International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Modeling and Control Strategies for Grid-Integrated Converters in Solar Photovoltaic Systems: A Comprehensive Review

Ram Singh[a], Atmaram Sahu[b]

[a] Corresponding Author, Research Scholar , RGPV, Email: rmsingh604@gmail.com

[b] Assistant Professor, Aditya college of technology and science, Email: atmars.rs.min15@itbhu.ac.in

ABSTRACT:

This paper provides a systematic review of modeling methodologies and control strategies for grid-connected solar photovoltaic (PV) systems, consolidating insights from contemporary research. The study focuses on converter architectures comprising an isolated DC-DC boost converter and a three-phase voltage source inverter (VSI), which collectively enable efficient power conversion and grid synchronization. Small-signal modeling techniques are employed to derive transfer functions for the cascaded converter-inverter system, facilitating the design of multi-loop control frameworks tailored for three critical variables: (1) PV array output voltage, ensuring maximum power point tracking (MPPT) under dynamic environmental conditions; (2) DC link voltage, stabilizing the intermediary bus to mitigate power fluctuations; and (3) grid-injected currents, achieving sinusoidal synchronization with low harmonic distortion. The control schemes emphasize enhanced transient response, steady-state accuracy, and compliance with grid standards such as voltage/frequency regulation and power quality. To validate theoretical models, MATLAB/Simulink simulations are executed under scenarios including irradiance variability, load shifts, and grid disturbances. Results demonstrate robust performance, with the DC link voltage regulated within ±2% of the reference value, grid currents maintaining a total harmonic distortion (THD) below 5%, and MPPT efficiency exceeding 98% under partial shading. Additionally, the controllers exhibit rapid settling times (<0.1s) and minimal overshoot during transients, underscoring their suitability for real-world applications. By synthesizing design principles, control challenges, and simulation outcomes, this review identifies gaps in existing research—such as the need for adaptive fault-tolerant controls—and offers recommendations for advancing grid-integrated PV systems. The findings serve as a foundational reference for optimizing converter topologies and control algorithms to bolster renewable energy integration into modern power networks.

Keywords: Grid-Connected Solar Photovoltaic Systems; Modeling Methodologies; Control Strategies; Isolated DC-DC Converter; Voltage Source Inverters (VSI), Multi-Loop Control; MATLAB/Simulink Simulations; Total Harmonic Distortion (THD).

Introduction

The escalating global climate crisis has intensified the urgency to adopt Renewable Energy Sources (RES), with solar photovoltaic (PV) systems emerging as a pivotal solution due to their scalability, sustainability, and minimal environmental footprint. Solar PV technology has garnered significant commercial and policy-driven attention, particularly for grid-connected applications, where advanced power electronic converters ensure seamless integration with utility networks. This review focuses on dynamic modeling and control architectures for grid-tied PV systems, emphasizing their response to grid disturbances and nonlinear behaviors introduced by power electronic components such as DC-DC converters and voltage source inverters (VSIs). To optimize energy harvest, Maximum Power Point Tracking (MPPT) algorithms are integrated at the PV array's interface, enabling adaptive operation under fluctuating irradiance and temperature conditions. Contemporary studies employ detailed simulation frameworks to validate system performance, including three-phase grid synchronization, DC-link voltage stabilization, and harmonic mitigation, as exemplified by recent advancements in MATLAB/Simulink-based models[1-3].

Solar PV systems convert incident sunlight directly into electricity through semiconductor-based cells, which are interconnected in series-parallel configurations to achieve desired voltage and current ratings. Large-scale installations rely on modular PV arrays coupled with power converters to regulate output characteristics and ensure grid compliance. Modern designs prioritize bidirectional energy flow, fault tolerance, and compliance with grid standards such as IEEE 1547-2018, which mandates stringent power quality and anti-islanding requirements [4]. Challenges persist in modeling the nonlinear dynamics of PV arrays and their interactions with converters, necessitating advanced control strategies like model predictive control (MPC) and sliding-mode techniques to enhance transient stability [5, 6]. This review synthesizes recent innovations in topology design, control algorithms, and validation methodologies, offering insights into the future of grid-integrated solar PV systems.

