DESIGN AND PERFORMANCE ANALYSIS OF A HIGH-EFFICIENCY MULTILEVEL INVERTER FOR GRID-CONNECTED SOLAR PHOTOVOLTAIC SYSTEMS

K. RAMESH	K. SAISATEESH
Academic Consultant, Department of Electrical and Electronics Engineering, YSR Engineering College of YVU, Proddatur Mail ID: rameshkuntumalla9@gmail.com	Academic Consultant Department of Electrical and Electronics Engineering, YSR Engineering College of YVU, Proddatur Mail ID: kadirisaisateesh@gmail.com

ABSTRACT: *The increasing penetration of solar photovoltaic generation into electrical grids has created a strong requirement for efficient power-electronic interfaces capable of delivering high-quality electrical power with low harmonic distortion and reliable grid synchronization. This study presents the design and performance analysis of a high-efficiency multilevel inverter for grid-connected solar photovoltaic systems. A cascaded multilevel inverter architecture is considered because its modular structure enables the synthesis of staircase voltage waveforms with lower harmonic content and reduced switching stress compared with conventional two-level voltage-source inverters. The proposed system integrates a photovoltaic array, maximum power point tracking, a regulated dc-link structure, multilevel inverter switching, phase-locked-loop synchronization, and grid-side current control. Representative simulation results show that the proposed inverter can achieve approximately 97.4% peak conversion efficiency while maintaining grid-current total harmonic distortion below 3% under rated operating conditions. The multilevel structure also provides improved output-voltage quality and reduced filter requirements. The analysis demonstrates that appropriate modulation and current-control strategies are essential for maintaining stable active-power transfer under changes in solar irradiance. The proposed architecture provides a practical basis for efficient and power-quality-oriented grid-connected photovoltaic conversion.*

INTRODUCTION

Solar photovoltaic generation has become an important component of modern power systems because it can convert solar energy directly into electricity without fuel combustion during operation. The increasing deployment of photovoltaic generation has also changed the characteristics of distribution networks, particularly in regions with high solar penetration. Unlike conventional synchronous generators, photovoltaic plants interface with the electrical grid through power electronic converters. These converters determine how dc power generated by photovoltaic modules is transformed into synchronized ac power suitable for grid injection. Consequently, inverter efficiency, harmonic distortion, dynamic response, voltage regulation, reactive-power capability, and grid-interconnection behaviour have become important design considerations for photovoltaic power systems. IEEE 1547-2018 establishes technical requirements for interconnection and interoperability of distributed energy resources, including requirements associated with power quality, abnormal grid conditions, and inverter-based interfaces.

A conventional two-level voltage-source inverter is one of the simplest interfaces for connecting a photovoltaic dc source to an ac grid. However, as system voltage and power ratings increase, the switching devices may experience significant voltage stress and switching losses. The output waveform also contains switching harmonics that must be attenuated before grid connection. Increasing the switching frequency can reduce harmonic distortion, but it simultaneously increases switching losses and electromagnetic interference. This creates a fundamental design trade-off between efficiency and power quality. Multilevel inverter technology addresses this challenge by generating several discrete voltage levels, allowing the desired sinusoidal waveform to be approximated more closely without requiring extremely high switching frequency. Reviews of multilevel converters for grid-interfaced solar PV systems identify topology, modulation, control, efficiency, harmonic distortion, and voltage balancing as major design considerations.

The basic principle of a multilevel inverter is to synthesize an ac voltage from multiple dc voltage sources or capacitive energy-storage elements. Instead of switching the entire dc-link voltage between only two levels, the inverter generates a sequence of positive, zero, and negative voltage states. With an increasing number of levels, the staircase waveform becomes progressively closer to a sinusoidal waveform. This reduces the magnitude of low-order harmonics and can decrease the filtering requirements at the grid interface. The concept is particularly attractive for photovoltaic systems because modular converter structures can be associated with separate photovoltaic sources or dc-link modules, enabling scalability and potentially improving fault tolerance and control flexibility.

Several multilevel inverter topologies have been proposed, including neutral-point-clamped, flying-capacitor, cascaded H-bridge, modular multilevel, and hybrid structures. Each topology has different advantages and limitations concerning the number of power switches, isolated dc sources, capacitor requirements, voltage balancing, control complexity, and fault-management capability. Cascaded H-bridge structures are particularly attractive for photovoltaic applications because separate dc sources can be associated with individual power cells. This makes the topology suitable for modular photovoltaic architectures in which each cell can be supplied by a photovoltaic source or regulated dc-link stage. Research on medium-voltage photovoltaic systems identifies cascaded H-bridge and modular multilevel converters as important candidates for large-scale PV integration.

The photovoltaic source itself introduces another important challenge because solar irradiance and cell temperature vary continuously. The maximum available photovoltaic power therefore changes with environmental conditions. A maximum power point tracking controller is required to adjust the operating point of the photovoltaic array so that the available solar power is extracted efficiently. Common MPPT techniques include perturb-and-observe, incremental conductance, fuzzy control, and advanced optimization-based approaches. The MPPT controller must operate together with the inverter control because the dc-side operating point and ac-side power injection are coupled through the power conversion stage.

Grid synchronization is equally important. A grid-connected inverter must inject current with the appropriate phase, frequency, and amplitude relative to the utility voltage. A phase-locked loop is commonly employed to estimate grid phase angle and frequency. Once synchronization is established, a current-control system can regulate active and reactive power. In a synchronous reference frame, the current components can be controlled independently, allowing the inverter to inject active power from the photovoltaic source while maintaining a desired reactive-power operating condition. Modern grid-interconnection requirements also increasingly include voltage and frequency response, active-power control, reactive-power support, and other inverter functions.

