Proceedings of CONF-FMCE 2026 Symposium: Artificial Intelligence and Smart Sensing for Mechanical and Electrical Systems
DOI: 10.54254/2755-2721/2026.BA36332

Review on Core Technologies and Development Trends of Grid-Connected Photovoltaic Inverters

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Abstract. In the context of high-penetration distributed photovoltaic generation in low-voltage distribution networks, photovoltaic inverters have evolved from single power conversion devices into key equipment for power quality regulation, grid support, and intelligent operation and maintenance. This paper reviews the literature, compares typical engineering applications, focusing on three common issues in recent photovoltaic inverter research: leakage-current suppression in transformerless structures, voltage support and harmonic adaptability during grid-connected operation, and data-driven modeling and parameter optimization under complex operating conditions. The reviewed studies show that common-ground, multilevel, and quasi-Z-source topologies can improve system efficiency and suppress leakage current; Volt-VAR control, energy storage coordination, and cascaded control can improve voltage quality; and black-box modeling, symbolic regression, and swarm intelligence optimization can enhance state prediction and parameter tuning. Future research should further establish unified experimental benchmarks, improve measured data coverage, and facilitate quantitative comparisons across different technical routes.

Keywords: photovoltaic inverter, transformerless topology, leakage current, voltage support, intelligent modeling

1. Introduction

The penetration of photovoltaic generation in distribution networks continues to increase, making photovoltaic inverters (PV) key equipment that affects power quality, system stability, and operational reliability, rather than merely serving as energy-conversion devices [1]. A typical grid-connected photovoltaic inverter system consists of a photovoltaic array, a front-end DC/DC converter, a DC bus, a rear-end DC/AC inverter bridge, a filter, and a grid-connected control unit. The front-end converter realizes maximum power point tracking for energy extraction and voltage matching. At the same time, the rear-stage inverter bridge generates AC via Pulse Width Modulation (PWM) modulation and connects to the grid after LCL filtering.

Recent studies indicate that the grid integration of high-penetration distributed photovoltaic systems brings three core challenges for inverters: common-mode voltage and leakage current issues caused by transformerless structures , voltage deviation problems and harmonic adaptability limitations in weak grids and low-voltage feeders, and the coordinated control of multiple inverters and energy storage units based on data-driven methods [2, 3]. Existing studies have proposed

DOI: 10.54254/2755-2721/2026.BA36332

optimization schemes from the perspectives of common-ground topologies, multilevel structures, Volt-VAR control, cascaded control strategies, and intelligent modeling algorithms. However, most existing studies focus on a single topology or operating condition, lacking a unified quantitative comparison framework [4].

This paper systematically reviews typical technologies from three dimensions: topology optimization, grid support capability, and intelligent modeling. This paper comprehensively analyzes the quantitative indicators reported in existing studies, including experimental platform parameters, power ratings, switching frequencies, total harmonic distortion (THD), efficiency, leakage current, and prediction error, to explore the applicable boundaries of different technical schemes. This study aims to clarify the evolutionary logic of core photovoltaic inverter technologies from device-level topology design to system-level coordinated control.

2. Analysis of typical challenges in photovoltaic inverters

Current photovoltaic inverters face three interrelated technical challenges. First, the contradiction between topology design and device stress and utilization remains prominent. The high-frequency common-mode voltage applied to parasitic capacitances induces leakage current, posing a threat to personal safety and accelerating the aging of power modules. To suppress leakage current, various topologies, including H5, H6, HERIC, common-ground structures, switched-capacitor five-level structures, and quasi-Z-source structures, have been extensively investigated. However, these technical routes generally entail trade-offs among efficiency, volume, and cost, and horizontal comparisons of multiple topologies under identical experimental conditions remain lacking [5]. Second, the power quality regulation and grid support capabilities of inverters remain insufficient. Modulation strategies, filter design optimization, Volt-VAR control and energy storage coordination are the mainstream methods for mitigating voltage deviation, harmonic distortion and power fluctuation. Third, system-level coordination and intelligent operation and maintenance technologies are not yet mature. Cascaded control, grid-forming control, black-start strategies, and data-driven models are adopted to enhance system stability under complex operating conditions.

These three research directions are mutually correlated rather than independent. Specifically, the inverter topology determines the leakage current characteristics, device stress and voltage level and further restricts the selection of modulation strategies. Grid-connected control strategies enable inverters to achieve voltage support functions beyond maximum power output. Intelligent modeling provides technical support for equipment thermal management, parameter tuning and fault early warning. Therefore, this paper classifies existing research achievements along three dimensions: topology optimization, grid-support technology, and intelligent modeling.

