Published by JScE as Proceedings of 4th International Conference on Role of Energy on Sustainable Social Development (RESSD-2025), 29-30 May, 2025, Kathmandu, Nepal

MICRO-INVERTER CONTROL STRATEGIES FOR GRID-CONNECTED PV SYSTEMS: A COMPREHENSIVE REVIEW

Madhusudan Nyaupane[1]*, Sujan Adhikari [1], Shanti Tiwari[2], Asha Khanal[3]

[1] Department of Electrical Engineering, Pulchowk Campus, Tribhuvan University, Nepal
[2] Department of Electrical Engineering , Pashchimanchal Campus, Tribhuvan University, Nepal
[3]Nepal Electricity Authority, Nepal

Abstract

This paper provides a comprehensive assessment of major micro-inverter configurations and control approaches used in photovoltaic (PV) systems, aiming to optimize power conversion efficiency, reduce total harmonic distortion (THD), and support reactive power regulation. It reviews several inverter structures, including push-pull, flyback, and dual buck-boost types, along with control strategies such as dq-axis transformation, Proportional-Resonant (PR) controllers, hysteresis modulation, and hybrid methods. Based on comparative research findings, THD levels vary between 2.46 % and approximately 7–8 %, while energy conversion efficiencies range from 88 % to over 93 %, depending on the specific system architecture and the Maximum Power Point Tracking (MPPT) technique implemented. The Quasi-Proportional Resonant (Q-PR) controller emerges as the most effective solution, offering superior dynamic response, excellent harmonic rejection, and robust performance under grid disturbances. Although many systems demonstrate accurate MPPT and fast transient behavior, they still face limitations related to scalability, reactive power capability, and adaptation to partial shading. The study concludes by emphasizing ongoing advancements in hybrid and sensorless control techniques as promising directions for developing economical and grid-compliant micro-inverter technologies for next-generation PV deployments.

Keywords: Microinverter, Hysteresis current mode control, Flyback converter, PR controller, Phase-locked loop

---

1. Introduction

As solar panels get cheaper and converters become more efficient, solar energy is becoming a more popular way to produce electricity (Kouro et al., 2015).With their ability to provide module-level power conversion, increased energy harvesting, and enhanced fault tolerance, microinverters have become a game-changing technology in photovoltaic (PV) systems. Because microinverters function independently at the panel level as opposed to centralized or string inverters, they can be more precisely controlled and adjusted to different environmental circumstances. Advanced control techniques are required for this decentralized design in order to guarantee grid compliance, system stability, and peak performance. Microinverter control approaches have advanced recently, focusing on problems including power quality, voltage regulation, and dynamic response to environmental changes. To improve voltage regulation in distribution systems with significant PV penetration. The research paper Xie et al. (2024) presented a Proportional-Integral-Derivative (PID) closed-loop based Volt-Var (VV) function in conjunction with a mode-switching mechanism. Comparing their method to conventional VV functions, they showed better mitigation of voltage infractions and greater equity among PV consumers. PID control techniques in PV inverters were also thoroughly examined by Ding and Gao (2024) , who noted how well they worked for grid integration and improving power quality. In order to attain optimal performance, they underlined the significance of choosing suitable PID schemes suited to particular operating conditions. Real-time handling of multivariable control limitations and difficulties has also drawn attention to Model Predictive Control (MPC). For PV inverters combined with battery energy storage systems in microgrids, Khanal et al. (2023) suggested an MPC scheme. Comparing MPC to conventional control techniques, their study showed

---

*Corresponding author: Madhusudan Nyaupane
Department of Electrical Engineering, Pulchowk Campus, TU
Email: nyaupanemadhusudan.hr@gmail.com
https://doi.org/10.3126/jsce.v12i2.91428

that MPC could both provide faster dynamic response and efficiently minimize THD. Additionally, a thorough analysis of grid-connected microinverter control schemes and topologies was presented on Premkumar et al. (2022) , which covered a range of tactics like MPPT methodologies, voltage control, and current management. Their research provides insightful information about how to choose and use control strategies that work for various PV system setups. This review is motivated by the need for an integrated understanding of micro-inverter control in grid-connected photovoltaic (PV) systems, as existing literature typically treats PV-side maximum power point tracking (MPPT) and grid-side control strategies in isolation. With increasing PV penetration, reduced system inertia, and more stringent grid-code requirements, the interaction between MPPT dynamics, DC-link regulation, and grid-current control has become a critical design challenge that is not sufficiently addressed in prior surveys. Accordingly, this paper provides a structured and comparative review of micro-inverter control strategies from a source-to-grid perspective by jointly analyzing commonly used MPPT techniques, including Perturb and Observe, Incremental Conductance, gradient-based, and hybrid methods, together with grid-side control approaches such as proportional–resonant, quasi-proportional–resonant, hysteresis, synchronous reference frame, sliding-mode, and adaptive control. The reviewed methods are evaluated using reported performance metrics, including conversion efficiency, grid-current total harmonic distortion, power factor, reactive power controllability, and transient response under grid disturbances. The main contribution of this work lies in the development of an integrated analytical framework that explicitly links PV-side power extraction with grid-side power injection, enabling a quantitative comparison of micro-inverter topologies and control strategies and revealing key trade-offs among control complexity, power quality, scalability, and grid compliance. In addition, the paper highlights the evolution of control architectures from conventional grid-following schemes toward adaptive and grid-forming micro-inverter control, providing a consolidated reference and identifying promising research directions for next-generation inverter-dominated power systems.

2. Literature Review

2.1. Low-cost Single-Stage Micro-Inverter Design

The study in Petreuş et al. (2013) presents a small, reasonably priced single-stage micro-inverter that improves the system resilience and efficiency over conventional central inverters for PV systems with 500W or less. Without the need for huge isolation transformers, it connects directly to the grid using a dual buck-boost architecture, which maximizes energy transmission and waveform quality. Hysteresis Current Mode Control (HCMC) is used in the system to precisely inject sinusoidal current and minimize THD. It also incorporates the Perturb and Observe (P & O) algorithm for effective MPPT, of which the Voltage and Current Loop Control is the most effective. The microinverter is a promising way to increase the scalability, dependability, and performance of contemporary photovoltaic systems, as demonstrated by experimental results showing that it achieves a THD of 4.7%, a power factor of 0.98, and an efficiency of 93%. The study in Ozdemir et al. (2014) presents a single stage three-phase three-level neutral point capsule (NPC) inverter for grid-interactive photovoltaic systems that removes the need for a separate DC - DC stage, improving simplicity and efficiency. A novel MPPT algorithm ensures robustness against irradiance and temperature variations, providing stable performance. The inverter achieves a THD of 3.45%, within international standards, and a system efficiency of 93.08%, making it a reliable and effective solution for large-scale PV systems connected to the grid. Atsu et al. (2024) present a compact and low-cost microinverter (200–600 W) with transformer(to perform the role of islanding) that improves reliability and scalability over conventional string inverters in low-voltage networks. Without bulky transformers, it connects directly to the grid with integrated MPPT for efficient energy extraction. The tests showed a voltage THD 2%, a current THD ranging from 7% (steady) to 34% (outdoor), and a power factor close to unity under stable conditions. The design demonstrates strong potential for high-performance and resilient PV systems. The proposed single-stage low-cost micro-inverter and control strategy is depicted in Figure 1.

The proposed micro-inverter, as in Figure 1, configuration illustrates the integration of a single-stage power conversion structure with hysteresis current control and MPPT. The figure highlights how reduced conversion stages minimize conduction losses while enabling direct grid-current shaping, which explains the reported trade-off between compactness and limited reactive power capability.