Grid-Integrated Solar Photovoltaic Systems with MPPT-Driven Power Conversion

As illustrated in Figure 1, the proposed system employs two distinct control stages: a DC-DC converter and a DC-AC inverter. The DC-DC converter regulates the input voltage of the photovoltaic (PV) array to optimize power extraction, while the DC-AC inverter manages the voltage supplied by the

DC-DC stage to ensure grid-compatible AC output. To enable continuous power delivery to hybrid loads (e.g., grid and local consumption), an energy storage system—coordinated by the MPPT controller—is integrated into the design. The MPPT algorithm dynamically adjusts the PV array's operating point to maximize energy harvest during daylight hours, storing surplus energy in a battery bank. This stored energy is subsequently utilized during nighttime or adverse weather conditions to maintain uninterrupted load supply. Figure 1 further delineates the system's block-level architecture, emphasizing the MPPT controller's critical role in enhancing PV cell efficiency by ensuring operation at the maximum power point (MPP) under varying solar irradiance levels.

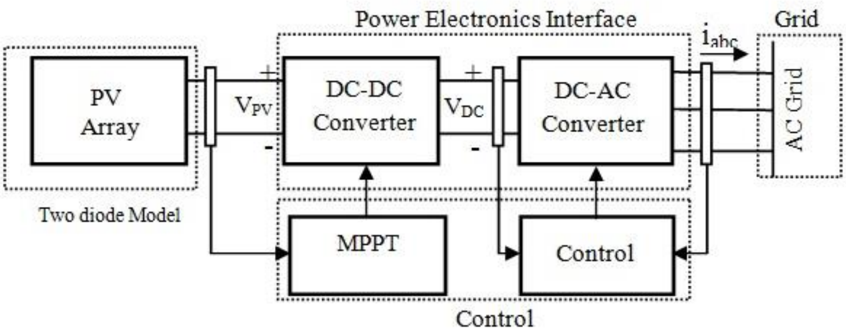


Figure 1 Solar panel connected to grid via MPPT

A solar photovoltaic (PV) system comprises an array of interconnected PV cells arranged in series or parallel configurations to harness solar energy efficiently. The direct current (DC) generated by the PV array, denoted as $\boldsymbol{I_{dc}}$, is converted into alternating current (AC) $\boldsymbol{I_{ac}}$ via an inverter for grid integration. As illustrated in Figure 2, the current-voltage (I-V) and power-voltage (P-V) characteristics of a PV array exhibit nonlinear behavior, influenced by varying solar irradiance and cell temperature. To optimize power extraction, a Maximum Power Point Tracking (MPPT) controller dynamically adjusts the inverter's reference voltage $\boldsymbol{V_{ref}}$ and regulates the DC voltage $\boldsymbol{V_{dc}}$ at the PV array's output.

Common MPPT techniques include the open-circuit voltage method, incremental conductance approach, ripple-based strategies, and Perturbation and Observation (P&O). Effective MPPT algorithms are critical for balancing cost and efficiency, as PV systems must maximize power output under fluctuating environmental conditions. The P&O method is widely favored for its simplicity: if an increase in PV voltage V_{pv} raises output power, subsequent perturbations continue in the same direction; conversely, a power decline triggers a reversal in voltage adjustment. This results in V_{pv} oscillating near the optimal maximum power point (MPP) voltage V_{out} . A key trade-off in P&O involves step size selection—larger steps enable faster tracking of environmental changes but introduce higher steady-state power losses, while smaller steps minimize losses but reduce responsiveness to rapid variations in irradiance or temperature [1].

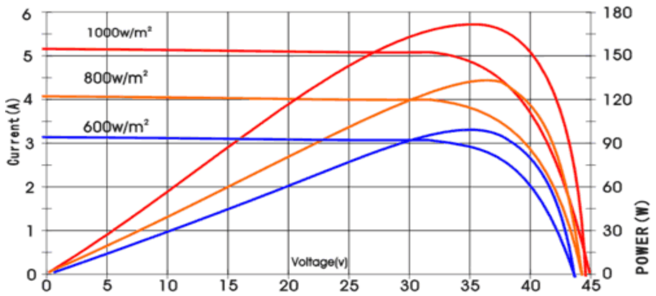


Figure 2: Power vs voltage Current Vs Voltage in PV

Design and Characterization of Solar Panel Arrays

The solar photovoltaic (PV) array exhibits nonlinear output characteristics, primarily influenced by the inherent variability of solar irradiance and temperature, as depicted in Figure 2. Since the PV array is directly interfaced with the power converter, the system is engineered to operate at the Maximum Power Point (MPP) under standard environmental conditions, such as nominal solar irradiance and temperature levels, to ensure optimal energy extraction [6].