3. Key technologies for topology structure and power quality

To address existing topology and power quality problems, this section reviews representative studies on transformerless topologies, multilevel and impedance-network topologies, and harmonic suppression strategies.

3.1. Transformerless and common-ground topologies

Traditional transformerless structures, such as H5, H6, and HERIC, suppress leakage current mainly by decoupling during the freewheeling stage. However, their performance may be degraded by junction capacitance and common-mode voltage fluctuations. Taking the experimental test of a

DOI: 10.54254/2755-2721/2026.BA36332

lightweight multilevel inverter as an example, with a 220 V, 1 kW prototype and a 20 kHz switching frequency, the peak leakage currents of H5 and HERIC topologies are approximately 350 mA and 70 mA, respectively. By contrast, the improved common-ground multilevel scheme reduces the leakage current to below 5 mA [6]. This indicates that establishing a direct galvanic connection between the DC and AC sides can significantly attenuate the parasitic capacitance leakage path, which explains the increasing research attention on common-ground topologies in recent years.

As shown in Figure 1, the single-phase common-ground inverter establishes a shared reference potential between the DC and AC sides, effectively short-circuiting the parasitic capacitance between the photovoltaic array and ground, thereby fundamentally suppressing leakage current. Existing studies have classified transformerless single-phase common-ground (TLSPCG) inverters based on device count, buck-boost capability, efficiency, cost, and application scenarios, demonstrating that common-ground structures have evolved into a diverse topology family [5]. Nevertheless, most current studies focus on the independent optimization of a single topology, lacking comprehensive horizontal comparisons among traditional decoupled topologies, common-ground topologies, and multilevel topologies under identical experimental conditions.

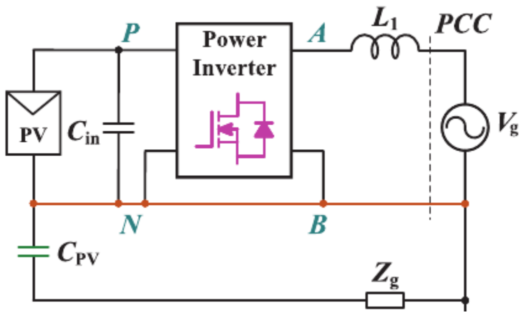

Figure 1. Typical structure of a transformerless single-phase common-ground inverter [4]

3.2. Multilevel, switched-capacitor, and quasi-Z-source structures

Multilevel structures reduce dv/dt values and filter stress by increasing the number of output voltage levels. The lightweight multilevel topology achieves an efficiency of over 96.1% across various output voltage levels, with efficiency maintained above 96.5% over the 650 W to 1.3 kW output power range. The THD of its grid-connected current remains lower than 2.56% [6]. The switched-capacitor five-level common-ground structure further integrates voltage boosting capability, common-ground connection, and multilevel output characteristics. It achieves a higher voltage gain via switched-capacitor units, and its technical feasibility is validated through MATLAB/Simulink simulation, PSIM loss analysis, and experimental tests [7].

The quasi-Z-source cascaded multilevel inverter achieves bidirectional voltage regulation (step-up and step-down) via an impedance network, enabling stable grid-connected operation under irradiance fluctuations and insufficient input voltage conditions. A study on separately controlled quasi-Z-source cascaded multilevel inverters adopts multi-carrier phase-shifted PWM, improved deadbeat control, and third-harmonic injection strategies to reduce the equivalent switching frequency, enhance dynamic response performance, and extend the adjustable range of power imbalance operation [8]. Compared with conventional two-stage structures, this topology eliminates the front-end power conversion link. However, there is clear coupling among impedance network

DOI: 10.54254/2755-2721/2026.BA36332

parameters, the shoot-through duty ratio, and semiconductor device stress. Therefore, further integrated analysis is required to optimize parameters and adapt operating conditions.

3.3. Harmonic suppression and modulation strategies

Modulation and control strategies are indispensable complements to topology optimization to improve grid-connected power quality. At a switching frequency of 20 kHz, the off-grid output current THD of the lightweight multilevel prototype is approximately 1.89%, the output voltage THD is 2.52%, and the grid-connected current THD is lower than 2.56% [6]. These results demonstrate that multilevel voltage levels can effectively reduce filter design requirements. Nevertheless, under weak grid conditions, current loops, phase-locked loops, and modulation strategies are still required to collaboratively suppress harmonic amplification.