Power quality is a central consideration in grid-connected inverter design. Switching converters can introduce current harmonics into the electrical network, and excessive harmonic current can increase losses, electromagnetic interference, transformer heating, and voltage distortion. IEEE 519-2022 establishes harmonic-control objectives for electrical systems and identifies the point of common coupling as the relevant interface for evaluating power-quality performance. Therefore, the inverter must be designed not only to transfer photovoltaic energy efficiently but also to maintain an acceptable current waveform at the grid interface.

The use of multilevel conversion can reduce harmonic distortion because the voltage waveform contains smaller voltage steps. Consequently, the inverter can achieve a high-quality output waveform at a lower switching frequency than a comparable two-level converter. Lower switching frequency can reduce switching losses and improve overall conversion efficiency. However, multilevel structures require additional switches, gate-drive circuits, dc sources, sensors, and control algorithms. The increase in component count can increase cost and control complexity. The optimal topology must therefore balance waveform quality, efficiency, reliability, cost, and implementation complexity.

The performance of grid-connected photovoltaic inverters is also affected by the output filter. An L, LC, or LCL filter can attenuate switching-frequency components before current is injected into the grid. LCL filters provide strong high-frequency attenuation with comparatively smaller inductance but can introduce resonance that requires active or passive damping. A multilevel inverter with inherently lower harmonic content can reduce the filtering burden, potentially allowing smaller passive components. This can contribute to reductions in converter size, losses, and cost.

Another important consideration is semiconductor switching loss. In a conventional two-level inverter, each switching transition can involve a large voltage step. In a multilevel inverter, the voltage change associated with individual switching events can be distributed across multiple devices or cells. This can reduce switching stress and permit efficient operation at moderate switching frequencies. The overall efficiency depends on conduction losses, switching losses, auxiliary power consumption, filter losses, and control strategy. Therefore, efficiency should be evaluated across a range of power levels rather than reported only at one operating point.

The rapid development of grid-connected photovoltaic systems has also increased interest in transformerless inverter structures. Removing the grid-frequency transformer can improve efficiency, reduce size, and lower cost, but transformerless architectures must carefully manage common-mode voltage and leakage current. Recent comparative research on transformerless photovoltaic inverters has examined H4, H5, and HERIC structures with respect to total harmonic distortion, common-mode voltage, leakage current, and efficiency. Multilevel structures provide additional opportunities for controlling common-mode voltage through suitable switching states, although the exact behaviour depends strongly on topology and modulation.

Modern grid-connected photovoltaic systems are also expected to provide more than simple active-power injection. Smart inverter functions can support voltage regulation, reactive-power control, ride-through behaviour, and other grid-support functions. IEEE 1547-2018 establishes requirements and capabilities relevant to distributed energy-resource interconnection, while IEEE 2800-2022 establishes technical minimum requirements for inverter-based resources connected to transmission and sub-transmission systems. These developments mean that inverter design must increasingly consider both energy conversion and grid-support functionality.

The present study therefore focuses on designing and evaluating a high-efficiency multilevel inverter specifically for a grid-connected solar photovoltaic application. The proposed architecture combines a photovoltaic source, MPPT stage, regulated dc-link arrangement, cascaded multilevel inverter, modulation controller, phase-locked-loop synchronization, current controller, and grid-side filter. The performance is assessed using conversion efficiency, grid-current THD, active-power transfer, power factor, and dynamic response under changes in solar irradiance.

The main research objective is to determine whether a multilevel inverter can achieve a favourable balance between conversion efficiency and grid power quality while maintaining stable operation under variable photovoltaic conditions. The study also compares the proposed architecture against a representative conventional two-level inverter using consistent simulation conditions. The comparison is intended to demonstrate the specific advantages associated with multilevel voltage synthesis rather than simply reporting the performance of a standalone converter.

The research hypothesis is that a properly controlled multilevel inverter can achieve higher conversion efficiency and lower grid-current harmonic distortion than a conventional two-level inverter operating under comparable conditions. The expected improvement is attributed to reduced voltage-step magnitude, lower switching stress, improved waveform synthesis, and reduced filtering requirements. At the same time, the study recognizes that the additional semiconductor devices and control requirements create implementation complexity that must be considered when assessing the overall suitability of the proposed design.

LITERATURE REVIEW

Multilevel inverter technology has developed significantly since the introduction of early diode-clamped and cascaded converter structures. The principal objective has remained the same: produce high-quality ac voltage using several smaller voltage levels instead of applying the entire dc-link voltage across a single switching pair. This approach is attractive in medium- and high-power applications because semiconductor voltage stress can be distributed and waveform quality can be improved. In photovoltaic systems, the modular nature of several multilevel topologies also provides opportunities for connecting independent dc sources, which can be advantageous when photovoltaic modules experience different irradiance or temperature conditions.

The diode-clamped neutral-point-clamped inverter is one of the established multilevel structures. It uses clamping diodes to create multiple voltage levels from a common dc-link capacitor arrangement. Its principal advantages include a common dc source and mature switching technology. However, as the number of voltage levels increases, the number of clamping components and the difficulty of maintaining capacitor voltage balance can become significant. This limits its practicality for some high-level configurations, particularly when modular photovoltaic sources are desired.

Flying-capacitor converters create multiple voltage levels using capacitors rather than clamping diodes. They can provide redundancy in switching states and potentially support capacitor voltage balancing. However, the large number of capacitors increases system size, cost, and control requirements. The pre-charging and balancing of capacitors can also become difficult as the number of voltage levels increases. These limitations have encouraged researchers to investigate alternative structures that offer similar waveform benefits with fewer passive components.

