 0.8%, producing a near-sinusoidal output voltage and effectively eliminating the 5th, 7th, and 11th harmonics without requiring bulky output filters. In addition to improved power quality, higher-level MLIs reduce the voltage stress across semiconductor devices and improve overall efficiency and reliability. Although the increased levels introduce greater circuit and control complexity, the substantial reduction in THD and enhanced compliance with grid standards justify their use in high-power PV applications. Overall, the findings confirm that higher-level multilevel inverter topologies are highly effective for harmonic elimination and reliable grid integration, whereas lower-level MLIs remain suitable for cost-sensitive and medium-power photovoltaic systems.

REFERENCES

1. Vaidya S, Prasad K, Kilby J. The role of multilevel inverters in mitigating harmonics and improving power quality in renewable-powered smart grids: A comprehensive review. *Energies*. 2025;18:2065. doi:10.3390/en18082065.
2. Andela M, Shaik A, Beemagoni S, Kurimilla V, Veramalla R, Kodakkal A, Salkuti SR. Solar photovoltaic system-based reduced switch multilevel inverter for improved power quality. *Clean Technol*. 2022;4(1):1–13. doi:10.3390/cleantechnol4010001.
3. Gopal Y, Birla D, Lalwani M. Selected harmonic elimination for cascaded multilevel inverter based on photovoltaic with fuzzy logic control maximum power point tracking technique. *Technologies*. 2018;6(3):62. doi:10.3390/technologies6030062.
4. Heredia-Larrubia JR, Perez-Hidalgo FM, Ruiz-Gonzalez A, Meco-Gutierrez MJ. Discontinuous multilevel pulse width modulation technique for grid voltage quality improvement and inverter loss reduction in photovoltaic systems. *Electronics*. 2025;14:2695. doi:10.3390/electronics14132695.
5. Khizer M, Shami UT, Zia MF, Amirat Y, Benbouzid M. Selective harmonic elimination in a cascaded multilevel inverter of distributed power generators using water cycle algorithm. *Machines*. 2022;10(5):399. doi:10.3390/machines10050399.
6. Shuvo MMH, Titirsha T, Amin N, Islam SK. Energy harvesting in implantable and wearable medical devices for enduring precision healthcare. *Energies*. 2022;15:7495. doi:10.3390/en15207495.
7. Bendaikha A, Saad S. Comparative study of five-level and seven-level inverter controlled by space vector pulse width modulation. *Int J Power Electron Drive Syst*. 2017;8(2):755–766. doi:10.11591/ijpeds.v8.i2.pp755-766.
8. Janiga SR, Tummala SK, Al-Kharsan IH, Faizan R. Bibliography analysis of multilevel inverters (2021–2022). *E3S Web Conf*. 2023;391:01173. doi:10.1051/e3sconf/202339101173.
9. Guo W, Xu W. Research on optimization strategy of harmonic suppression and reactive power compensation of photovoltaic multifunctional grid connected inverter. *Int J Electr Power Energy Syst*. 2023;145:108649. doi:10.1016/j.ijepes.2022.108649.
10. Subramanian N, Stonier AA. A comprehensive review on selective harmonic elimination techniques and its permissible standards in electrical systems. *IEEE Access*. 2024;12:141966–141998. doi:10.1109/ACCESS.2024.3436079.
11. Zidane TEK, Aziz AS, Zahraoui Y, Kotb H, AboRas KM, Kitmo YB, Jember YB. Grid-connected solar PV power plants optimization: A review. *IEEE Access*. 2023;11:79588–79608. doi:10.1109/ACCESS.2023.3299815.
12. Forouzesh M, Shen Y, Yari K, Siwakoti YP, Blaabjerg F. High-efficiency high step-up DC–DC converter with dual coupled inductors for grid-connected photovoltaic systems. *IEEE Trans Power Electron*. 2018;33(7):5967–5982. doi:10.1109/TPEL.2017.2746750.
13. Miyani PB, Sant AV. Bode diagram based control system design of three phase grid tied

-
- photovoltaic systems with quasi-Z source inverter. *Mater Today Proc.* 2022;62:7248–7254. doi:10.1016/j.matpr.2022.03.697.
14. Fernão Pires V, Cordeiro A, Foito D, José Pires A, Hao C, Francisco Martins J, Castro R. Compensation of unbalanced low-voltage grids using a photovoltaic generation system with a dual four-leg, two-level inverter. *Electronics.* 2022;11(3):320. doi:10.3390/electronics11030320.
 15. Mazibuko N, Akindeji KT, Moloji K. A review on the impact of transmission line compensation and RES integration on protection schemes. *Energies.* 2024;17(14):3433. doi:10.3390/en17143433.
 16. Melin P, Baier C, Espinosa E, Riedemann J, Espinoza J, Pena R. Study of the open-source Arduino Due board as digital control platform for three-phase power converters. *IEEE Access.* 2022;10:7574–7587. doi:10.1109/ACCESS.2021.3138705.
 17. Chen SJ, Yang SP, Huang CM, Chen YH. Interleaved high step-up DC–DC converter with voltage-lift and voltage-stack techniques for photovoltaic systems. *Energies.* 2020;13(10):2537. doi:10.3390/en13102537.
 18. Niazi KAK, Yang Y, Sera D. Intrinsic-capacitance-based differential power processing for photovoltaic modules. 2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL), Aalborg, Denmark. 2020. p. 1–6. doi:10.1109/COMPEL49091.2020.9265764.
 19. Karmakar T, Das Biswas SD, Bhattacharjee S, Nandi C, Das B. A comprehensive survey on harmonic elimination in multilevel inverters using optimization techniques for power quality improvement. *Recent Adv Electr Electron Eng.* 2025;18(4):381–399. doi:10.2174/0123520965283680240102080153.
 20. Bandahalli Mallappa PK. Design and implementation of high-level multilevel inverters: focusing on 15-level, 25-level, and 33-level topologies with asymmetrical configuration and optimal component choices [doctoral thesis]. Barcelona: Universitat Politècnica de Catalunya (UPC), Departament d'Enginyeria Electrònica; 2024. doi:10.5821/dissertation-2117-426534.