Intelligent optimization provides an effective alternative for the parameter tuning of modulation and control schemes. For a 1.2 kW two-stage single-phase photovoltaic system, eight key control parameters are optimized, and comprehensive evaluation indices are established based on power extraction error, power transmission error, current THD, and voltage THD. Experimental results show that the optimized sliding-mode MPPT control achieves a global efficiency of 95.80%, which is significantly higher than 84.42% obtained by the conventional incremental conductance method. The corresponding current THD and voltage THD are 3.07% and 2.59%, respectively. Accordingly, optimization algorithms can improve the multi-objective comprehensive performance of inverters, whereas their robustness requires further verification under variable

4. Grid support and system coordination control

While the previous section addressed single-inverter topology and power quality, this section examines system-level grid support and multi-device coordination.

4.1. Voltage-reactive power support

Volt-VAR control mitigates voltage violations in distribution networks by regulating reactive power during grid voltage deviations. In a test of a 3.5 kW single-phase grid-connected photovoltaic inverter, ten 320 W photovoltaic modules form a 3.2 kW photovoltaic array. With a rated grid voltage of 127 Vrms and a switching frequency of 10 kHz, the effectiveness of the control strategy is validated via PSIM simulation and Typhoon hardware-in-the-loop (HIL) tests [2]. Under low-voltage operating conditions, the point of common coupling (PCC) voltage rises from 0.9023 p.u. to 0.9310 p.u., whereas under high-voltage conditions, it drops from 1.0907 p.u. to 1.0605 p.u. For a load power of 5376.3 W, the proposed control scheme restores the PCC voltage from 0.9472 p.u. to 0.9631 p.u.

Although existing studies have verified that local Volt-VAR control can alleviate typical voltage disturbances, its performance is constrained by inverter capacity, reactive power margin, and feeder impedance. From an engineering perspective, the advantages of Volt-VAR control lie not only in single-point voltage restoration but also in suppressing the impact of photovoltaic output fluctuations on end-user voltage profiles. Current hardware-in-the-loop tests have validated the dynamic control performance under irradiance variations and load switching scenarios. However, the coordinated operation of multiple inverters, the influence of communication delays, and the fair allocation of reactive power still require further quantitative investigation.

DOI: 10.54254/2755-2721/2026.BA36332

4.2. Energy storage, cascaded systems, and multi-mode coordination

Energy storage configuration and cascaded control address similar system coordination problems, though on different scales. Energy storage provides temporal energy buffering for peak shaving and for suppressing photovoltaic fluctuations. In contrast, cascaded inverters provide module-scale voltage superposition and power distribution capabilities for medium- and high-voltage grid access and large-capacity system scalability. A bi-level optimization study of distributed energy storage coordinates economic efficiency and voltage constraints from the perspectives of capacity configuration and operation scheduling, reducing voltage violations and photovoltaic curtailment through multi-mode photovoltaic inverter control [3].

A cascaded grid-connected photovoltaic inverter forms an AC output by connecting multiple photovoltaic units in series. Each unit coordinates grid-connected current, DC voltage, and power distribution. In a decentralized control study, PV unit 1 is set as a current source, and the remaining units operate as voltage sources. The strategy is verified on an OPAL-RT OP4510 hardware-in-the-loop platform [9]. Under a 10% drop or 10% rise in grid voltage amplitude, and when the frequency changes from 50 Hz to 49.5 Hz and then to 50.5 Hz, the system still maintains grid-connected operation and tracks the maximum power point. Decentralized cascaded control thus reduces dependence on centralized control, but power-balancing performance under communication failures, module faults, and uneven irradiance still requires further evaluation.

4.3. Grid-forming and black-start capability

In weak grids, islanded microgrids, and post-disaster restoration scenarios, inverters also need voltage-source characteristics, frequency support, and black-start capability. A study on grid-forming control for black start adopts a five-bus photovoltaic black-start test system. It compares three strategies: WECC generic photovoltaic control, conventional voltage-oriented control, and virtual synchronous machine-based grid-forming control [10]. In the simulation, the system switches in a 10 MW load at 1 s, energizes a transmission line at 5 s, and connects another 20 MW load at 10 s. The results show that grid-forming control outperforms the other control schemes in transient voltage and frequency regulation.

Therefore, while existing studies focus on mode-switching stability, current research on grid-forming control also seeks to integrate topology and current-quality constraints, Volt-VAR regulation, and energy storage coordination. The core goal is to establish a continuous control framework across grid-connected, islanded, and black-start operation modes.