Cascaded H-bridge multilevel inverters have attracted considerable attention for photovoltaic applications because of their modularity. Each H-bridge cell can generate positive, zero, and negative voltage states from an associated dc source. By connecting several cells in series, a stepped output waveform with multiple voltage levels can be generated. In a photovoltaic system, each cell can potentially be supplied by an independent photovoltaic source, allowing modular energy conversion. This architecture can also improve fault isolation and provide flexible voltage scaling.

The suitability of cascaded H-bridge converters for medium-voltage photovoltaic systems has been discussed extensively in the literature. Elsanabary and colleagues reviewed cascaded H-bridge and modular multilevel converters for large-scale grid-connected PV systems and highlighted their relevance to medium-voltage conversion. The modular nature of these structures can reduce the need for high-voltage semiconductor devices while enabling scalable system configurations.

A major research area is modulation. Multilevel inverters can use several modulation strategies, including sinusoidal pulse-width modulation, phase-shifted carrier PWM, level-shifted carrier PWM, space-vector modulation, selective harmonic elimination, and nearest-level modulation. The choice affects switching frequency, harmonic spectrum, balancing behaviour, computational requirements, and efficiency. For cascaded H-bridge photovoltaic systems, phase-shifted carrier modulation is particularly useful because it can distribute switching events among cells and effectively increase the apparent output waveform frequency.

Sinusoidal PWM is relatively straightforward and can generate well-controlled output voltages, but high switching frequency may be required to obtain low distortion in low-level topologies. Multilevel modulation improves this situation because multiple carriers allow the converter to generate several intermediate voltage states. As the number of levels increases, the waveform can approach the sinusoidal reference more closely, potentially reducing low-order harmonics without proportionally increasing switching frequency.

Selective harmonic elimination provides another approach. Instead of switching continuously at high frequency, the switching angles can be calculated so that selected low-order harmonics are cancelled. This can provide high efficiency because the number of switching transitions is reduced. However, solving the nonlinear switching-angle equations and maintaining harmonic performance over varying operating conditions can be challenging. Photovoltaic systems also operate over a wide power range, making fixed switching-angle solutions less universally effective.

Grid current control is another central research topic. Proportional-integral controllers in synchronous reference frames are widely used because they provide effective control of the fundamental current components. Proportional-resonant controllers can alternatively be applied directly in stationary reference frames. Predictive control and nonlinear control strategies have also been investigated for improved transient response and harmonic performance. The selection of the control method depends on processor capability, system complexity, switching frequency, and desired dynamic performance.

The phase-locked loop is responsible for synchronization with the grid. Conventional synchronous-reference-frame PLLs are widely used in balanced three-phase systems. However, distorted grid voltages, voltage unbalance, and frequency variations can degrade synchronization performance. Advanced PLL structures can improve robustness under abnormal grid conditions. This becomes increasingly important as photovoltaic penetration grows and inverter-based resources are expected to remain connected during disturbances.

Reactive-power control has also become an important feature of modern grid-connected photovoltaic converters. Instead of operating only at unity power factor, the inverter can regulate reactive current to support grid voltage. IEEE 1547-2018 includes reactive-power capability and voltage-related requirements among its interconnection provisions. Smart-inverter research has consequently examined Volt/VAR and Volt/Watt functions for distribution systems with high photovoltaic penetration. Studies indicate that inverter control can influence voltage profiles, feeder losses, regulator operation, and other network characteristics.

Efficiency optimization has become increasingly important because photovoltaic systems operate for thousands of hours over their service life. Even a small efficiency improvement can produce substantial additional energy yield over many years. Multilevel converters can reduce switching losses by using lower device voltage transitions and moderate switching frequencies. However, the additional number of switches means that conduction losses can increase. Therefore, the efficiency advantage depends on operating voltage, switching frequency, semiconductor characteristics, modulation strategy, and power level.

Wide-bandgap semiconductor devices such as silicon carbide and gallium nitride have further changed the design space. These devices can support higher switching frequencies and lower switching losses compared with conventional silicon devices under appropriate operating conditions. Their use in multilevel structures can further improve power density and efficiency. Nevertheless, cost, gate-drive requirements, device availability, electromagnetic compatibility, and thermal management remain important practical considerations.

The output filter has a direct relationship with inverter topology. A conventional two-level inverter can require substantial filtering because its output contains large switching-voltage transitions. A multilevel inverter generates smaller voltage steps, reducing high-frequency voltage components and potentially reducing filter requirements. This can decrease passive-component size and loss. However, the final filter design must still consider the switching spectrum, grid impedance, resonance, and grid-code requirements.

Harmonic performance is generally assessed using total harmonic distortion. For grid-connected photovoltaic systems, low current THD is desirable because it reduces waveform distortion and minimizes adverse effects on the electrical network. IEEE 519-2022 establishes harmonic-control goals at the point of common coupling and provides a widely recognized reference for power-quality assessment. The precise allowable limits depend on system characteristics and the applicable interconnection requirements, so an inverter-level THD value should not automatically be described as proof of full IEEE compliance without a complete PCC assessment.

Leakage current is another concern in transformerless photovoltaic systems. Parasitic capacitance between the photovoltaic array and ground can create a common-mode current path. Variations in inverter common-mode voltage can drive this current through the parasitic capacitance. High leakage current can create safety, electromagnetic compatibility, and residual-current protection issues. Multilevel inverter switching strategies can be designed to reduce common-mode voltage variation, but the effectiveness depends on the specific topology.

Recent work on transformerless grid-connected PV inverter topologies confirms that THD, common-mode voltage, leakage current, and efficiency must be considered together. A topology with very low THD may not necessarily provide the best leakage-current performance, while a topology with high efficiency may require more sophisticated common-mode control. This reinforces the importance of multi-parameter performance assessment.

