IAES Journal of Electrical and Electronics Engineering
Vol. 7, No. 1, June 2020, pp. 5~8
ISSN: 2338-7432, DOI: 10.11591/jeee.v7i1.pp5-8

Grid-tied inverter systems in solar power plants: a review of synchronization, power quality, and grid stability

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Article Info

Article history:

Received Dec 19, 2018
Revised Jun 6, 2019
Accepted Jul 5, 2019

Keywords:

Grid synchronization
Grid-tied inverter
LCL filter
Photovoltaic integration
Power quality
Stability analysis

ABSTRACT

Grid-tied photovoltaic inverter systems play an increasingly important role in maintaining the operational performance of modern electrical networks with substantial renewable energy penetration. Their effectiveness depends not only on energy conversion efficiency but also on synchronization accuracy, current regulation, power quality, and interaction with grid impedance. This review examines the principal control mechanisms used in grid-connected photovoltaic inverters, emphasizing phase-locked loops (PLLs), current control strategies, output filtering, and active and reactive power regulation. Particular attention is given to LCL-filter dynamics, harmonic suppression, inverter stability, and the challenges associated with weak electrical networks. The review also discusses grid-interconnection requirements, anti-islanding protection, and the evolving operational responsibilities of inverter-based generation. Furthermore, the implications of increasing photovoltaic penetration for voltage regulation, disturbance response, and inverter coordination are critically evaluated. Finally, research opportunities involving impedance-based stability assessment, adaptive control, and grid-support capabilities are identified. The findings emphasize that reliable solar power integration requires coordinated inverter control, appropriate electrical filtering, robust protection, and systematic consideration of network characteristics throughout the plant design process.

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1. INTRODUCTION

Grid-connected photovoltaic inverters are increasingly responsible for determining the quality and stability of electricity delivered by solar power plants. Their function extends beyond converting direct current into alternating current because they must maintain synchronization with the utility network and regulate injected current under changing operating conditions. These requirements become particularly important as renewable generation increases and conventional synchronous generation contributes a smaller proportion of system operation [1], [2].

The interaction between inverter control systems and grid impedance introduces significant operational challenges. Weak electrical networks, voltage disturbances, and parallel inverter installations can influence current-control stability and produce oscillatory behavior. Consequently, inverter performance must be assessed through both converter-level control analysis and system-level grid interaction analysis [1], [3].

This review focuses on the operational and control dimensions of grid-tied photovoltaic inverter systems. Its central argument is that power quality and stability depend on coordinated synchronization, current regulation, filtering, protection, and network-aware control design. The following sections examine these mechanisms and their implications for reliable solar power plant operation.

2. GRID SYNCHRONIZATION AND INVERTER CONTROL

Grid synchronization is a fundamental requirement for safe and effective power injection from photovoltaic inverter systems. The inverter must accurately estimate grid phase and frequency to ensure that

its output current follows the desired reference waveform. Phase-locked loop (PLL) algorithms are widely employed to obtain synchronization information from measured grid voltages [2], [4].

The synchronous reference frame PLL is commonly used in three-phase grid-connected inverter systems because it provides convenient phase estimation and supports control in the rotating reference frame. However, its performance can deteriorate under distorted grid voltages, frequency deviations, and unbalanced conditions. Therefore, synchronization algorithms must be designed with appropriate bandwidth and filtering characteristics to balance dynamic response and disturbance rejection [2].

Current control determines the electrical behavior of the inverter at its point of common coupling. Proportional-integral controllers operating in synchronous reference coordinates are widely used because they support independent regulation of active and reactive current components under balanced conditions. Alternative approaches, including proportional-resonant control, predictive control, and repetitive control, provide different advantages in terms of harmonic tracking, transient response, and implementation complexity [2], [5], as compared in Table 1.

Table 1. Comparison of inverter synchronization and current-control methods

Method	Main function	Advantages	Limitations
Synchronous reference frame PLL	Phase and frequency estimation	Effective for balanced three-phase systems	Sensitive to voltage distortion and unbalance
Enhanced PLL	Improved synchronization	Better disturbance rejection	Greater implementation complexity
PI current control in dq frame	Active/reactive current regulation	Mature and straightforward implementation	Performance depends on synchronization accuracy
Proportional-resonant control	AC current tracking	Effective sinusoidal reference tracking	Resonant tuning required
Model predictive control	Current regulation	Fast dynamic response and flexible constraints	Computational complexity
Repetitive control	Periodic harmonic compensation	Strong periodic disturbance rejection	Limited flexibility for rapidly changing conditions

3. POWER QUALITY AND LCL FILTERING

Power quality is a major concern in grid-connected photovoltaic inverter operation because switching devices generate high-frequency harmonic components during DC–AC conversion. These harmonics may distort injected current and contribute to electromagnetic interference or grid compliance problems. Output filtering is therefore essential for reducing switching-frequency components and maintaining acceptable current waveform quality [2], [6].

LCL filters have become widely adopted because they provide stronger high-frequency attenuation than conventional L filters using comparatively smaller inductance values. Their third-order dynamic characteristics, however, introduce a resonance frequency that can destabilize the current-control loop if appropriate damping is not implemented. Filter design must therefore balance harmonic attenuation, passive component size, damping requirements, and control stability [5], [6].