5. Intelligent modeling, common challenges, and improvement directions

Topology and control technologies improve the hardware performance and grid-connected capability of inverters, but as operating scenarios become more complex, analytical models struggle to cover factors such as temperature, aging, weak grids, and multi-device coupling. A common strength of data-driven modeling, symbolic regression, and swarm intelligence optimization lies in using measured or simulated data to describe nonlinear relationships for thermal management, dynamic identification, and control parameter tuning. Existing explorations of these methods reveal common issues: limited coverage of training conditions, a lack of unified benchmarks for comparison across models, and a trade-off between model interpretability and real-time deployment capability.

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5.1. Data-driven modeling and thermal management

Data-driven methods are primarily applied to the identification of inverter dynamic characteristics and thermal management. Nonlinear AutoRegressive with eXogenous (NARX) black-box modeling can describe inverter dynamic characteristics when complete physical parameters are unavailable. A study on three-phase single-stage photovoltaic inverters achieves an MSE of 3.7×10^{-9}, an NMSE of 5.5×10^{-5}, and a fitting degree of 99.3% on simulation data. It also verifies responses to voltage, frequency, and phase disturbances on a 1 MW hardware test platform, where the fitting degree of the frequency-variation dataset reaches 99.2%, and the overall hardware-test fitting degree remains above 95% [11]. Neural network models can thus capture nonlinear dynamics, though their training performance depends on the coverage of operating conditions.

Thermal management is another application of data-driven methods. A PSO-based symbolic regression study on temperature prediction focuses on the Yaskawa PVI 36TL-480 inverter. The device has a rated power of 36 kW and an input voltage range of 540-800 VDC. The data are from one year of hourly records from a rooftop photovoltaic system in Montería, Colombia, and are split into a 70% training set and a 30% test set [12]. The model predicts temperature using active power, DC bus voltage, and environment-related variables. The test-set RMSE is about 4.12, and the MAE is about 3.31, outperforming multiple linear regression and symbolic regression with genetic algorithms. Compared with pure black-box models, symbolic regression can also provide an interpretable analytical expression.

5.2. Optimization design and common challenges

Intelligent optimization is expanding from single MPPT parameter tuning to multi-objective system design. A study that optimizes sliding-mode MPPT control using genetic algorithm (GA), particle swarm optimization (PSO), and grey wolf optimizer (GWO) shows that, in a 1.2 kW two-stage single-phase photovoltaic inverter, the optimization method can simultaneously consider power extraction, energy transfer, and harmonic indexes. The global efficiency of the optimized control reaches 95.80%, which is higher than the 84.42% obtained with the conventional incremental conductance scheme [13]. This indicates that intelligent optimization is suitable for handling the coupling among topology parameters, control gains, and power quality indexes, but computational cost, parameter sensitivity, and real-time implementation complexity still need attention.

Based on the above cases, intelligent methods in the inverter field have covered dynamic modeling, thermal management, parameter tuning, and other stages. Different studies involve different power ratings, sampling frequencies, temperature ranges, load disturbances, and evaluation indices. The lack of unified benchmarking and data foundations makes it difficult to directly compare results such as RMSE, THD, or efficiency. Further research should establish a unified experimental basis by recording training data under the same irradiance, temperature, load, and grid impedance conditions, while reporting error, computation time, model size, and interpretability indexes. Only in this way can researchers determine whether data-driven methods are truly suitable for engineering deployment, not just effective for offline fitting on a single case.

6. Conclusion

The development of key photovoltaic inverter technologies is shifting from improving single-inverter efficiency toward comprehensive optimization of topology, power quality, grid support, and intelligent operation and maintenance. Recent studies show that common-ground, multilevel, switched-capacitor, and quasi-Z-source topologies can reduce leakage current and improve efficiency; modulation optimization and intelligent control can reduce harmonics and improve MPPT and energy transfer performance; Volt-VAR control, energy storage coordination, and decentralized cascaded control can enhance inverter adaptability to voltage and frequency disturbances in distribution networks; and NARX black-box modeling symbolic regression, and swarm intelligence optimization can provide new tools for temperature prediction, dynamic identification, and parameter tuning.

This paper still has certain limitations. First, it mainly relies on secondary data from published literature, without reproducing different topologies and control methods under unified experimental conditions. Therefore, quantitative comparisons across studies remain affected by differences in experimental platforms. Second, some measured data reported in the literature are concentrated on rated conditions or short-term disturbances, with insufficient coverage of long-term aging, extreme temperatures, and complex weak-grid scenarios. Future work could establish a literature database to uniformly extract power rating, switching frequency, THD, efficiency, leakage current, and error indexes, and verify key conclusions through simulation or experimental reproduction.

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