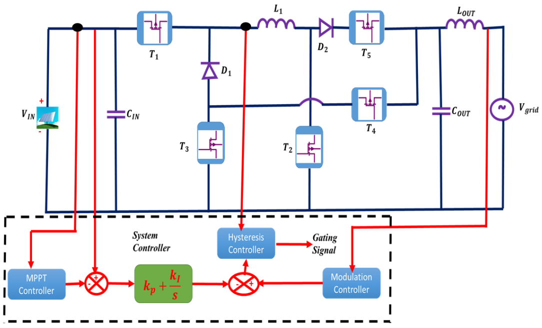

Figure 1. The proposed micro-inverter configuration

2.2. Active and Reactive Power Management

This study in Burbano-Benavides et al. (2021) offers an extensive control method for a low-cost, grid-connected solar microinverter with a focus on power quality, efficiency, and accurate active (P) and reactive (Q) power regulation. The system is designed in two stages: a DC-AC dual-buck inverter and a DC-DC active clamp flyback converter. A 2P2Z controller and state-space averaging are used to produce MPPT using a single-diode PV model that takes temperature and irradiance into consideration. Modeled as an LCL filter, the dual-buck inverter regulates current using a 2P2Z controller and feedback linearization. While dq-frame control allows for independent P-Q regulation, a SOGI-based PLL guarantees grid synchronization. Simulations show high MPPT accuracy (98%), fast voltage settling (0.35 s), and compliance with IEEE 1547 THD limits. Experimental tests with 150W panels confirmed (88–91%) efficiency and acceptable THDi (7–8%), validating the system's practicality for decentralized energy with off-grid capability and robust grid support. This study in Hossain et al. (2024) reviews next-generation inverter technologies aimed at improving grid resilience, reliability, and adaptability. Conventional limitations are addressed through smart inverter features, IoT integration, AI/ML-based control, and advanced materials (SiC, GaN). Different inverter topologies; central, string, module-integrated, multi-string, and multilevel; are compared in terms of efficiency, power quality, reactive power support, and harmonic mitigation. The work also highlights cyber-physical security challenges and proposes AI and blockchain-based solutions for predictive control and fault tolerance. A directional roadmap is presented toward resilient inverters capable of supporting stable, secure, and adaptive grid operation under disturbances.This study in Flota-Bañuelos et al. (2023) proposes an experimental control approach for a grid-connected PV inverter to improve power factor, reactive power support, and overall power quality. The system consists of a PV array with a parallel DC capacitor, an H-bridge inverter, and an RL filter, controlled through a Sliding Mode Control (SMC) current loop for active/reactive current regulation and a PI-based voltage loop that allows the capacitor to act as a virtual source during non-generation periods. A dq-axis transformation with PLL ensures grid synchronization, while a multicarrier PWM switching strategy reduces distortion. Simulation results confirm unity PF, reduced THD, and stable voltage regulation, and laboratory tests with a DSP-controlled 150 W setup validate performance with inverter current THD around 5.1 %, unity PF, and robust operation under intermittent PV availability, demonstrating the practicality of PV inverters functioning as both active power suppliers and STATCOM devices for dual P–Q regulation. The overall microinverter configuration and control strategy implemented for active and reactive power management are as shown in Figure 2 and Figure 3. This Figure 2 presents the overall microinverter topology used for active and reactive power management. The separation of the DC–DC and DC–AC stages enables independent optimization of MPPT and grid-current regulation, which is critical for achieving accurate P–Q decoupling under varying grid conditions. The DC–DC control loop in Figure 3 demonstrates how incremental conductance MPPT is tightly coupled with a 2P2Z controller to stabilize the PV operating point. This structure explains the fast voltage settling and high MPPT accuracy reported in the corresponding study. The DC–AC control loop in Figure 4 illustrates dq-frame current regulation synchronized through a PLL. The figure clarifies how decoupled Id–Iq control enables independent active and reactive power injection, directly contributing to IEEE 1547 compliance. The Figure 5 defines the feasible operating region of the microinverter under reactive power constraints. It highlights the inherent limitation of low-power microinverters in delivering reactive support without compromising active power extraction.

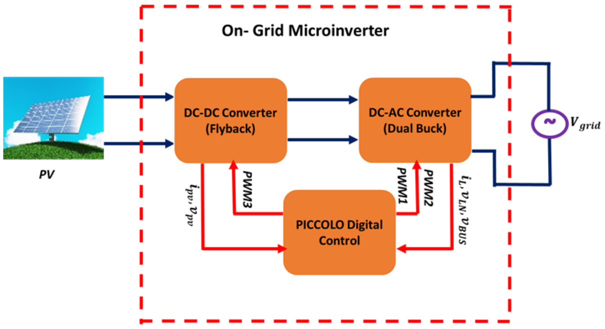

Figure 2. Proposed Microinverter.

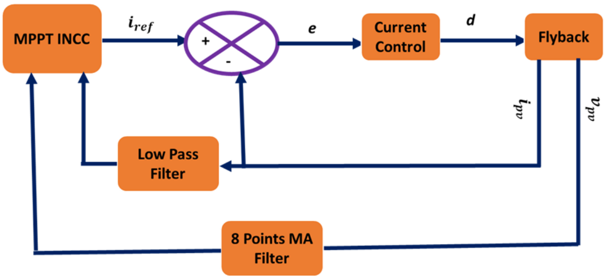

Figure 3. DC-DC stage control loop; the current-based incremental conductance MPPT is regulated by a 2P2Z controller.

2.3. Hybrid Current Control Method

A hybrid current control approach for a PV microinverter is presented in IEEE (2009) . The paper introduces a high-performance micro-inverter that uses a hybrid control

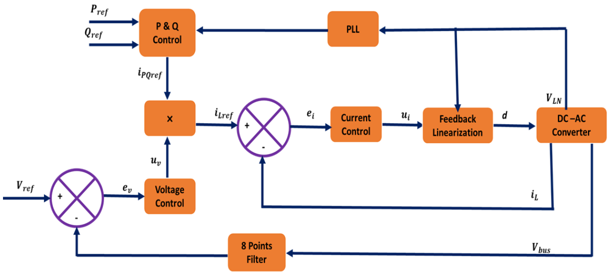

Figure 4. Control loop of the DC-AC stage.Burbano-Benavides et al. (2021)

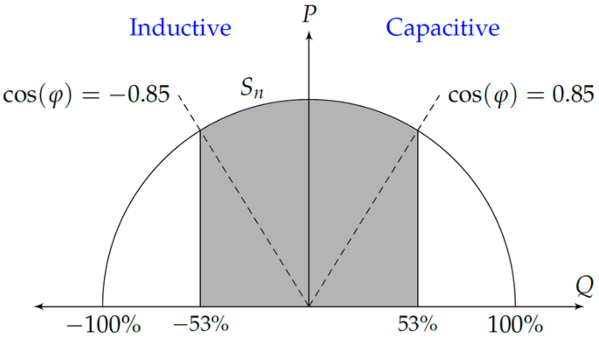

Figure 5. Possible working range of the microinverter based on reactive power.