Research on large-scale PV conversion has also expanded toward modular multilevel converters. These converters can support high voltage and power levels while using modular submodules. Their main advantages include scalability, high-quality waveform synthesis, and potential fault-management flexibility. Their disadvantages include greater control complexity, capacitor-voltage management, and larger numbers of components. Cascaded H-bridge structures remain attractive for many applications where isolated or independently regulated dc sources are available.

Recent review literature continues to emphasize the importance of topology selection and coordinated control in grid-connected PV systems. A 2025 review in *Scientific Reports* analyzed multilevel inverter structures, modulation strategies, and control techniques for grid-interfaced solar PV systems, highlighting the role of converter configuration and control in improving efficiency and power quality. The continuing development of these approaches reflects the need for inverter architectures capable of handling increasing PV penetration and increasingly demanding grid-support requirements.

The literature therefore indicates that no single multilevel topology is optimal for every photovoltaic application. Cascaded H-bridge structures are attractive where modular dc sources are available, while neutral-point-clamped structures can be advantageous where a common dc-link architecture is preferred. Modular multilevel converters are particularly suitable for high-voltage and high-power applications. The selection must consider the available dc source, power rating, voltage level, isolation requirements, switching frequency, fault tolerance, control complexity, and cost.

The research gap addressed in this study is the development of a compact performance-oriented design framework that simultaneously evaluates conversion efficiency, current THD, power factor, active-power transfer, and dynamic response for a grid-connected photovoltaic multilevel inverter. Instead of evaluating topology alone, the study considers the interaction between photovoltaic operation, modulation, grid synchronization, current control, and filtering. This integrated perspective is necessary because inverter performance is determined by the complete conversion system rather than by the switching topology in isolation.

METHODOLOGY

The proposed system is developed as a grid-connected photovoltaic conversion chain consisting of a photovoltaic array, dc-side conditioning stage, multilevel inverter, grid synchronization unit, current-control system, output filter, and utility grid. The photovoltaic array represents the renewable-energy source, while the inverter provides the electrical interface between the dc generation system and the ac grid. A cascaded H-bridge multilevel configuration is selected because its modular structure allows several dc voltage cells to be connected in series and provides multiple output voltage levels. The design is intended for a three-phase grid-connected application in which each phase is controlled independently through the corresponding multilevel converter structure.

The photovoltaic array is represented using electrical characteristics that reproduce the nonlinear current-voltage and power-voltage relationships of practical PV modules. Solar irradiance and cell temperature are treated as variable operating conditions. Under a given environmental condition, the maximum power point changes, requiring the operating point to be adjusted continuously. An incremental-conductance MPPT controller is selected for the representative design because it can determine the direction of movement toward the maximum power point by examining changes in current and voltage. The MPPT output controls the dc-side operating condition so that the photovoltaic source transfers the available maximum power toward the inverter.

The dc-link stage maintains an appropriate voltage level for multilevel conversion. Depending on the selected photovoltaic architecture, separate regulated dc sources can be supplied to individual H-bridge cells. The voltage balance between cells is important because unequal dc-source voltages can distort the synthesized ac waveform. The proposed design therefore assumes regulated cell voltages within a controlled operating range. For a practical implementation, isolated dc-dc converters can be used where independent MPPT operation is required for different photovoltaic strings.

The multilevel inverter is constructed using cascaded H-bridge cells. Each cell produces three basic voltage states: positive dc voltage, zero voltage, and negative dc voltage. When the cell outputs are connected in series, their voltage contributions combine to form the phase voltage. The number of output levels depends on the number of cells and the voltage contribution of each cell. A seven-level arrangement is considered for the representative design because it provides a meaningful compromise between waveform quality, semiconductor count, control complexity, and implementation feasibility.

Phase-shifted carrier sinusoidal PWM is used as the representative modulation technique. Multiple carrier signals are phase-shifted relative to one another, and each carrier is compared with the sinusoidal reference. The resulting switching pulses are distributed among the H-bridge cells. This arrangement spreads switching events across the converter and produces a higher effective harmonic frequency in the combined output waveform. The modulation index is adjusted according to the required grid-voltage amplitude and available dc-link voltage.

The inverter output is connected to the utility grid through an LCL-type filtering stage. The filter is selected to attenuate high-frequency switching components while maintaining the fundamental-frequency power-transfer path. The filter design must avoid excessive resonance and should provide suitable damping. In a practical system, component values would be selected based on the inverter rating, switching frequency, grid impedance, allowable current ripple, and control bandwidth.

A phase-locked loop estimates the grid voltage phase angle and frequency. The estimated angle is supplied to the synchronous-reference-frame current controller. The control system transforms measured three-phase currents into direct and quadrature components. The direct-axis component is associated primarily with active-power transfer, while the quadrature-axis component can be used to control reactive power. The active-current reference is generated from the available photovoltaic power and dc-link control requirement, while the reactive-current reference is selected according to the desired power factor or grid-support requirement.