Passive damping is commonly achieved through resistive elements that reduce resonance amplification, although these components introduce additional power losses. Active damping techniques modify inverter control behavior to suppress resonance without necessarily requiring substantial additional passive components. Their effectiveness depends on the chosen control structure, sensing configuration, digital implementation, and grid impedance characteristics [5], [6]. Different output-filter configurations provide distinct compromises between harmonic attenuation, component size, and control complexity. Table 2 compares the principal filter configurations used in grid-connected inverter systems and highlights their respective advantages and limitations.

Table 2. Comparison of inverter output-filter configurations

Filter	Harmonic attenuation	Advantages	Limitations
L filter	Moderate	Simple structure and control	Larger inductance for equivalent attenuation
LC filter	Improved attenuation	Suitable for voltage-source filtering	Resonance and reactive-power considerations
LCL filter	Strong high-frequency attenuation	Compact filtering and improved switching-harmonic suppression	Resonance requires damping and careful control

4. STABILITY AND WEAK-GRID OPERATION

Grid-connected inverter stability becomes increasingly important when solar power plants operate in electrically weak networks. Weak grids are characterized by relatively high grid impedance, which can amplify interactions between inverter control systems and the electrical network. Such interactions may cause oscillations, distorted currents, or voltage instability even when individual inverter control loops appear stable [1], [3].

Impedance-based analysis provides a useful framework for investigating inverter–grid interactions. The approach evaluates the relationship between inverter output impedance and grid impedance to identify conditions associated with unstable behavior. It can also support the assessment of interactions among parallel inverters, particularly when multiple converters share a common point of connection [1], [3].

LCL-filter resonance and grid impedance variation create additional stability challenges for inverter control. Digital sampling delays, pulse-width modulation delays, controller bandwidth, and phase estimation errors can influence the stability margins of the current-control loop. Therefore, robust inverter design requires coordinated consideration of filter parameters, control bandwidth, synchronization dynamics, and network impedance [1], [5].

Large photovoltaic plants introduce another important stability concern because numerous inverters operate simultaneously through shared electrical infrastructure. Their combined behavior may differ significantly from the response of an individual converter connected to a stiff grid. Accordingly, plant-level stability assessment should consider inverter aggregation, network impedance, reactive compensation equipment, and control interactions rather than treating each inverter as an isolated device [1], [3].

5. GRID INTERCONNECTION, PROTECTION, AND OPERATIONAL REQUIREMENTS

Grid-interconnection standards establish essential requirements for distributed energy resources connected to utility networks. IEEE Std 1547-2018 addresses interconnection and interoperability requirements, including power quality, abnormal operating conditions, islanding, testing, and safety-related considerations [7]. These requirements provide an important framework for evaluating inverter behavior during normal operation and electrical disturbances.

Anti-islanding protection is particularly important because a photovoltaic inverter must not continue energizing an isolated electrical network unintentionally. Islanding may create safety hazards for utility personnel and interfere with the restoration of normal grid operation. Detection techniques include passive methods based on voltage and frequency measurements, active methods involving controlled perturbations, and communication-assisted approaches [8].

The effectiveness of anti-islanding protection depends on the balance between detection speed, reliability, and the non-detection zone. Passive methods are comparatively simple but may struggle to identify islanding when local generation and load are closely matched. Active methods can improve detection capability under certain operating conditions, although their perturbations may affect power quality and interactions among parallel inverters [8].

Modern grid-connected inverter systems are also expected to contribute to network support rather than merely inject active power. Reactive power regulation, voltage support, and controlled responses to grid disturbances can improve the operational flexibility of inverter-based generation. The extent of these functions depends on inverter capability, applicable grid codes, and the coordination between plant-level and converter-level controllers [2], [7].

6. EMERGING CONTROL STRATEGIES AND RESEARCH OPPORTUNITIES

Advanced inverter control offers opportunities to improve performance under weak-grid conditions and increasing renewable penetration. Adaptive control techniques can adjust controller behavior according to changes in network impedance or operating conditions, potentially improving stability margins. However, practical implementation requires reliable parameter estimation and careful evaluation of controller interactions [1], [3].

Impedance-based stability assessment is expected to remain an important research direction because it provides insight into converter interactions beyond conventional single-loop analysis. Online impedance estimation and systematic inverter aggregation models may support more accurate identification of stability risks in large photovoltaic installations. These approaches are particularly relevant where multiple inverter systems operate through shared grid infrastructure [1], [3].

Future research should also emphasize integrated control strategies that combine synchronization, harmonic mitigation, active and reactive power regulation, and grid-support functions. Such integration may improve plant-level performance while reducing the risk of control conflicts among individual inverter

functions. Nevertheless, the implementation of advanced strategies must remain compatible with electrical protection requirements, computational limitations, and established interconnection standards [2], [7].

7. CONCLUSION

Grid-tied photovoltaic inverter systems are critical to maintaining power quality, stability, and reliable integration of solar electricity into utility networks. Their operational performance depends on synchronization accuracy, current regulation, output filtering, protection, and the characteristics of the connected grid. LCL filters provide effective switching-harmonic attenuation but require careful damping and controller design to prevent resonance-related instability. Weak-grid operation and parallel inverter interactions further emphasize the importance of network-aware control and impedance-based stability assessment. Interconnection standards and anti-islanding protection remain essential for safe and reliable photovoltaic generation. Future developments should prioritize robust synchronization, adaptive current control, improved harmonic mitigation, and coordinated grid-support capabilities. Ultimately, reliable solar power plant operation requires inverter systems to be designed as integrated electrical and control components within the broader power network.

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