technique that combines Generalized Hysteresis Current Control (GHCC) with Proportional-Resonant (PR) control. It is based on a full-bridge inverter architecture. In order to increase efficiency, this design aims to eliminate switching losses and improve grid current quality. A broader band reduces switching frequency and losses, and GHCC makes sure the inverter current follows a reference within a hysteresis band. For the purpose of maintaining precise current monitoring at the grid frequency, a PR controller is included to compensate for the associated low-frequency distortions brought on by practical constraints such as low inductance and digital delays. Because of its integrated control method, the micro-inverter can provide low-distortion, efficient AC power, which makes it perfect for compact, transformer-less PV systems. Specifically, low-frequency harmonic errors persist in the output current even while the instantaneous inverter current closely tracks the reference at high frequencies. As a correction layer, a PR (Proportional-Resonant) controller is added to mitigate these low-frequency distortions. The PR controller's resonant term is specifically engineered to remove steady-state errors at a particular frequency, usually the grid fundamental frequency. This system senses the actual grid current and compares it to the reference. Grid current quality is greatly improved as a result of the PR controller correcting any low-frequency mistakes that are found. In order to provide an output that is nearly a pure sine wave, the PR controller suppresses harmonics around the grid frequency. This study in Elangovan and Mohanty (2024) presents an adaptive control scheme for grid-tied PV inverters aimed at improving power quality by regulating active and reactive power while minimizing harmonic distortions. The inverter employs a grid-tied architecture where adaptive algorithms dynamically adjust controller parameters in real time under varying irradiance, load, and grid conditions. Unlike fixed-parameter methods, the adaptive strategy enhances harmonic suppression, ensures low THD in grid current, and provides robust power factor correction and reactive power support. Simulation and experimental validations confirm that the inverter delivers nearly sinusoidal output, stable operation under disturbances, and strong compliance with grid standards, making it well-suited for resilient next-generation PV systems.The Mahendravarman et al. (2023) study focuses on a cascaded multilevel inverter system powered by a hybrid symmetrical hybrid (SH), switched inductor (SL), and switched capacitor (SC) boost converter and controlled using a Cascaded Feedforward Neural Network (CFNN). The main objective of this approach is to reduce total harmonic distortion (THD) below 5 %, thereby improving the quality of power integration into the grid. The CFNN acts as an intelligent predictive controller, determining the optimal switching and voltage levels for the multilevel inverter. By accurately forecasting the required voltage steps, the CFNN ensures smooth voltage transitions and minimizes harmonic content in the output waveform. Unlike conventional current-control methods, this strategy does not directly control the inverter current; instead, it focuses on voltage-level management and overall power quality enhancement. This intelligent control approach enables the inverter to operate efficiently while maintaining low distortion, making it suitable for applications where high-quality AC output and reduced THD are critical.An H-bridge inverter and a push-pull DC-DC converter form the foundation of the suggested microinverter system in Jiang, Cao, Peng, and Li (2012) for grid-connected solar applications. A push-pull converter with a high-frequency center-tapped transformer is used in this microinverter design to boost voltage from the PV panel to the DC-link capacitor and isolate galvanics. It incorporates a hybrid MPPT algorithm that combines Incremental Conductance (IC) and Perturb & Observe (P& O) with a customizable step size to guarantee quick and precise tracking of the global maximum power point (GMPP), even in situations with partial shade. A cascade structure manages an H-bridge microinverter on the DC-AC side, while a PI controller controls the PV voltage and transformer flux balancing. The technology maintains phase alignment between the grid voltage and the inverter output current for the best active power transfer by using a Phase-Locked Loop (PLL).

Experimental results show exceptional MPPT performance, with tracking efficiencies of 99.33% for a 150W PV panel and 99.83% for a 60W panel. The hybrid MPPT algorithm demonstrated resilience under partial shading, achieving 99.75% tracking efficiency, and the inverter maintained excellent dynamic stability and current tracking even with rapid reference current changes. The overall microinverter configuration and control strategy implemented for Hybrid Current Control Method are as depicted in Figures 8 and Figure 9.

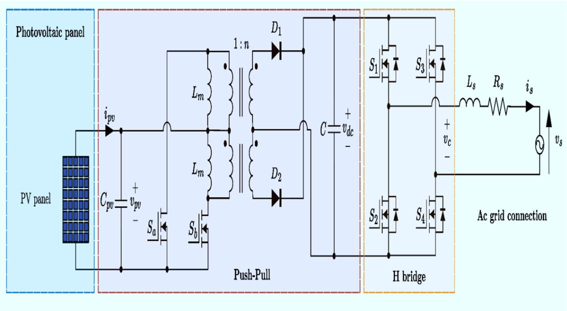

Figure 6. Push–pull Microinverter proposed in Jiang, Cao, Peng, and Li (2012).

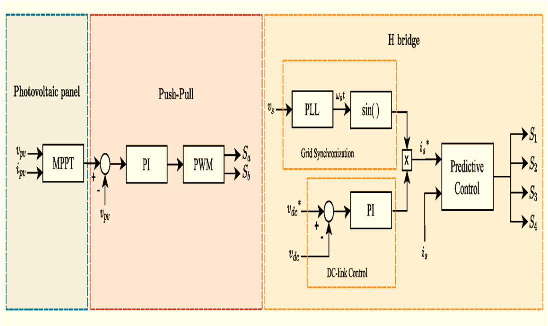

Figure 7. Control applied in the topology proposed in Jiang, Cao, Peng, and Li (2012).

Figures 8 and Figure 9 illustrate the complementary roles of the power-stage topology and the associated control architecture in ensuring robust microinverter operation. As shown in Figure 8, the push–pull microinverter topology employs a high-frequency transformer to provide galvanic isolation and voltage boosting, enabling reliable operation over a wide PV voltage range and enhancing robustness under partial shading conditions. This benefit is achieved at the cost of an increased component count and higher design complexity. Figure 9 presents the corresponding cascaded control strategy, integrating MPPT, DC-link voltage regulation, and grid synchronization. This coordinated control structure enables high MPPT efficiency and stable grid interfacing; however, its performance is sensitive to controller parameter tuning, particularly under rapidly varying irradiance and grid conditions.