Methodology

Tan et al. [7] proposes a detailed analytical framework to evaluate the dynamic interaction of a self-commutated inverter interfacing a solar PV array with the grid, as explored in [8, 9]. These studies posit that maintaining a constant reference voltage (V_{ref}) for the inverter is critical to achieving Maximum Power Point Tracking (MPPT) under steady-state conditions. Simulations suggest PV systems must react instantaneously (within milliseconds) to abrupt solar irradiance variations. However, experimental validation using three inverters—two commercially available—reveals inconsistencies with simulation outcomes, demonstrating substantially delayed response times in real-world scenarios. The model emphasizes accurately capturing the PV system's behavior during gradual solar irradiance shifts. Yet, under sudden, large-scale irradiance disturbances, the system exhibits nonlinear dynamics and divergent operational modes, underscoring the complexity of transient responses in practical PV configurations.

Converter Control

In this configuration, the Solar PV array interfaces with a DC-DC converter, where the array's output voltage (V_{out}) serves as the variable input voltage (V_{in}) for the converter. To regulate V_{in}, a linear control system incorporating linear compensators is developed for the PV-fed DC-DC converter. This system aims to stabilize the converter's input voltage under fluctuating solar conditions, ensuring consistent performance despite variations in V_{in} caused by changes in irradiance or temperature [10].

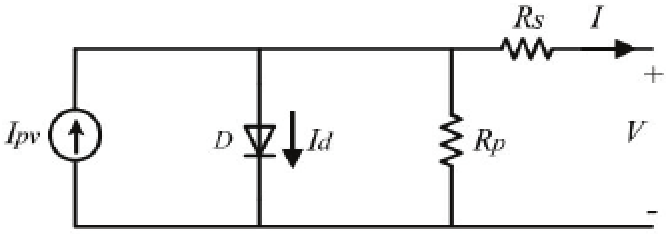


Figure 3 PV array equivalent Circuit

Dynamic Modelling and Control of Power Conditioning Units for Renewable Energy Integration

Molina and Juanico [11] highlights that grid-connected solar photovoltaic (PV) systems primarily function as distributed generation sources, aiming to deliver consistent energy to the grid while maintaining uninterrupted operation at maximum efficiency, regardless of weather fluctuations. This necessitates integrating power electronic interfaces equipped with Maximum Power Point Tracking (MPPT) controllers to ensure seamless synchronization with the AC grid. A Power Conditioning System (PCS) regulates bidirectional power exchange with the grid, enabling independent control of both active and reactive power flows. Unlike single-stage architectures, a two-stage cascaded design (DC-DC boost converter and grid-tied inverter) offers enhanced operational flexibility. This configuration allows multiple control objectives—such as voltage regulation and energy optimization—to be managed independently without modifying the PCS topology. PV arrays are typically connected in series to meet voltage requirements for grid injection, while parallel configurations adjust current output, ensuring alignment with the distribution network's energy demands.

Maximum Power Point Tracking (MPPT)

MPPT is a smart technology used in solar setups to maximize energy harvest. Solar panels generate varying power levels due to changing sunlight, temperature, or shading. Each condition has an optimal operating point (the "maximum power point") where panels produce peak efficiency. MPPT controllers, embedded in charge controllers or inverters, continuously adjust the electrical load to maintain this point.

By dynamically tweaking voltage and current (using algorithms like Perturb and Observe), MPPT ensures panels operate at their highest efficiency, even as conditions shift. For example, if clouds reduce sunlight, the controller adapts to extract the most available power. This process boosts energy capture by up to 30% compared to non-MPPT systems, making it vital for both grid-tied and off-grid installations.

Key benefits include enhanced energy yield, adaptability to environmental changes, and long-term cost savings. MPPT is particularly valuable in regions with inconsistent weather, ensuring solar systems remain efficient and effective.

Voltage Source Inverter (VSI)

The Voltage Source Inverter (VSI) as shown in **Error! Reference source not found.** is the critical element within the Power Conversion System (PCS). Constructed from semiconductors capable of being turned off (like IGBTs), these three-phase, power electronic-based devices connect in parallel to the distribution grid at the Point of Common Coupling (PCC). Their function is to generate a three-phase AC voltage output: three sinusoidal waveforms at the fundamental grid frequency, each phase-shifted by 120 degrees relative to the others. Consequently, the solar PV system effectively functions as a combined current and voltage source. VSIs are the preferred solution due to their cost-effectiveness.