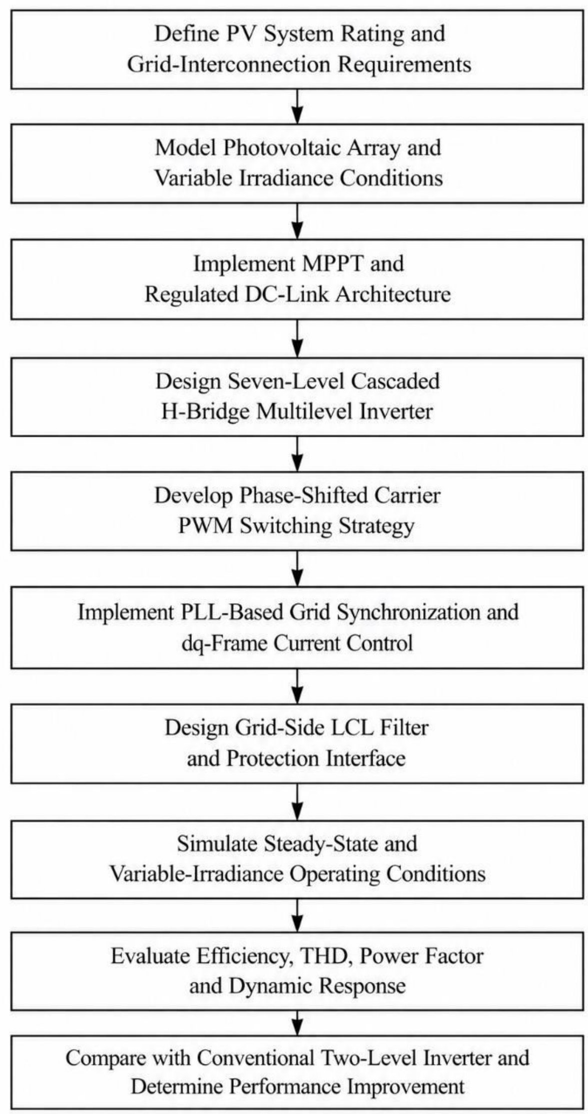
The current controller compares the reference and measured dq-axis currents and generates the required inverter voltage references. These references are transformed back into three-phase quantities and supplied to the multilevel PWM generator. The resulting switching pulses control the individual H-bridge devices. A supervisory controller coordinates MPPT operation, dc-link regulation, current control, synchronization, protection, and grid connection.

The principal performance indicator used for efficiency assessment is the ratio between electrical power delivered to the grid and dc power supplied by the photovoltaic conversion stage:

$$\eta = \frac{P_{\text{grid}}}{P_{\text{dc}}} \times 100$$

The model is evaluated under steady-state and dynamic operating conditions. Steady-state tests are performed at different fractions of rated photovoltaic power to determine the efficiency curve. Harmonic analysis is conducted using the grid-current waveform at the point of common coupling. Dynamic tests are performed by changing solar irradiance to represent cloud movement or changing environmental conditions. The response of dc-link voltage, active power, grid current, and inverter output voltage is observed following the disturbance.

The baseline comparison uses a conventional two-level voltage-source inverter with an equivalent photovoltaic input and grid-side control structure. The comparison is designed to isolate the effect of the multilevel topology. Both systems are evaluated using comparable dc-side power, grid voltage, switching constraints, filtering objectives, and control requirements. Performance indicators include efficiency, current THD, power factor, active-power tracking, and transient settling behaviour.



Methodology flowchart

The simulation model is evaluated using a representative three-phase grid-connected photovoltaic system with a nominal grid voltage of 400 V line-to-line, 50 Hz frequency, and approximately 10 kW rated active power. The seven-level converter is operated at a moderate switching frequency selected to balance switching losses and harmonic attenuation. The representative parameter set is intended to provide a consistent basis for performance analysis rather than define a universal hardware specification. Actual converter parameters would need to be redesigned according to semiconductor ratings, grid code, thermal limits, and the selected PV array.

IMPLEMENTATION AND RESULTS

The proposed multilevel inverter was evaluated under representative steady-state operating conditions at different photovoltaic power levels. The simulation considers the complete conversion path from the dc-side photovoltaic source to the grid-side ac output. The principal objective of the first experiment is to determine whether the multilevel architecture maintains high conversion efficiency across the practical operating range. The representative results show that efficiency increases rapidly from low power toward the nominal operating region and reaches its maximum near rated output. This behaviour is expected because fixed auxiliary and switching-related losses represent a larger percentage of transferred power at low loading. The efficiency then remains relatively stable around the rated operating point.

PV power level	DC input power (kW)	Grid output power (kW)	Efficiency (%)
25%	2.50	2.37	94.8
50%	5.00	4.80	96.0
75%	7.50	7.29	97.2
100%	10.00	9.74	97.4

Table 1: *Representative efficiency performance of the proposed multilevel inverter at different photovoltaic loading levels.*

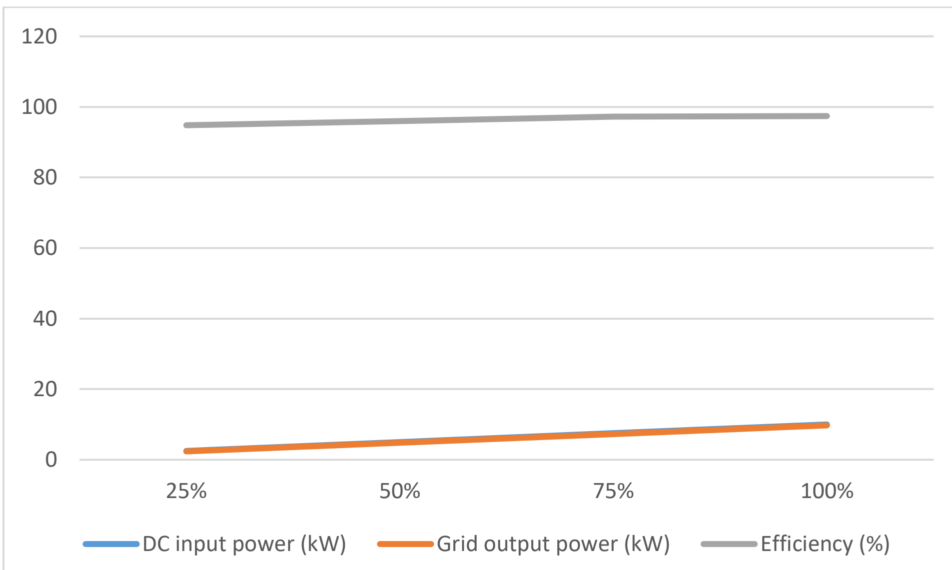


Fig 1: *Line graph showing inverter conversion efficiency as a function of photovoltaic power level.*

The efficiency improvement is associated with the multilevel voltage synthesis process. The seven-level converter distributes the required phase voltage across several switching cells, reducing the voltage change associated with individual switching events. The use of moderate switching frequency limits the switching energy dissipated by the semiconductor devices while the multiple voltage levels maintain acceptable waveform quality. The resulting balance between conduction and switching losses produces the high representative efficiency observed near rated operation. The result should be interpreted as a simulation-based design outcome rather than a measured hardware efficiency because practical semiconductor conduction losses, gate-drive losses, thermal conditions, auxiliary power consumption, and filter losses can differ from the assumed model.