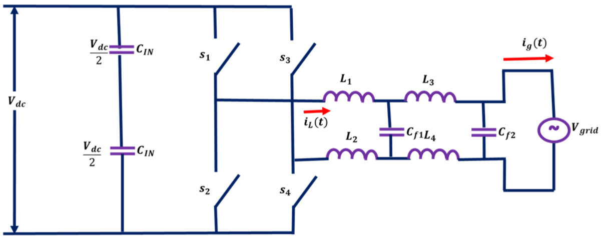

Figure 8. Microinverter's topology for Hybrid Current Control

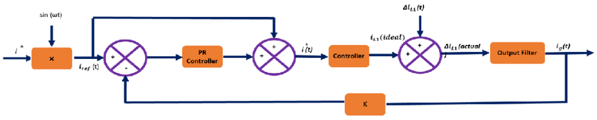

Figure 9. Control strategy for Hybrid Current Control

2.4. Dual Stage Micro-Inverters Control

A two-stage control technique for a photovoltaic (PV) microinverter is suggested in H. Zhang et al. (2018) and Jiang, Cao, Li, and Peng (2012). The boost half-bridge DC-DC converter and full-bridge inverter are used in the microinverter control method to achieve grid integration and effective energy conversion. The DC-DC stage uses a PI controller with PWM modulation to perform Maximum Power Point Tracking (MPPT), which minimizes the error between measured and reference values in order to control the PV panel voltage. A Repetitive Controller (RC) in the inner current loop makes sure the inverter output current exactly matches a grid-synchronized sinusoidal reference, while a PI controller in the outer voltage loop controls the DC-link voltage and creates the peak current reference. This dual-loop control structure is used by the DC-AC stage. The system's dynamic response to abrupt changes in load or irradiance is enhanced by a feedforward current reference, while a Phase-Locked Loop (PLL) offers precise grid phase detection. This hybrid control architecture guarantees fast transient response, low harmonic distortion, precise injection of grid current, and efficient power extraction from PV panels. This study proposed in Nakaso and Koizumi (2021), a half-bridge photovoltaic (PV) microinverter integrated with a five-level inverter topology. By forming a five-level terminal voltage, the design reduces both filter inductance and switching losses, outweighing the conduction losses introduced by additional switches. The system employs phase-shift PWM (PSPWM) to generate a three-level dc input voltage from the inverter, which is then processed by an H-bridge to produce a five-level ac output. A small-scale experimental prototype confirmed the theoretical operation, showing an efficiency of 83. 9 % at 62.5 W, while simulations achieved 89.8 % under the same conditions. At higher ratings (250 W and 500 W), simulation results demonstrated that the proposed circuit consistently outperforms the conventional dual-boost half-bridge with H-bridge inverters, achieving higher conversion efficiency (up to 97.5 %) with reduced switching and filter-related losses. Compared to the conventional approach, this topology enables lower filter requirements, improved efficiency, and better scalability for integration at the module level.This study Saeedinia et al. (2022) in proposes a two-stage single-phase photovoltaic (PV) microinverter rated at 300 W for grid connection. The system combines a SEPIC DC–DC converter with coupled inductors for high voltage gain at low duty cycles and a full-bridge DC–AC inverter for grid interfacing. The architecture ensures continuous input current, reduced ripple, and low switch stress, while film capacitors in the DC-link enhance reliability and lifetime. Eliminating the active power decoupling circuit (APDC) further improves durability and efficiency. Simulation and analysis show 95% efficiency (93.8% theoretical), a grid current THD of 2.01% (well below the 5% limit), unity (or near-unity) power factor, and 99% MPPT accuracy. Compared to conventional microinverter topologies, this design achieves higher reliability, fewer components, superior power quality, and extended operational lifetime. This topology illustrates in Figure 10, the implementation of a hybrid current control scheme combining hysteresis and PR control. The figure emphasizes how fast transient tracking is achieved while maintaining acceptable steady-state harmonic performance. The control block diagram in Figure 11 explains the complementary roles of GHCC and PR control, where the PR controller compensates low-frequency harmonic errors inherent to hysteresis-based methods. The dual-stage microinverter topology highlights the functional separation between voltage boosting and grid interfacing, enabling improved scalability and harmonic mitigation compared to single-stage designs. The corresponding control architecture shows nested voltage and current loops with repetitive control, explaining the low steady-state current distortion and improved sinusoidal tracking.

2.5. Interleaved Flyback Converters and Q-PR Control

This study in Díaz et al. (2023) suggests and examines a microinverter system for photovoltaic (PV) grid-connected applications that is based on an interleaved flyback converter and a full-bridge inverter. The microinverter has a two-stage architecture. A flyback DC-DC converter in Discontinuous Conduction Mode (DCM) is used in a two-stage micro-inverter to increase PV voltage and partially sinusoidally shape current. For effective energy extraction, a hybrid MPPT algorithm that is based on the optimal gradient approach modifies the duty cycle of the converter. To guarantee grid compatibility, a full-bridge inverter with an LC filter controls the AC output. A double closed-loop control system is employed, with the outer loop stabilizing PV voltage and the inner loop controlling grid current. At first, a PI controller was employed to regulate the current, but it displayed excessive harmonics and steady-state errors close to zero crossings. In order to overcome this, a quasi-proportional resonant (Q-PR) controller is suggested, which maintains high gain at the fundamental frequency of the grid while providing improved harmonic suppression and decreased steady-state tracking errors. The findings in Díaz et al. (2023) show that the suggested Q-PR control approach successfully improves microinverter performance by lowering harmonic distortion, enhancing dynamic stability, and strengthening resilience to grid disruptions. This ensures grid standards are met and higher-quality injected power is produced. P. Zhang et al. (2024) propose a two-stage microinverter system for PV grid-connected applications, employing an interleaved flyback converter and a full-bridge inverter. An optimized gradient MPPT algorithm maximizes power extraction, while a quasi-proportional resonant (Q-PR)

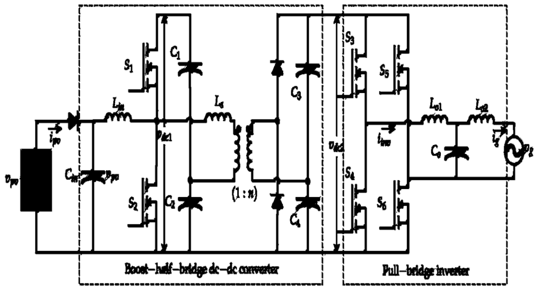

Figure 10. Topology of microinverter's proposed in H. Zhang et al. (2018),Jiang, Cao, Li, and Peng (2012).

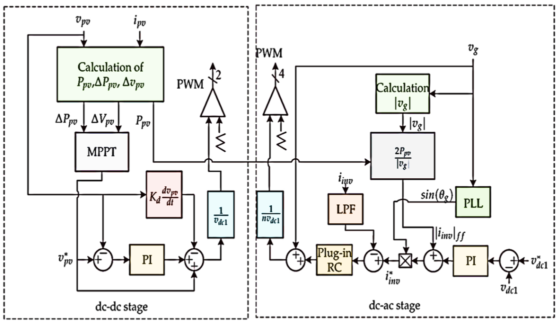

Figure 11. Control strategy proposed in H. Zhang et al. (2018),Jiang, Cao, Li, and Peng (2012).

current control strategy reduces harmonic distortion and eliminates steady-state tracking error. Simulation results show low THD, improved robustness against grid disturbances, and higher energy utilization compared to conventional centralized inverters, ensuring compliance with grid standards and superior power quality. Jian and Bingqing (2016) present an accurate modeling approach and a sliding mode control method to enhance current sharing in PV grid-connected interleaved flyback microinverters. A fourth-order model is developed to analyze the dynamic behavior and pole–zero locations under different operating conditions, improving control effectiveness at low power. To address load imbalance caused by mismatched parameters between the interleaved flyback circuits, a sliding mode controller is designed, ensuring balanced current distribution and improved reliability. Simulation and experimental results validate the proposed method, demonstrating enhanced current sharing performance and stable grid-connected operation. The overall microinverter configuration and control strategy implemented as Interleaved Flyback Converters and Q-PR Control is as depicted in Figure 12.

This overall control block diagram for interleaved flyback microinverters illustrates current sharing and coordinated grid-current shaping, which directly contributes to reduced ripple and enhanced reliability.

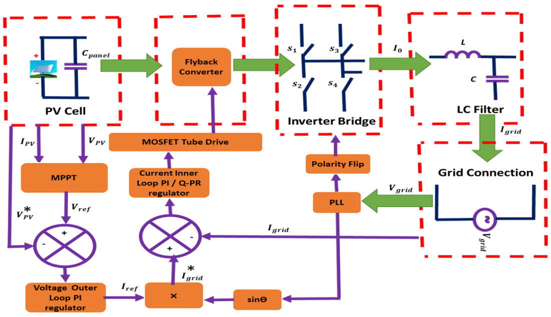

Figure 12. MI Overall Control Block Diagram .

2.6. Comparative Reactive Power Control Methods

The study Díaz et al. (2023) compares two designs of micro-inverter systems with an emphasis on maximum power extraction, current quality, and reactive power management control methodologies. An interleaved boost converter and a three-phase Voltage Source Inverter (VSI) are elements of the initial design. The three-phase VSI-based microinverter configuration demonstrates how synchronous reference frame control enables precise regulation of active and reactive power in multi-phase systems. For grid synchronization, it uses a Phase-Locked Loop (PLL) algorithm and the Perturb and Observe (P&O) algorithm for MPPT. The I_q component is independently controlled by a PI controller to manage the reactive power via the synchronous reference frame d-q, while the I_d component regulates the active power. The system uses a PWM technique to generate inverter switching signals and incorporates feedforward terms and cross-coupling in the inner loops for improved dynamic responsiveness. The PI controller then uses the error to create the active current reference I_d^*. In order to precisely control the active and reactive powers fed into the grid, the inner current loops simultaneously regulate the current loops I_d and I_q independently.

