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Grid-tied inverter systems in solar power plants: a review of architectures, MPPT strategies, and power conversion technologies

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ABSTRACT

Grid-tied inverter systems are essential components of solar photovoltaic (PV) power plants because they convert direct current generated by PV modules into alternating current compatible with utility networks. Their performance is strongly influenced by solar irradiance, temperature variations, power conversion architecture, and maximum power point tracking (MPPT) strategies. This review examines the fundamental configurations of grid-connected PV inverter systems, including central, string, multi-string, and module-level architectures. Particular attention is given to single-stage and two-stage conversion systems, DC–DC converter integration, inverter topologies, and transformerless configurations. Conventional MPPT algorithms, including perturb and observe and incremental conductance, are evaluated in terms of tracking efficiency, implementation complexity, and dynamic performance. Furthermore, the relationships between converter efficiency, voltage regulation, harmonic distortion, and PV energy utilization are discussed. The review identifies practical considerations for selecting inverter architectures in utility-scale and distributed solar installations. Finally, emerging technological directions involving modular conversion, improved semiconductor devices, and advanced MPPT algorithms are highlighted to support reliable, efficient, and economically competitive PV power generation.

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1. INTRODUCTION

Grid-tied inverter systems have become indispensable in modern photovoltaic (PV) power plants because they enable solar electricity to be integrated directly into utility networks. Unlike standalone PV installations, grid-connected systems generally operate without requiring batteries as their primary energy storage mechanism. Their electrical output depends on solar irradiance, module temperature, conversion efficiency, and grid operating conditions [1], [2].

The principal challenge in PV generation is maintaining efficient energy conversion under continuously changing environmental conditions. Solar modules exhibit nonlinear voltage–current characteristics, and their maximum power operating point changes with irradiance and temperature. Consequently, the combination of maximum power point tracking (MPPT) and suitable inverter control is necessary to improve the utilization of available solar energy [3], [4].

This article reviews grid-tied inverter architectures and associated power conversion technologies from a system-design perspective. Its central contribution is to explain how PV array configuration, MPPT implementation, converter selection, and inverter topology jointly influence energy yield and operational performance. The discussion also provides practical guidance for selecting appropriate architectures for solar power plants.

2. ARCHITECTURE OF GRID-TIED PHOTOVOLTAIC SYSTEMS

Grid-connected PV systems are generally organized into PV arrays, power conversion stages, grid-interface filters, protection systems, and monitoring equipment. The PV array supplies direct-current electricity, while the inverter converts this energy into synchronized alternating current for grid injection. Depending on the architecture, an intermediate DC–DC converter may regulate the PV operating voltage and establish the required DC-link voltage [1], [2].

The principal architectural distinction concerns the location of MPPT and the degree of power conversion centralization. Centralized systems use a large inverter for multiple PV strings, whereas string and module-level systems distribute conversion equipment closer to individual generation units. These arrangements produce different compromises in installation cost, energy harvesting, maintenance, and performance under partial shading, as summarized in Table 1.

Table 1. Comparison of grid-tied PV inverter architectures

Architecture	MPPT arrangement	Advantages	Limitations	Typical application
Central inverter	Centralized	High power capacity; fewer inverter units	String mismatch losses; centralized failure risk	Utility-scale plants
String inverter	Per string	Improved mismatch management; modular installation	More inverter units required	Commercial and residential PV
Multi-string inverter	Individual DC–DC stages with shared inverter	Independent string optimization	Additional converter complexity	Medium and large PV systems
Microinverter	Module-level	Individual module optimization; enhanced shading tolerance	Higher equipment counts and installation cost	Residential and distributed PV

3. MAXIMUM POWER POINT TRACKING AND DC–DC CONVERSION

MPPT is a fundamental function of grid-tied PV systems because PV modules rarely operate at their maximum available power without appropriate control. Irradiance variations, module temperature changes, and partial shading modify the PV power–voltage characteristic, requiring the operating voltage to be adjusted continuously. MPPT controllers regulate the electrical operating point through the connected power converter to maximize energy extraction [3], [4].

The perturb and observe algorithm is widely used because it is relatively simple and requires limited computational resources. Its operating principle involves perturbing the PV operating voltage and observing the resulting power variation to determine the subsequent control direction. Although this method is attractive for practical implementation, its continuous perturbation can produce steady-state oscillations around the maximum power point and reduce energy harvesting efficiency [3].

Incremental conductance provides an alternative tracking mechanism that evaluates changes in PV current and voltage to identify the maximum power operating condition. This approach can offer improved tracking behavior during rapidly changing irradiance, although its performance depends on measurement accuracy, sampling frequency, and controller implementation. Advanced intelligent and optimization-based MPPT techniques can improve global maximum power tracking under partial shading, but their additional computational requirements may complicate embedded implementation [3].

DC–DC converters provide an effective interface between the PV array and the inverter by adjusting the electrical operating point independently of the grid-side conversion stage. Boost converters are commonly employed when the PV array voltage is lower than the required DC-link voltage, while buck and buck–boost converters support different voltage conversion requirements. Therefore, converter topology must be selected according to PV voltage range, DC-link requirements, power rating, efficiency, and control objectives [1], [5]. The conceptual relationship between PV generation, inverter conversion, building loads, and utility power exchange is illustrated below.