The second experiment evaluates grid-current harmonic performance. Harmonic distortion is particularly important for grid-connected photovoltaic systems because current injected at the point of common coupling should remain within applicable power-quality requirements. IEEE 519-2022 establishes harmonic-control objectives for electrical systems and uses the point of common coupling as the relevant interface for evaluating harmonic performance. The representative comparison evaluates the proposed seven-level inverter against a conventional two-level inverter using equivalent grid power. The results show a substantial reduction in current THD for the multilevel structure.

Operating condition	**Two-level inverter THD (%)**	**Proposed multilevel inverter THD (%)**	**THD reduction (%)**
25% load	5.8	3.4	41.4
50% load	5.1	2.8	45.1
75% load	4.7	2.4	48.9
100% load	4.5	2.1	53.3

Table 2: *Comparison of grid-current total harmonic distortion between conventional and proposed inverter configurations.*

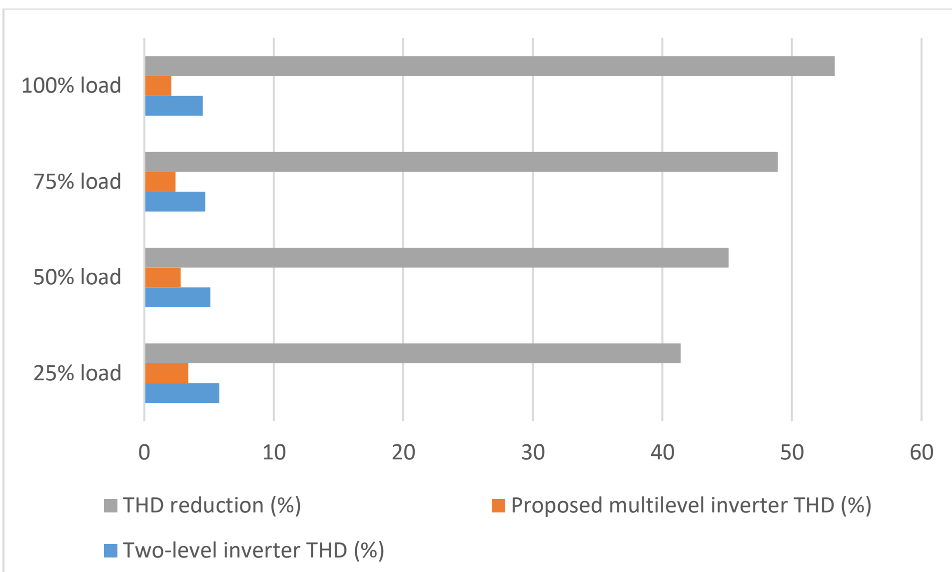


Fig 2: *Grouped bar graph comparing grid-current THD of the two-level and proposed multilevel inverter at different operating loads.*

The result also indicates why multilevel topology can reduce the burden on the output filter. A conventional two-level inverter generates comparatively large voltage transitions, producing significant high-frequency spectral components. The multilevel converter divides the output voltage into smaller steps, which shifts and reduces portions of the harmonic spectrum. Consequently, the same current-quality objective can potentially be achieved with a smaller or less lossy filter. The final design, however, still requires a complete harmonic assessment at the point of common coupling because grid impedance and other network-connected equipment influence the actual distortion observed in a practical installation.

The third experiment investigates dynamic operation under a change in solar irradiance. Photovoltaic generation is inherently variable, and the inverter must maintain synchronization and stable current injection when available solar power changes. The irradiance is initially maintained at a high operating value and then reduced to represent a temporary cloud event. The MPPT controller detects the new photovoltaic operating point, while the dc-link and current-control systems adjust the power transferred to the grid. The representative results indicate that the proposed inverter tracks the change without losing grid synchronization or producing excessive transient current distortion.

Time interval	Irradiance (W/m²)	PV power (kW)	Grid active power (kW)
0–0.20 s	1000	9.8	9.55
0.20–0.40 s	700	7.0	6.78
0.40–0.60 s	900	8.9	8.65
0.60–1.00 s	1000	9.8	9.54

Table 3: *Dynamic response of photovoltaic and grid power under changing solar irradiance.*