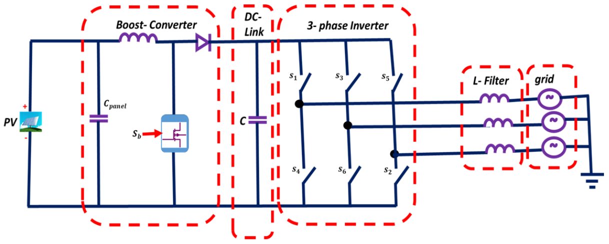

Figure 13. Three-phase grid-connected circuit configuration of the micro-inverter PV system in Díaz et al. (2023).

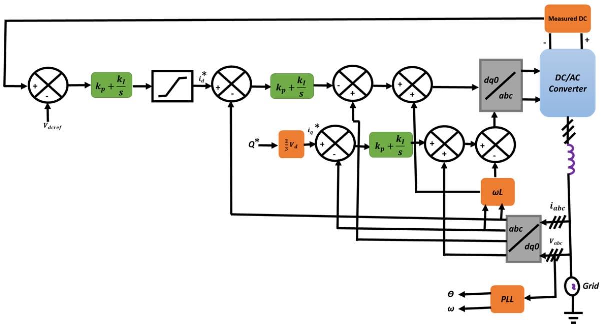

Figure 14. Control of three-phase micro-inverter photovoltaic system in Díaz et al. (2023).

The second micro-inverter design combines a Current Source Inverter (CSI) with interleaved flyback converters to improve output quality and reactive power control. It uses third-harmonic current injection, managed by a PI controller, to enhance power factor and reduce THD. A modified current-based P & O MPPT algorithm ensures fast, accurate tracking under varying irradiance. Phase-shifted flyback converters reduce ripple and boost efficiency, while the CSI uses sector-based, phase-delayed switching to produce sinusoidal output. Dynamic control of duty cycles and a PI-based power balancing loop ensure system stability and equal current sharing.

2.7. Transformerless Buck-Boost Designs for BIPV

In this paper Noori and Hassan (2021), a transformerless single-stage buck-boost microinverter (TSBBM) for

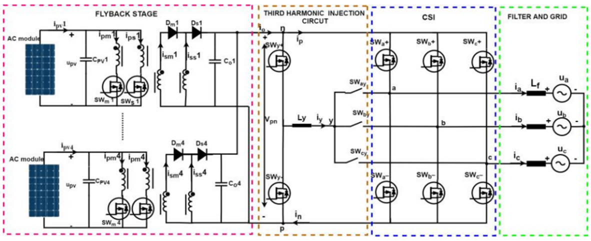

Figure 15. Schematic diagram of three-phase micro-inverter topology in Díaz et al. (2023).

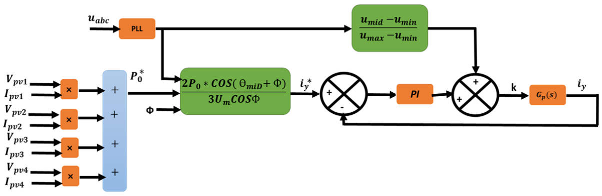

Figure 16. Block diagram for control of micro-inverter in Díaz et al. (2023).

building-integrated photovoltaic (BIPV) systems is highlighted with a sensorless control approach. Conventional microinverters increase in size, complexity, and expense since they frequently rely on existing sensors. On the other hand, The TSBBM microinverter uses a sensorless design operating in DCM, estimating PV current through voltage and duty cycle correlations, which reduces size, complexity, and cost. With PI controllers and the P&O MPPT method, it achieves high efficiency (93.3%), low THD (4%), and minimal leakage current, making it well-suited for compact, reliable BIPV applications.This paper Mathew and Naidu (2020) introduces a transformerless, single-stage buck–boost microinverter (TSBBM) aimed at building-integrated photovoltaic (BIPV) systems, focusing on reducing size, cost, and complexity compared to traditional designs that use multiple stages or transformers. The inverter is built with fewer components and is inherently protected against shoot-through faults, while its operation in Discontinuous Conduction Mode (DCM) enables simple control, fast dynamics, and reduced switching losses. A sensorless control technique is employed, where the PV current is derived from voltage and duty cycle information instead of being measured directly, eliminating the need for current sensors. Using PI controllers along with the Perturb and Observe (P&O) MPPT algorithm, the system delivers high efficiency (above 90%), low total harmonic distortion (4–5%), and very small leakage current, making it a compact, efficient, and reliable solution for integrating PV power into buildings. The work in Mathew et al. (2021) introduces a buck–boost single-stage microinverter (BBSM) for building-integrated photovoltaic (BIPV) systems, addressing the drawbacks of conventional isolated and multi-stage inverters that suffer from increased component count, reduced efficiency, and larger form factors. The proposed topology utilizes a reduced number of active and passive devices and a shoot-through free structure, thereby improving reliability and minimizing conduction losses. The inverter operates in discontinuous conduction mode (DCM), enabling simplified control, reduced switching losses, and stable grid interaction. A two-step control strategy, incorporating Perturb and Observe (P&O) MPPT and PI-based regulation of PV voltage and grid current, ensures effective power tracking and sinusoidal current injection. Simulation and experimental validation of a 70 W prototype confirm an efficiency of 96.4%, grid-current THD of 4.09%, negligible leakage current, and near-unity power factor. The work in Rodriguez et al. (2023) introduces a transformerless seven-level PV microinverter that employs a single-loop, current-sensorless control strategy to minimize hardware complexity and computational demand while ensuring stable grid integration. The topology combines a multilevel boost converter, a four-level buck-type stage, and an H-bridge, producing a seven-level output with natural capacitor self-balancing and eliminating the need for AC-side current sensors. The control approach integrates a Perturb and Observe (P&O) MPPT algorithm with a single PI regulator for DC-link voltage, unlike conventional systems that rely on multiple cascaded controllers and extensive sensing. Simulation and experimental validation of a 1.5 kW prototype demonstrate high efficiency, a grid current THD below 3.5%, and unity power factor, with reliable performance under varying irradiance. These results highlight that the proposed microinverter achieves low THD, simplified control, high efficiency, and cost-effectiveness for distributed PV applications.

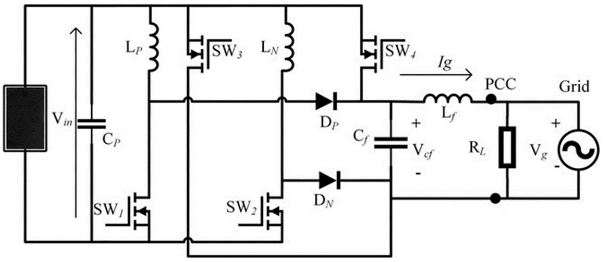

Figure 17. Schematic diagram of the TSBBM in Noori and Hassan (2021).

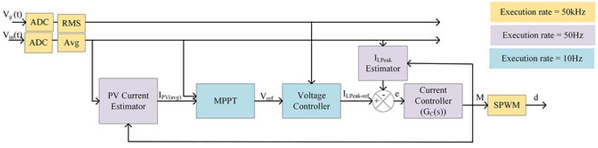

Figure 18. Block diagram of the sensorless control technique in Noori and Hassan (2021).

