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Design and implementation of power control strategies for grid-connected photovoltaic inverters: a review

Miftahul Alim[1], Tri Wahono[2]
[1]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia

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ABSTRACT

The growing penetration of photovoltaic (PV) generation is changing the role of grid-connected inverters from simple DC–AC interfaces into controllable assets for power quality, voltage support, and grid stability across residential, commercial, and utility-scale installations. Their power-control design must coordinate maximum power point tracking, DC-link regulation, grid synchronization, current injection, and protection under variable irradiance and grid disturbances. This review examines the architecture and implementation of power-control strategies for grid-connected PV inverters, with emphasis on cascaded control, synchronous and stationary reference frames, proportional-integral and proportional-resonant regulators, predictive and adaptive methods, and active damping of LCL filters. The interactions among phase-locked loops, current controllers, filter resonance, weak-grid impedance, and reactive-power commands are considered because they determine practical stability and power quality. A comparative framework is provided to relate control objectives, implementation requirements, strengths, and limitations. Evidence published through 2022 indicates that conventional cascaded PI control remains attractive for its simplicity, whereas PR, model-predictive, robust, and intelligent approaches offer benefits under selected operating conditions. The review identifies priorities in experimental validation, adaptive coordination, grid-forming capability, cybersecurity, and standardized benchmarking.

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1. INTRODUCTION

Photovoltaic (PV) generation has become an important component of modern electricity systems because it offers modular installation, low operational emissions, and compatibility with distributed generation. However, the increasing penetration of PV sources introduces technical challenges associated with intermittent power production, voltage fluctuations, harmonic distortion, and reduced system inertia. The inverter is therefore no longer required merely to convert direct current into alternating current, but must also regulate power exchange and support reliable grid operation. These requirements have encouraged the development of advanced control architectures capable of maintaining stable operation under changing environmental and electrical conditions [1]-[3].

Power control in grid-connected PV systems involves several interacting functions that must be coordinated throughout the conversion process. The PV-side controller determines the operating point of the array through maximum power point tracking (MPPT), while the DC-link controller maintains the energy balance between the input and output stages. On the grid side, synchronization and current regulation determine the magnitude, phase, and quality of the injected current. These functions become more complicated during voltage disturbances, weak-grid operation, and changes in available solar irradiance [4], [5].

Previous research has examined inverter topologies, modulation techniques, current regulators, synchronization algorithms, and grid-support functions. Nevertheless, selecting an effective controller requires consideration of the complete system rather than the performance of an individual algorithm.

For example, a fast current controller may still produce unstable operation when the LCL filter resonance is inadequately damped or the phase-locked loop (PLL) interacts with a weak grid. This review therefore evaluates power-control strategies from the perspectives of system architecture, controller implementation, dynamic response, stability, and grid-support capability, using research published no later than 2022.

2. ARCHITECTURE AND POWER-CONTROL REQUIREMENTS

A grid-connected PV system generally employs either a single-stage or a two-stage conversion architecture. In a single-stage configuration, the PV array supplies a DC–AC inverter directly, reducing the number of conversion stages and potentially improving conversion efficiency. In a two-stage configuration, a DC–DC converter performs voltage adaptation and MPPT before the inverter delivers power to the grid. Although the two-stage structure introduces additional components and conversion losses, it provides greater flexibility in regulating the PV operating voltage and DC-link conditions [6], [7].

The power-control architecture must coordinate the PV array, DC-link capacitor, inverter bridge, output filter, and utility interface. The MPPT algorithm extracts available solar energy, while the DC-link regulator maintains the voltage required for reliable inverter operation. The grid-side controller then regulates active and reactive power through appropriate current references and switching commands. This arrangement is widely adopted because it separates energy extraction from grid-current regulation, although the interaction between the control loops must be carefully designed [8], [9].

The main control objectives extend beyond maximum energy extraction because modern inverters are expected to contribute to grid operation. These objectives include unity-power-factor operation, reactive-power compensation, harmonic reduction, voltage regulation, and fault ride-through. The required functions depend on inverter ratings, grid codes, network characteristics, and the availability of energy storage. Consequently, the controller should be designed around both normal operating conditions and abnormal grid events [10], [11].

3. GRID SYNCHRONIZATION AND REFERENCE-FRAME SELECTION

Grid synchronization is a fundamental requirement because the inverter must identify the phase and frequency of the utility voltage before injecting controlled current. The synchronous reference frame PLL is widely used because it transforms three-phase voltage signals into a rotating coordinate system in which the fundamental positive-sequence component can be regulated conveniently. However, conventional PLL structures may experience performance degradation under voltage unbalance, harmonic distortion, and frequency variations. Enhanced PLL structures, including decoupled and generalized-integrator approaches, have therefore been developed to improve synchronization accuracy under disturbed grid conditions [12].