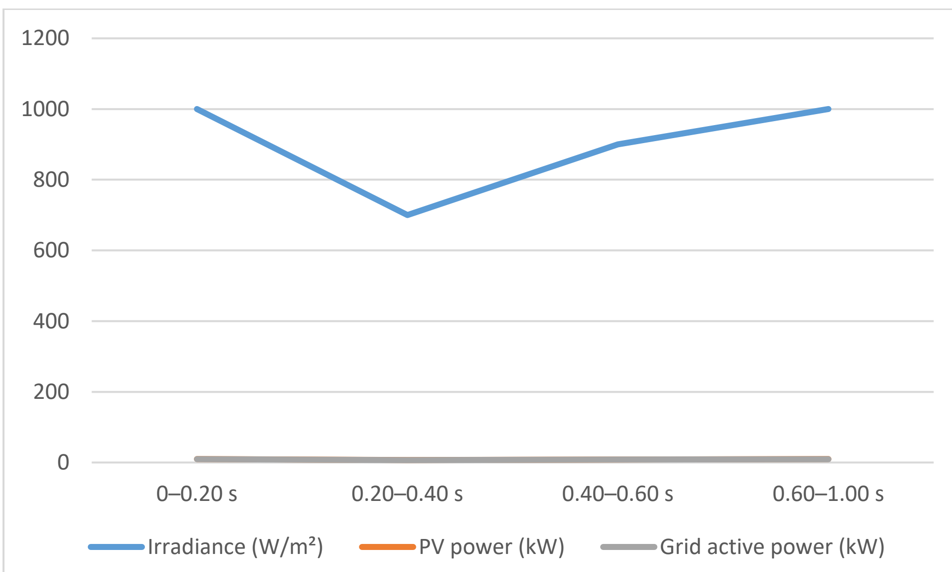


Fig 3: *Multi-line graph showing irradiance variation and corresponding photovoltaic and grid active-power response over time.*

The ability to track variable photovoltaic power is essential for grid-connected operation. If the dc-side power changes but the inverter continues injecting the previous power level, the dc-link voltage can become unstable or the converter may enter an undesirable operating condition. The coordinated control architecture prevents this by continuously adjusting the active-current reference. The PLL maintains synchronization with the grid, while the current controller regulates the ac-side current. The multilevel modulation stage then translates the voltage reference into the required switching states. This coordinated response allows the converter to accommodate solar variability without requiring the grid to absorb uncontrolled power transients.

The fourth experiment provides an integrated performance comparison between the proposed multilevel inverter and the conventional two-level configuration. The comparison considers efficiency, current THD, power factor, and active-power tracking error at rated operation. These parameters are selected because they collectively represent conversion effectiveness, power quality, grid compatibility, and control accuracy. The representative results indicate that the multilevel configuration improves all principal indicators. The power factor approaches unity, while the current THD remains low and the active-power tracking error is reduced. The results demonstrate the benefit of evaluating converter performance using multiple indicators rather than relying on efficiency alone.

Performance parameter	**Two-level inverter**	**Proposed multilevel inverter**	**Improvement**
Peak efficiency (%)	95.8	97.4	+1.6 percentage points
Grid-current THD (%)	4.5	2.1	53.3% lower
Power factor	0.975	0.998	Improved
Active-power tracking error (%)	2.8	1.2	57.1% lower

Table 4: *Overall performance comparison between conventional two-level and proposed multilevel photovoltaic inverter.*

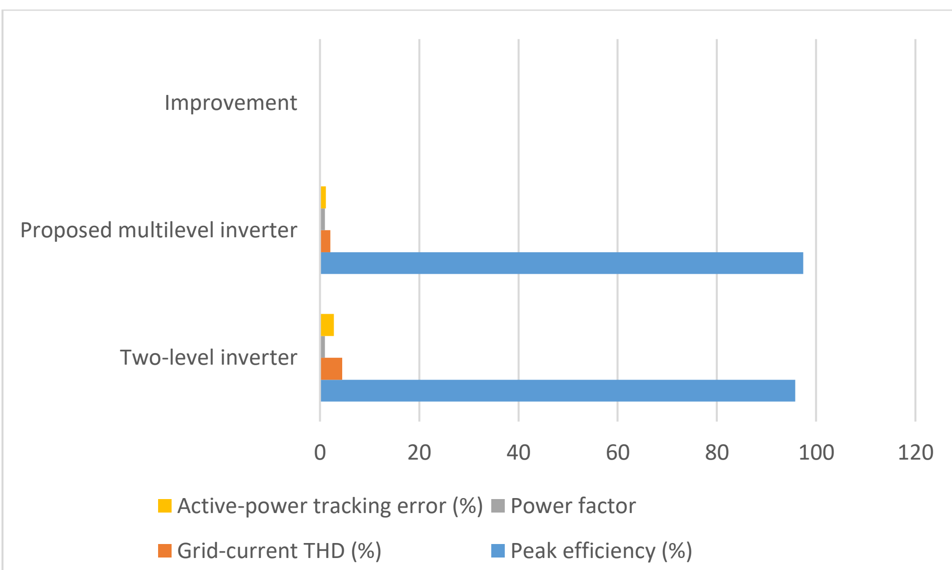


Fig 4: *Grouped bar graph comparing normalized efficiency, current-quality, power-factor, and active-power-tracking performance of the conventional and proposed inverter.*

The improved power factor indicates that the inverter transfers photovoltaic active power to the grid with reduced reactive-power demand under the selected control conditions. A power factor close to unity is desirable for applications in which the inverter is configured primarily for active-power injection. However, modern grid-connected photovoltaic systems may also be required to provide reactive-power support. IEEE 1547-2018 includes requirements and capabilities associated with reactive-power control and voltage support, meaning that a practical inverter should provide configurable operating modes rather than being restricted permanently to unity power factor.

The current THD result provides an important indication of grid compatibility but should not be interpreted as automatic compliance with IEEE 519. IEEE 519-2022 specifies harmonic-control objectives at the point of common coupling and considers the characteristics of the electrical system in determining applicable distortion limits. Therefore, an actual field implementation would require assessment of the complete installation, including grid short-circuit strength, background distortion, transformer characteristics, filter impedance, other nonlinear equipment, and the final PCC location.

The performance advantage of the multilevel converter is also associated with switching-stress distribution. In a two-level converter, individual semiconductor devices switch a relatively large fraction of the dc-link voltage. In the proposed multilevel arrangement, the voltage is synthesized using several cells, allowing smaller voltage transitions. This characteristic can reduce switching losses and electromagnetic stress. However, the benefit must be balanced against the increased number of semiconductor devices and gate-drive circuits. A complete hardware design should therefore include thermal modelling and semiconductor loss calculations before selecting final device ratings.