2.8. Hybrid Energy Storage Integration

The control approach for a three-phase microinverter with a hybrid energy storage system (HESS) is presented in Tapia et al. (2022). Both the battery and the supercapacitor, which are part of the HESS, are managed by a DC-DC bidirectional converter. A photovoltaic panel managed by a three-phase inverter and a Boost converter is also part of the system. Power flow between the photovoltaic panel, the HESS, and the grid is managed by the control strategy. The three-phase inverter is controlled by PI control in the Park plane, and the panel's voltage is managed by the boost converter using input-output feedback linearization. The virtual impedance governs the HESS. During load impacts, the supercapacitor reduces the battery current, and in the steady state, the supercapacitor current is zero, as the article demonstrates. As evidenced by above, the HESS shields the battery from abrupt fluctuations in load. The proposed microinverter and overall control strategy presented in Tapia et al. (2022) are as shown in Figure 19, Figure 20, Figure 21 and Figure 22 respectively. The proposed microinverter with hybrid energy storage system (HESS) highlights integrated power flow paths among the PV source, energy storage units, and the grid, enabling enhanced transient support and improved system flexibility during dynamic operating conditions. As illustrated in Figure 20, the HESS control scheme employs virtual impedance and bidirectional converter coordination to mitigate battery stress during sudden load and irradiance transients, thereby improving storage lifetime and system reliability. Figure 21 presents the PV-side control loop with decoupled voltage regulation, which ensures stable operation of the boost converter and effective power extraction under fluctuating irradiance. Finally, Figure 22 shows the inverter control structure based on Park-frame PI regulation, enabling stable three-phase grid interaction while supporting reactive power control and compliance with grid-code requirements.

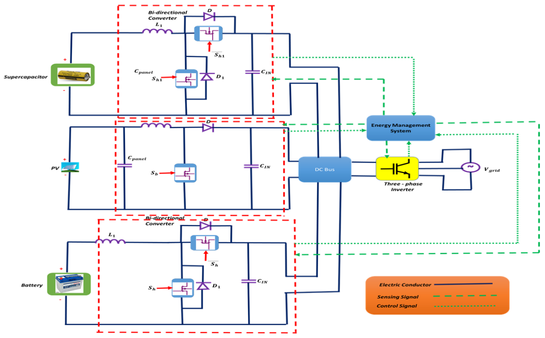

Figure 19. Proposed micro inverter model in Tapia et al. (2022)

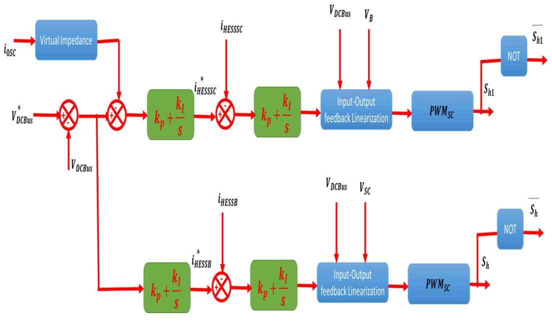

Figure 20. HESS control scheme

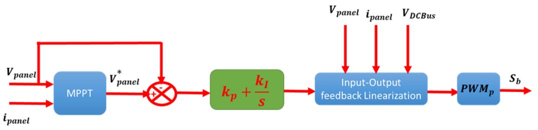

Figure 21. Solar panel control scheme

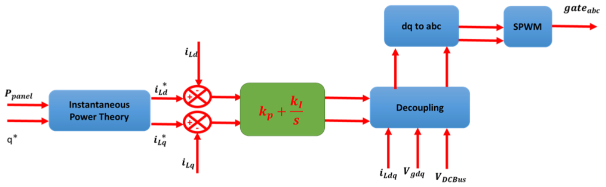

Figure 22. Inverter control scheme

3. Performance Comparison

Table 1 and Table 2 provide an in depth comparative synthesis of the micro inverter topologies and control strategies reported in the literature, clearly illustrating how architectural choices and control philosophies govern efficiency, power quality, grid support capability, and practical deployability. Single stage and transformerless buck boost micro inverters achieve relatively high efficiencies typically in the 93 to 96 percent range primarily because of reduced power processing stages and lower conduction losses. However, their operation in discontinuous conduction mode and reliance on simple PI based or sensorless control limit their ability to independently regulate active and reactive power, resulting in moderate grid current THD of approximately 4 to 5 percent and constrained scalability beyond low power residential or BIPV applications. In contrast, dual stage and isolated micro inverter architectures particularly those employing flyback SEPIC or push pull DC DC converters followed by full bridge inverters consistently demonstrate improved grid current quality with THD values as low as 2 to 3 percent due to the decoupling of MPPT dynamics from grid current control, which allows tighter regulation of the inverter output current

Table 1. Comparison of all control strategies

Ref.	Topology	MPPT Method	Control Strategy	Efficiency (%)	THD (%)	Reactive Power Control	Special Features	Limitations
Petreus (2013)	Single-stage Dual Buck-Boost	P&O	Hysteresis Current Control	~93	4.7	Not addressed	Compact, transformerless; PF ~0.98; good sinusoidal injection	No reactive power; limited scalability; ≤500 W
Ozdemir (2014)	Three-phase NPC Inverter	Novel MPPT	PI-based loop	93.08	3.45	Not addressed	Single-stage; eliminates DC–DC stage	High-voltage complexity; MPPT details missing
Atsu (2024)	Microinverter with isolation transformer	Integrated MPPT	DSP-based digital control	Not reported	V: ~2%, I: 7–34	Not addressed	Resilient; scalable 200–600 W; islanding detection	High THD outdoors; variable current quality
Burbano (2021)	Active Clamp Flyback + Dual-Buck	Incremental Conductance	2P2Z (dq-frame) + SOGI-PLL	88–91	2–5	Independent P/Q	Fast MPPT; IEEE 1547 compliant	EMI concerns; limited scalability
IEEE (2009)	Full-Bridge Inverter	Not specified	GHCC + PR	Not stated	<5	Not addressed	PR suppresses low-frequency harmonics	No MPPT; poor performance under fluctuations
Elangovan (2024)	Grid-tied VSI	Not specified	Adaptive PR / dq	Not reported	<3	Independent P/Q	Adaptive and robust under fluctuations	High tuning complexity; not validated at high power
Jiang (2012), Zhang (2018)	Boost-Half-Bridge + Full-Bridge	P&O	Repetitive + PI + PLL + feedforward	Not reported	<3	dq-frame	Good tracking; repetitive control improves sinusoidal current	Medium complexity; simulation only
IEEE 9661716	Dual Boos Half-Bridge + 5-level inverter	P&O	Phase-Shift PWM	89.8 (sim), 83.9 (exp)	Not reported	Not addressed	5-level output reduces filter size; scalable 250–500 W	More switches; ow-power efficiency drop
Saeedinia (2022)	SEPIC + Full-Bridge	P&O	PI with coupled inductors	95 (sim), 93.8 (theory)	2.01	Unity PF	Low ripple; long lifetime; excellent quality	SEPIC complexity; DC-link stress (no APDC)
Jiang (2012), Diaz (2023)	Push–Pull + H-Bridge	Hybrid (P&O + IncCond)	Predictive + PI	~99.3 (MPPT)	7–8	Phase-synced	Accurate GMPP; robust dynamics	High THD; parameter sensitive
Diaz (2023)	Interleaved Flyback + Full-Bridge	Gradient-based Hybrid	Q-PR Controller	Not reported	2.61	Not addressed	Excellent THD suppression; grid-drop tolerance	High hardware complexity
Zhang (2024)	Interleaved Flyback + Full-Bridge	Optimized Gradient MPPT	Q-PR	Not reported	<3	Not addressed	Strong grid compliance	High computational burden
IEEE 7871138	Interleaved Flyback + Full-Bridge	Sliding-mode MPPT	Sliding Mode Control	Not reported	<4	Not addressed	SMC improves reliability; good current sharing	Sensitive to stage mismatch

under irradiance fluctuations and grid disturbances. This enhanced performance comes at the expense of increased component count higher electromagnetic interference more complex controller coordination and greater sensitivity to parameter variations. The tables further reveal that the selection of current control strategy plays a decisive role