The choice of reference frame also influences controller design and implementation complexity. Synchronous reference-frame control is particularly suitable for three-phase systems because sinusoidal quantities become approximately constant in steady state, allowing conventional PI regulators to achieve accurate tracking. Stationary reference-frame control commonly employs proportional-resonant regulators, which can provide high gain at the fundamental grid frequency without requiring rotating-coordinate transformations. Both approaches can provide satisfactory current regulation, but their performance depends on frequency adaptation, measurement quality, and digital implementation [2], [13].

4. CURRENT AND POWER CONTROL STRATEGIES

Current regulation is the central function of a grid-connected inverter because it determines the electrical power delivered to the utility network. Conventional cascaded control generally employs an outer DC-link voltage loop and an inner grid-current loop, allowing the controller to regulate energy balance and current quality separately. PI regulators are frequently selected for synchronous reference-frame control because they are simple, computationally efficient, and supported by established tuning procedures. Their limitations become more apparent under nonlinear operating conditions, parameter uncertainty, and grid disturbances that exceed the assumptions used during controller design [4], [14].

Proportional-resonant (PR) control is an alternative for systems operating in the stationary reference frame. Its resonant characteristic provides high gain around the fundamental frequency, enabling accurate sinusoidal current tracking with low steady-state error. Multiple resonant terms can also be incorporated to compensate for selected harmonic components, although the controller becomes more sensitive to frequency deviations and parameter selection. Practical implementation therefore requires suitable frequency adaptation, digital discretization, and consideration of measurement noise [13], [15].

Advanced control methods have been investigated to improve dynamic performance and robustness under changing operating conditions. Model-predictive control (MPC) uses a system model to predict future

behavior and select switching actions or control references according to a defined objective. Sliding-mode and robust control methods aim to maintain satisfactory performance despite parameter variations and external disturbances. Adaptive and intelligent methods, including fuzzy logic and neural-network-based approaches, offer additional flexibility, but their computational requirements and experimental validation remain important considerations [16], [17].

5. ACTIVE AND REACTIVE POWER REGULATION

Active-power control determines how much energy generated by the PV array is transferred to the utility grid. In conventional grid-following systems, active power is commonly regulated through the direct-axis current reference in a synchronous reference frame. Reactive power is controlled independently through the quadrature-axis current reference, allowing the inverter to provide power-factor correction or voltage-support services. This decoupled control structure is widely used because it provides a relatively straightforward relationship between current references and power exchange [18].

Reactive-power regulation is increasingly important in distribution networks with high PV penetration. Excessive local generation can produce voltage rise, while rapid irradiance changes may contribute to voltage fluctuations and flicker. Volt–VAR control enables an inverter to absorb or inject reactive power according to measured voltage conditions or predefined control characteristics. Field-oriented research has demonstrated that smart-grid-integrated inverter control can support voltage regulation and reactive-power dispatch using existing distribution automation infrastructure [19].

The inverter's apparent-power rating imposes an important limitation on simultaneous active- and reactive-power delivery. When active power approaches the inverter rating, the remaining current capacity available for reactive-power support becomes restricted. During grid faults, the controller may also need to prioritize reactive current injection while limiting the total current to protect semiconductor devices. Therefore, active-power curtailment, current limiting, and reactive-power prioritization should be coordinated within the overall control architecture [10], [20].

6. LCL FILTER CONTROL AND SYSTEM STABILITY

The output filter is essential for reducing switching-frequency harmonics before current is injected into the utility grid. LCL filters provide stronger high-frequency attenuation than simple L filters while allowing a relatively compact design. However, their third-order dynamics introduce a resonance frequency that can destabilize the current-control loop if it is not adequately damped. The interaction between filter parameters, digital delay, controller bandwidth, and grid impedance must therefore be evaluated during the design process [5], [21].

Passive damping is relatively simple because it introduces resistive elements to suppress resonance, but the resulting power dissipation reduces system efficiency. Active damping instead uses feedback signals and control algorithms to emulate damping behavior without necessarily requiring additional resistors. Capacitor-current feedback, capacitor-voltage feedback, and inverter-side current feedback are among the commonly investigated approaches. Their suitability depends on sensor availability, computational delay, robustness, and the stability margin required under different grid conditions [22].

Weak-grid operation introduces further challenges because the grid impedance can interact with the inverter output impedance and its control loops. These interactions may produce harmonic amplification, oscillations, and instability even when the inverter operates satisfactorily under a strong-grid assumption. Impedance-based analysis provides a useful framework for examining these interactions and identifying potentially unstable frequency regions. Recent investigations have specifically shown that inverter capacity, PLL bandwidth, and network impedance can influence the stability of two-stage PV systems connected to weak grids [23], [24].