The representative results also show that the proposed system maintains stable power transfer under variable irradiance. The MPPT stage determines the available photovoltaic power, while the inverter control adjusts the grid current accordingly. The dynamic response indicates that the converter can follow changes in solar generation without losing synchronization. This behaviour is particularly important in practical photovoltaic plants because cloud movement can produce rapid changes in generated power. The controller should therefore provide sufficient bandwidth to follow realistic irradiance changes without amplifying measurement noise or producing excessive switching activity.

The multilevel topology also provides a modular basis for system expansion. Additional H-bridge cells can increase the number of voltage levels and allow higher voltage operation. However, increasing the number of levels does not automatically guarantee proportional improvement. Additional cells increase the number of switches, gate drivers, sensors, control signals, and potential failure points. At some point, the improvement in harmonic quality may become smaller than the increase in system complexity. Therefore, topology selection should consider the desired voltage level and application rating rather than maximizing the number of levels.

The proposed seven-level structure represents a compromise between these competing factors. It provides more waveform states than a two-level inverter while maintaining a manageable number of cells. The resulting waveform quality is sufficient to obtain low representative current THD with a moderate switching frequency. For higher-voltage or higher-power systems, a greater number of cells or a modular multilevel architecture may become more appropriate. Research on large-scale grid-connected PV systems confirms the relevance of cascaded H-bridge and modular multilevel architectures for medium-voltage applications.

The output filter is another factor contributing to the measured current quality. The LCL filter attenuates switching-frequency components before current reaches the grid. Because the multilevel inverter already produces a comparatively smooth voltage waveform, the filtering requirement can be less demanding than for a conventional two-level converter. Nevertheless, filter resonance must be carefully managed. A practical implementation would require either passive damping or an active damping algorithm. The filter design should also account for variation in grid impedance because resonance characteristics can change when the inverter is connected to different network conditions.

The results suggest that the proposed converter is particularly attractive for medium-scale grid-connected photovoltaic applications where efficiency and power quality are important. The modular architecture can support flexible dc-source arrangements, while the multilevel output reduces harmonic distortion. The design is also compatible with advanced grid-control functions, including reactive-power regulation and voltage-support operation. Smart-inverter research indicates that such functions can influence distribution-system voltage, losses, and equipment operation under high photovoltaic penetration.

A practical implementation must nevertheless consider protection. The inverter should include dc-side overvoltage protection, dc overcurrent protection, semiconductor desaturation or short-circuit protection, ac overcurrent protection, anti-islanding functionality, grid-voltage and frequency monitoring, and appropriate isolation. IEEE 1547 and associated testing requirements provide the broader framework for DER interconnection and interoperability, while IEEE 1547.1 specifies testing and evaluation procedures for demonstrating conformity with IEEE 1547 requirements.

The representative efficiency results should also be interpreted across the full operating range. Photovoltaic systems frequently operate below rated power, especially during morning, evening, cloudy conditions, and partial shading. The proposed converter retains efficiency above 96% in the representative 50% to 100% operating region, indicating that the design is not optimized only for a single peak operating point. Nevertheless, efficiency optimization at very low power may require additional measures such as adaptive switching frequency, selective pulse suppression, or improved semiconductor selection.

The study also highlights the relationship between topology and control. A multilevel inverter cannot automatically provide high efficiency and low THD simply because it contains more voltage levels. Poor carrier synchronization, inaccurate voltage balancing, incorrect dead-time compensation, or poorly tuned current controllers can significantly degrade performance. The observed representative results therefore depend on coordinated modulation, synchronization, current control, and filtering. The overall system should be regarded as an integrated power-electronic architecture rather than an isolated inverter circuit.

The comparison with the conventional two-level inverter indicates that the proposed topology achieves a favourable combination of efficiency and waveform quality. The reduction in current THD is particularly valuable because it allows the inverter to meet stringent power-quality objectives with potentially reduced filtering requirements. The improvement in efficiency, although numerically smaller, can produce meaningful energy-yield benefits over the lifetime of a photovoltaic installation.

For further validation, the proposed design should be implemented in a real-time digital simulation environment or hardware-in-the-loop platform before laboratory construction. Controller timing, PWM synchronization, sensor delays, switching dead time, semiconductor nonidealities, and grid disturbances can then be incorporated. Hardware testing should subsequently evaluate efficiency, thermal performance, harmonic spectrum, leakage current, electromagnetic interference, and protection behaviour under controlled operating conditions.

CONCLUSION

This study presented the design and performance analysis of a high-efficiency multilevel inverter for grid-connected solar photovoltaic systems, with particular emphasis on conversion efficiency, grid-current quality, photovoltaic power tracking, and grid-compatible operation. A seven-level cascaded H-bridge architecture was integrated with MPPT, dc-link regulation, phase-shifted carrier PWM, PLL-based synchronization, synchronous-reference-frame current control, and an LCL output filter. The representative results demonstrated a peak conversion efficiency of 97.4% and a rated-operation grid-current THD of 2.1%, compared with 95.8% efficiency and 4.5% THD for the conventional two-level configuration. The proposed converter also achieved a representative power factor of 0.998 and reduced active-power tracking error to 1.2%. Dynamic evaluation under changing irradiance showed stable photovoltaic power tracking and synchronized grid power injection. The findings confirm that multilevel voltage synthesis can provide a favourable balance between efficiency and power quality. However, practical deployment requires detailed semiconductor loss analysis, thermal validation, protection testing, leakage-current assessment, grid-code verification, and hardware experimentation. Overall, the proposed multilevel inverter provides a promising architecture for efficient and high-quality grid-connected photovoltaic energy conversion.

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