Table 2. Continued from previous page

Diaz (2023)	Boost + 3-phase VSI	P&O	dq-control (Id–Iq)	90.76	5.3	Id–Iq control	Effective P/Q regulation	Higher THD than CSI; limited scalability
Diaz (2023)	Flyback + CSI	Modified P&O	3rd Harmonic Injection + PI	95.07	2.46	3rd Harmonic	Improved PF; THD reduction	High control complexity
Noori (2021)	TSBBM (Transformerless Buck-Boost)	P&O	Sensorless PI (DCM)	93.3	~4	Not addressed	Ideal for BIPV; compact; low leakage current	No reactive power; not suitable for high power
Mathew (2021)	Buck–Boost Single-stage	P&O	PI (sensorless, DCM)	96.4	4.09	Not addressed	Low losses; shoot-through free; validated at 70 W	Limited scalability; small prototype
Rodriguez (2022)	7-Level Transformerless	P&O	PI (single-loop, sensorless)	>95 (1.5 kW)	<3.5	Not addressed	Natural capacitor balancing; compact multilevel	Multilevel complexity; limited validation
Tapia (2022)	3-phase inverter + HESS	Not specified	PI (Park frame) + Virtual Impedance	Not reported	Low (assumed)	dq-frame	SC buffers transients; reduces battery stress	High cost; no MPPT integration

in harmonic mitigation, as proportional resonant and quasi proportional resonant controllers significantly outperform conventional PI and hysteresis based approaches by providing high gain at the grid fundamental frequency, thereby minimizing steady state tracking error and suppressing low frequency harmonics even under distorted grid voltages. Architectures employing synchronous reference frame dq control or current source inverter concepts enable explicit decoupling of active and reactive power through independent Id Iq regulation, which improves voltage support and compliance with modern grid codes, while third harmonic current injection techniques further reduce THD and enhance power factor at the cost of increased computational and implementation complexity. Sensorless and discontinuous conduction mode based designs represent a pragmatic compromise by eliminating current sensors and isolation transformers, thereby reducing cost and improving reliability, yet they remain limited in reactive power support and high power scalability. Overall, the detailed comparisons in Table 1 and Table 2 demonstrate that achieving low THD fast dynamic response and advanced grid support functions necessitates higher control and hardware complexity, whereas simpler and more economical solutions trade off these capabilities, emphasizing that optimal micro inverter selection must be application driven and motivating future research toward unified adaptive MPPT grid control frameworks capable of balancing performance cost and scalability.

4. Progression of Control Architectures

The Figure 23 depicts the functional evolution of PV microinverter control architectures as a progression from converter-centric, grid-following operation toward intelligent, grid-forming behavior, emphasizing the increasing coupling between MPPT, inverter dynamics, and power-system interaction. Rather than a chronological sequence, the evolution reflects a hierarchy in which control objectives expand from local power extraction and current regulation to grid-aware compliance, robustness, and ultimately system-level intelligence. Along this trajectory, control architectures transition from statically tuned, model-based designs to adaptive and data-driven frameworks, while inverter behavior shifts from passive current injection to active shaping of voltage, frequency, inertia, and fault response. Early control schemes rely on decoupled MPPT and PI/PR current regulation under the assumption of a stiff grid, offering limited robustness and suitability for weak-grid conditions. Subsequent grid-code-compliant, robust, and adaptive strategies explicitly incorporate grid constraints, uncertainty handling, and online parameter adaptation, enabling improved stability and disturbance rejection at the expense of increased computational complexity and implementation challenges. The integration of intelligent control further co-optimizes MPPT, inverter regulation, and ancillary services through learning-based decision-making, while raising issues of explainability, certification, and cyber resilience. The evolution culminates in grid-forming microinverter control, where inverters establish voltage and frequency references and coordinate MPPT with system stability requirements, a capability essential for inverter-dominated and low-inertia power systems. Collectively, the figure underscores that future PV-integrated grids require unified MPPT–grid control co-design and hybrid classical–AI frameworks to achieve resilient, autonomous, and scalable operation.

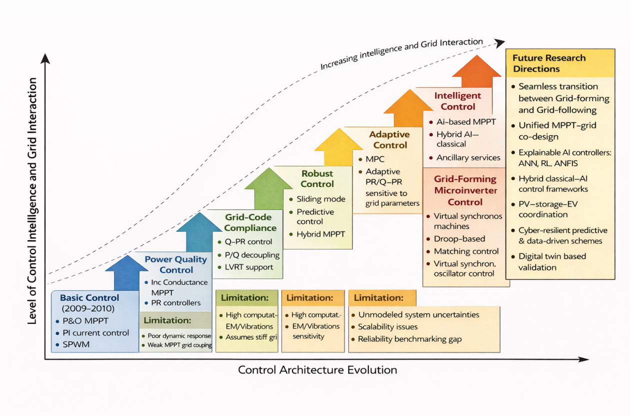

Figure 23. Hierarchy of PV Microinverter Control Strategies

5. Discussion and Conclusion

This paper presented a critical review of micro-inverter control strategies for grid-connected photovoltaic systems, emphasizing the interplay between converter topology, current control methodology, and grid-support functionality. The review demonstrates that single-stage and transformerless micro-inverters achieve high efficiency and reduced hardware complexity, making them attractive for low-power and cost-sensitive applications; however, their reliance on simplified control and discontinuous conduction operation limits reactive power capability and results in moderate grid-current harmonic distortion. Dual-stage and isolated architectures, particularly flyback, SEPIC, and push–pull based designs, enable effective decoupling of MPPT and grid-current regulation, leading to superior dynamic response and lower THD, albeit at the expense of increased component count, higher electromagnetic interference, and more demanding controller coordination. Independent of topology, current control strategy is shown to be a dominant factor in power quality, with proportional–resonant and quasi–proportional–resonant controllers consistently providing near-zero steady-state error and improved harmonic suppression compared to PI and hysteresis-based approaches. Moreover, synchronous reference frame and current-source inverter configurations facilitate explicit active and reactive power decoupling, enhancing voltage support and grid-code compliance. Despite these advances, the literature reveals persistent gaps, including limited validation of advanced control schemes under weak-grid conditions, partial shading, and high PV penetration, as well as insufficient attention to scalability, controller tuning robustness, and long-term reliability. In addition, most existing approaches treat MPPT and grid interaction independently, resulting in suboptimal transient performance during fast irradiance or grid disturbances. Future research should therefore focus on unified MPPT–grid control co-design, adaptive and intelligent control frameworks capable of handling grid uncertainty, and sensorless and transformerless implementations that reduce cost without sacrificing compliance. The integration of local energy storage and grid-forming capabilities at the micro-inverter level also emerges as a key direction for enhancing system resilience in inverter-dominated power systems.