4. GRID-TIED INVERTER TOPOLOGIES

Grid-tied inverter topologies can be classified according to conversion stages, switching configuration, and the presence of galvanic isolation. Single-stage architectures directly convert PV DC power into grid-compatible AC electricity, whereas two-stage architectures employ a DC–DC converter followed by a DC–AC inverter. The two-stage arrangement provides greater flexibility in MPPT and DC-link regulation, although additional conversion components may introduce losses and increase system complexity [1], [2].

Transformer-based inverter configurations provide galvanic isolation and facilitate voltage adaptation between the PV system and the grid. However, line-frequency transformers increase equipment weight, volume, installation complexity, and conversion losses. Transformerless architectures reduce these disadvantages and are widely investigated for improving conversion efficiency and power density [1], [5]. Transformerless inverters nevertheless require careful attention to common-mode voltage and leakage current because PV modules possess parasitic capacitances relative to ground. Uncontrolled common-mode voltage variations may produce leakage currents that affect safety, electromagnetic compatibility, and system performance. Consequently, topology selection must consider not only conversion efficiency but also grounding arrangements, leakage-current mitigation, and applicable electrical protection requirements [1], [5].

Multilevel inverter configurations provide another attractive option for improving voltage waveform quality and reducing switching-related harmonic components. Their distributed voltage levels can reduce semiconductor voltage stress and improve output waveform characteristics, although additional switching devices and control complexity may increase system cost. The appropriate topology therefore depends on the power rating, grid voltage, efficiency target, harmonic requirements, and economic constraints of the installation [2]. The major power conversion technologies used in grid-tied PV systems exhibit different functional characteristics, efficiency considerations, and implementation challenges. Their principal functions and limitations are compared in Table 2.

Table 2. Comparison of major power conversion technologies

Technology	Main function	Strength	Main concern
Boost converter	PV voltage step-up	Simple voltage elevation and MPPT interface	Limited voltage flexibility
Buck converter	PV voltage step-down	Efficient lower-voltage conversion	Cannot elevate voltage
Buck–boost converter	PV voltage step-up or step-down	Flexible PV operating range	More complex control and losses
Two-level VSI	DC–AC conversion	Mature and relatively simple	Switching harmonics
Multilevel inverter	DC–AC conversion	Improved waveform quality	More switches and control complexity
Transformerless inverter	Grid interfacing	Higher efficiency and lower weight	Leakage-current concerns

5. EFFICIENCY, ENERGY YIELD, AND SYSTEM DESIGN

The overall energy yield of grid-tied PV plants depends on the coordinated performance of PV modules, MPPT controllers, DC–DC converters, inverters, and grid-interface components. Inverter efficiency alone cannot represent total system performance because mismatch losses, partial shading, operating voltage, and environmental conditions also influence energy production. Therefore, system evaluation should consider energy conversion efficiency across the complete operating range rather than relying exclusively on nominal inverter efficiency [2], [5].

Converter sizing is another important design consideration because PV generation varies substantially throughout the day and across seasons. Oversizing the PV array relative to inverter capacity may increase energy production during low-irradiance conditions, but excessive DC power can result in clipping during periods of high solar availability. Accordingly, DC-to-AC capacity selection should consider local irradiance characteristics, installation orientation, temperature, and economic objectives [2].

Modular inverter arrangements can improve maintenance flexibility and reduce the consequences of individual equipment failures. String-based and multi-string architectures provide opportunities for replacing or servicing individual units without necessarily interrupting the entire plant. In contrast, centralized architectures may offer advantages in equipment consolidation and large-scale installation economics, especially when PV strings experience relatively uniform operating conditions [5].

6. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Future grid-tied inverter development is expected to emphasize higher efficiency, improved MPPT performance, reduced component size, and enhanced operational reliability. Advanced semiconductor devices and optimized switching strategies offer opportunities to reduce switching losses while improving power density. These developments may facilitate more compact inverter systems and improve energy conversion performance under demanding operating conditions [1], [2].

Intelligent MPPT algorithms also represent an important research direction because conventional algorithms may experience reduced effectiveness under rapidly changing irradiance and partial shading.

Global optimization approaches can improve tracking of multiple local maxima, although their practical implementation must balance computational complexity, tracking speed, stability, and energy benefits. The most promising solutions will likely combine robust conventional control with selective advanced optimization techniques [3].

7. CONCLUSION

Grid-tied inverter systems determine how effectively PV energy is converted into electricity suitable for utility networks. Their performance depends on the coordinated selection of PV architecture, MPPT algorithms, DC–DC converters, inverter topology, and electrical protection arrangements. Central, string, multi-string, and module-level configurations each provide distinct advantages depending on system size, shading conditions, maintenance requirements, and installation economics. Two-stage conversion architectures offer flexibility in PV operating-point control, whereas transformerless and multilevel inverter technologies provide opportunities for improved efficiency and waveform quality. Future developments should prioritize efficient global MPPT, reduced leakage current, modular power conversion, and reliable operation across diverse environmental conditions. An integrated system-design approach remains essential for maximizing PV energy utilization and achieving sustainable grid-connected solar power generation.

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