The specific VSI modeled is a three-phase, three-level DC-to-AC converter utilizing Insulated Gate Bipolar Transistors (IGBTs). IGBTs are chosen for their compact size and relatively low switching losses. Professional control of the output voltage (Vout) is achieved using Pulse Width Modulation (PWM) techniques. The VSI connects to the utility grid via a delta-star step-up transformer. Additionally, second-order low-pass filters are incorporated. Together, the transformer and filters mitigate high-frequency switching harmonics produced by the VSI's PWM control, reducing potential perturbations on the distribution system [12].

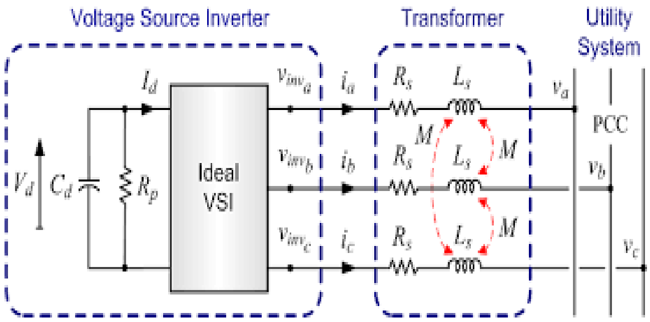


Figure 4: VSI integrated with utility

Grid Integrated with 3-phase inverter

A three-phase DC-to-AC inverter interfaces with the grid via coupling inductors (La, Lb, Lc), as depicted in Figure 4. This converter receives DC voltage and current from a Full Bridge converter and delivers active power to the AC grid. The DC link capacitor voltage (V_{link}) is regulated and maintained at a stable setpoint value (V_{link}) by a voltage controller. Concurrently, the output currents (I_a, I_b, I_c) flowing through the coupling inductors are precisely controlled by a current controller [13].

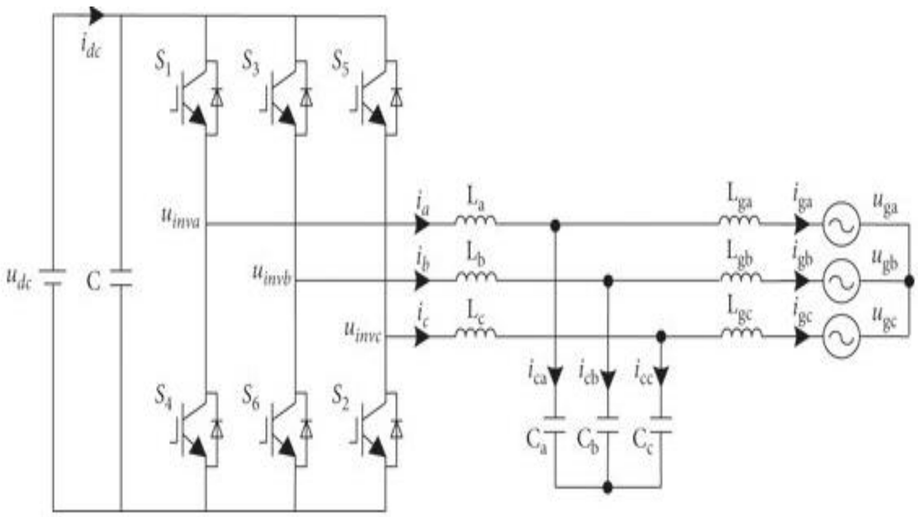


Figure 4: Grid Integrated with VSI

The equivalent circuit is provide in **Error! Reference source not found.**.

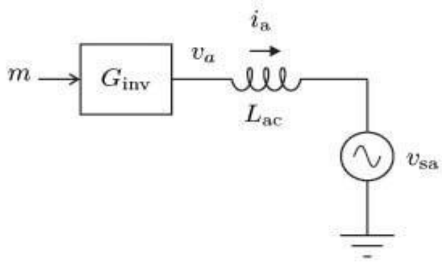


Figure 6: Equvalent circuit of 3-phase grid connected VSI

Control of the DC link voltage

In the circuit model shown in Figure 5, the DC-link capacitor is connected between two equivalent current sources representing the DC-DC converter and the DC-AC inverter. This capacitor transfers energy from the DC-DC converter to the DC-AC inverter. The capacitor voltage fluctuates (increases or decreases) based on the imbalance between the input current (from the DC-DC converter) and the output current (to the DC-AC inverter). To maintain a stable average DC-link voltage, the average input current and average output current must be equal [14, 15].