References

Atsu, D., Seres, I., & Farkas, I. (2024). Power quality assessment and compliance of grid-connected pv systems in low voltage networks using microinverters. *Energy Systems*. https://doi.org/10.1007/s12667-024-00665-9

Burbano-Benavides, D. S., Ortiz-Sotelo, O. D., Revelo-Fuelagán, J., & Candelo-Becerra, J. E. (2021). Design of an on-grid microinverter control technique for managing active and reactive power in a microgrid. *Applied Sciences*, *11*(11), 4765. https://doi.org/10.3390/app11114765

Díaz, M., Muñoz, J., Rivera, M., & Rohten, J. (2023). A comprehensive control strategy for a push–pull microinverter connected to the grid. *Energies*, *16*(7), 3196. https://doi.org/10.3390/en16073196

Ding, H., & Gao, Y. (2024). Control strategy based on pid control in photovoltaic inverters. *MATEC Web of Conferences*, *404*, 02001. https://doi.org/10.1051/matecconf/202440402001

Elangovan, P., & Mohanty, N. K. (2024). An adaptive grid-tied inverter control scheme for power quality enrichment in photovoltaic system. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, *48*, 303–315. https://doi.org/10.1007/s40998-023-00667-w

Flota-Bañuelos, M., Espinosa-Trujillo, M., Cruz-Chan, J., & Kamal, T. (2023). Experimental study of an inverter control for reactive power compensation in a grid-connected solar photovoltaic system using sliding mode control. *Energies*, *16*(2), 853. https://doi.org/10.3390/en16020853

Hossain, M. T., Hossen, M. Z., Badal, F. R., Islam, M. R., Hasan, M. M., Ali, M. F., Ahamed, M. H., Abhi, S. H., Islam, M. M., Sarker, S. K., Das, S. K., Das, P., & Tasneem, Z. (2024). Next generation power inverter for grid resilience: Technology review. *Heliyon*, *10*(21), e39596. https://doi.org/10.1016/j.heliyon.2024.e39596

IEEE. (2009). Ieee application guide for ieee std 1547(tm), ieee standard for interconnecting distributed resources with electric power systems.

Jian, Y., & Bingqing, Y. (2016). Accurate modeling and sliding mode control method to improve the current sharing performance for pv grid-connected interleaved flyback mirco-inverter. *2016 IEEE International Conference on Power and Renewable Energy (ICPRE)*, 558–564. https://doi.org/10.1109/ICPRE.2016.7871138

Jiang, S., Cao, D., Li, Y., & Peng, F. Z. (2012). Grid-connected boost-half-bridge photovoltaic microinverter system using repetitive current control and maximum power point tracking. *IEEE Transactions on Power Electronics*, *27*(11), 4711–4722. https://doi.org/10.1109/TPEL.2012.2185714

Jiang, S., Cao, D., Peng, F. Z., & Li, Y. (2012). Grid-connected boost-half-bridge photovoltaic microinverter system using repetitive current control and maximum power point tracking. *Proceedings of the 27th Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 590–597. https://doi.org/10.1109/APEC.2012.6165845

Khanal, S., Bhattarai, B. R., & Dahal, N. (2023). A model predictive power control scheme for pv inverter and battery energy storage system for a microgrid. *Journal of Engineering and Sciences*, *2*(1), 30–34.

Kouro, S., Leon, J. I., Vinnikov, D., & Franquelo, L. G. (2015). Grid-connected photovoltaic systems: An overview of recent research and emerging pv converter technology. *IEEE Industrial Electronics Magazine*, *9*(1), 47–61. https://doi.org/10.1109/MIE.2014.2376976

Mahendravarman, I., Ragavendiran, A., & Chithradevi, S. A. (2023). Improved power quality for photovoltaic grid integration power system using an intelligent controller fed sl–sc boost converter supplied reduced switch cascade multilevel inverter. *Electrical Engineering*, *106*, 419–441. https://doi.org/10.1007/s00202-023-01981-6

Mathew, D., Farrag, M. E., Naidu, R. C., Muthu, R. K., Sivaprakasam, A., & Somasundaram, P. (2021). Buck-boost single-stage microinverter for building integrated photovoltaic systems. *Energies*, *14*(23), 7854. https://doi.org/10.3390/en14237854

Mathew, D., & Naidu, R. C. (2020). Investigation of single-stage transformerless buck–boost microinverters. *IET Power Electronics*, *13*(8), 1487–1499. https://doi.org/10.1049/iet-pel.2019.1237

Nakaso, K., & Koizumi, H. (2021). A dual-boost half-bridge inverter with five-level inverter for photovoltaic microinverter. *2021 IEEE International Future Energy Electronics Conference (IFEEC)*, 1–5. https://doi.org/10.1109/IFEEC53238.2021.9661716

Noori, F. T., & Hassan, T. K. (2021). Performance comparison of reactive power control methods of photovoltaic micro-inverter. *Journal of Physics: Conference Series*, *1973*(1), 012064. https://doi.org/10.1088/1742-6596/1973/1/012064

Ozdemir, S., Altin, N., & Sefa, I. (2014). Single stage three level grid interactive mppt inverter for pv systems. *Energy Conversion and Management*, *80*, 561–572. https://doi.org/10.1016/j.enconman.2014.01.048

Petreuş, D., Daraban, S., Ciocan, I., Patarau, T., Morel, C., et al. (2013). Low cost single stage micro-inverter with mppt for grid connected applications. *Solar Energy*, *92*, 241–255. https://doi.org/10.1016/j.solener.2013.03.016

Premkumar, M., Jangir, P., Ramakrishnan, C., Kumar, C., Sowmya, R., Deb, S., & Kumar, N. M. (2022). A review on solar pv based grid connected microinverter control schemes and topologies. *International Journal of Renewable Energy Development*, *11*(2), 1–10.

Rodriguez, J. R., Mejia-Ruiz, G. E., Paternina, M. R. A., Velazquez-Ibanez, A., Salgado-Herrera, N. M., Santoyo-Anaya, M. A., Zamora-Mendez, A., & Chamorro, H. R. (2023). A single-loop and current-sensorless control for on-grid seven-level photovoltaic microinverter. *IET Power Electronics*, *16*(6), 905–916. https://doi.org/10.1049/pel2.12436

Saeedinia, S., Shamsi-Nejad, M. A., & Eliasi, H. (2022). A two-stage grid-connected single-phase sepic-based micro-inverter with high efficiency and long lifetime for photovoltaic systems application. *Iranian Journal of Electrical and Electronic Engineering*, *18*(2), 117–130. https://doi.org/10.22068/IJEEE.18.2.2355

Tapia, O., Muñoz, J., & Venegas, L. (2022). Control strategy for a three-phase microinverter with an embedded hybrid energy storage system. *2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 1–6. https://doi.org/10.1109/EEEIC/IC/PSEUROPE54979.2022.9854708

Xie, S., Kaneko, A., & Hayashi, Y. (2024). A decentralized voltage regulation scheme using improved volt-var function of pv smart inverter. *IEEJ Transactions on Electrical and Electronic Engineering*, *19*(8), 1300–1310. https://doi.org/10.1002/tee.24080

Zhang, H., Li, X., Xiao, S., & Balog, R. S. (2018). Hybrid hysteresis current control and low-frequency current harmonics mitigation based on proportional resonant in dc/ac inverter. *IET Power Electronics*, *11*(13), 2093–2101. https://doi.org/10.1049/iet-pel.2018.5384

Zhang, P., Li, R., Du, P., Wang, C., & Sun, W. (2024). Study of micro-inverter-based pv grid-connected control strategy simulation. *2024 4th Power System and Green Energy Conference (PSGEC)*, 40–46. https://doi.org/10.1109/PSGEC62376.2024.10720946