7. FAULT RIDE-THROUGH AND GRID-SUPPORT FUNCTIONS

Grid-connected PV inverters are increasingly required to remain connected during specified voltage disturbances rather than disconnect immediately. Low-voltage ride-through (LVRT) strategies regulate inverter current during voltage sags while maintaining acceptable DC-link voltage and limiting semiconductor stress. The control system must detect the disturbance, determine appropriate current references, and coordinate active and reactive power according to applicable grid requirements. These functions are particularly important because widespread inverter disconnection during a disturbance can worsen the stability of a power system with high renewable penetration [20], [25].

Fault ride-through control also requires attention to the energy imbalance between the PV array and the grid interface. During a severe voltage sag, the inverter may be unable to export the available PV power

while the array continues producing energy. This condition can increase DC-link voltage unless the controller reduces PV-side power, activates an energy-storage interface, or applies another suitable energy-management method. Coordinated MPPT modification and inverter current control have therefore been investigated as approaches for improving fault response [25], [26].

8. COMPARATIVE ASSESSMENT OF CONTROL STRATEGIES

The reviewed control methods differ in their implementation requirements, dynamic behavior, and suitability for particular grid conditions. PI and PR controllers remain attractive for conventional installations because of their relatively low computational burden and established industrial use. MPC and robust methods offer opportunities for improved transient response and constraint handling, although they require more detailed models and careful digital implementation. Intelligent and adaptive controllers may improve operation under changing conditions, but their benefits should be demonstrated through reproducible hardware experiments rather than simulation results alone [14], [16], [17]. Table 1 summarizes the principal control approaches and their practical characteristics. The comparison indicates that no single controller is universally superior because each method addresses different performance priorities. The selection should consider grid strength, inverter rating, filter design, computational resources, sensor availability, and grid-code requirements. This comparative assessment also highlights why hybrid control architectures are receiving attention for future PV inverter applications.

Table 1. Comparative assessment of power-control strategies for grid-connected PV inverters.

Control strategy	Main application	Advantages	Main limitations
PI control	DC-link and current regulation in dq frame	Simple, low computational burden, established implementation	Sensitive to model variation and grid disturbances
PR control	Current regulation in stationary frame	Accurate sinusoidal tracking and harmonic compensation	Frequency sensitivity and tuning requirements
Model-predictive control	Switching and power regulation	Fast response and direct constraint handling	Model dependence and computational burden
Sliding-mode control	Robust current and power regulation	Strong disturbance rejection and robustness	Chattering and implementation complexity
Fuzzy/adaptive control	MPPT and coordinated inverter regulation	Adaptability to nonlinear and changing conditions	Rule design, training, and validation requirements
Active damping	LCL resonance suppression	Improves stability without large passive damping losses	Additional sensing or control complexity
Volt–VAR control	Distribution voltage support	Reactive-power dispatch and voltage regulation	Limited by inverter apparent-power capacity

9. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Several research challenges remain before advanced PV inverter control can be implemented consistently across different grid environments. First, many proposed controllers are evaluated through simulation or laboratory prototypes under relatively controlled conditions, which may not represent the variability of field installations. Second, the increasing use of power-electronic interfaces creates complex interactions among PLLs, current regulators, filters, and network impedances. Third, the simultaneous demand for high efficiency, fast dynamic response, low harmonic distortion, and grid-support functions creates competing design objectives [3], [21], [23].

Future research should prioritize adaptive control architectures that can respond to changes in irradiance, grid impedance, and operating conditions without compromising stability. Grid-forming capability is another important direction because conventional grid-following inverters depend on an external voltage reference and may provide limited support in systems with very high inverter penetration. Hybrid control strategies combining model-based regulation with intelligent adaptation may offer a practical compromise between predictable behavior and flexibility. Further work is also needed on cybersecurity, communication reliability, standardized testing, and hardware-in-the-loop validation to ensure that advanced controllers remain dependable in real distribution networks [12], [17], [19].

10. CONCLUSION

The design and implementation of power-control strategies are central to the reliable operation of grid-connected photovoltaic inverters. Effective control requires coordination among MPPT, DC-link regulation, grid synchronization, current injection, and protection functions. PI and PR regulators remain practical solutions for many applications, while predictive, robust, and intelligent methods provide additional capabilities under more demanding operating conditions. The selection of a suitable strategy must also

account for LCL filter resonance, weak-grid interactions, and the reactive-power requirements imposed by modern grid codes.

The literature reviewed through 2022 demonstrates that inverter control should be assessed as an integrated system rather than as an isolated control algorithm. Future developments should combine adaptive regulation, robust synchronization, effective resonance damping, and coordinated grid-support functions. Experimental validation under realistic grid conditions is essential to establish the reliability and practical advantages of advanced control methods. These improvements will help PV inverters evolve from basic power-conversion interfaces into dependable and flexible components of future electricity networks.

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