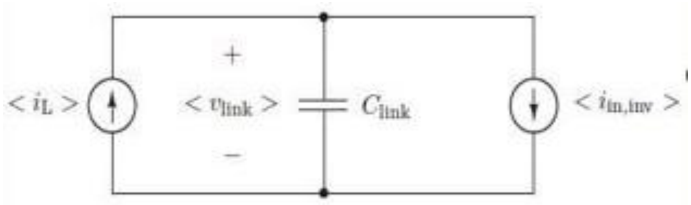


Figure 5 DC link Equivalent Circuit

DC to DC Boost Converter

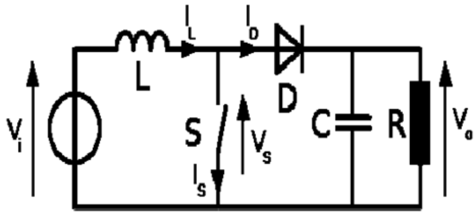


Figure 8 Boost converter

Integrating solar PV arrays into the VSI's DC bus requires dedicated power conversion to manage voltage-current disparities. This necessitates varying the PV terminal voltage to control power generation while maintaining stable DC-link voltage in the VSI. A standard unidirectional IGBT-based DC-DC boost converter is used for this purpose as shown in figure 8. The converter employs PWM to generate a chopped output voltage (Vout), regulating the average DC voltage (V_{dc}) relationship between its input and output. This ensures continuous matching of the PV array's characteristics under all climatic conditions [16].

Simulation Results and Discussion

This section presents a comparative analysis of experimental results from literature reviewed in this study. Reference [1] demonstrates the response of an experimental solar PV system to various disturbances. Figures 11(a) and 12(a) illustrate the introduced disturbances used to evaluate the model's performance. During these disturbances, Figures 11(b) and 12(b) show the active power injected into the grid by the PV unit. Simulation results (denoted by crosses) and experimental outcomes (solid lines) are compared in Figures 11(c) and 12(c), with the operational trajectory superimposed on the PV array's I-V characteristics. Figures 11(d) and 12(d) depict the reactive power generated by the PV unit.

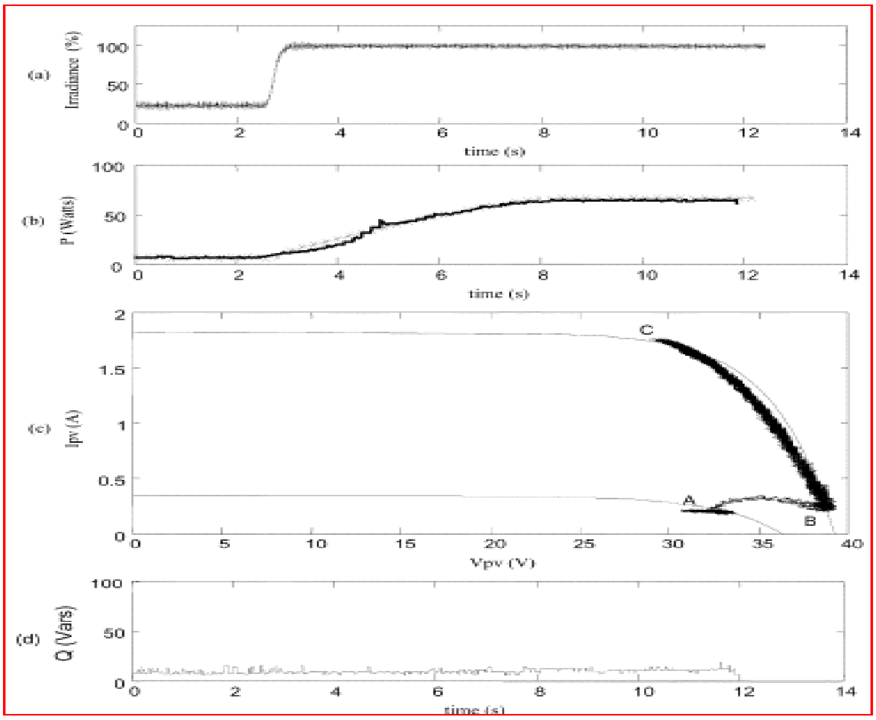


Figure 6: Transient Analysis of PV Generator Under Abrupt Solar Irradiation Surge [1]

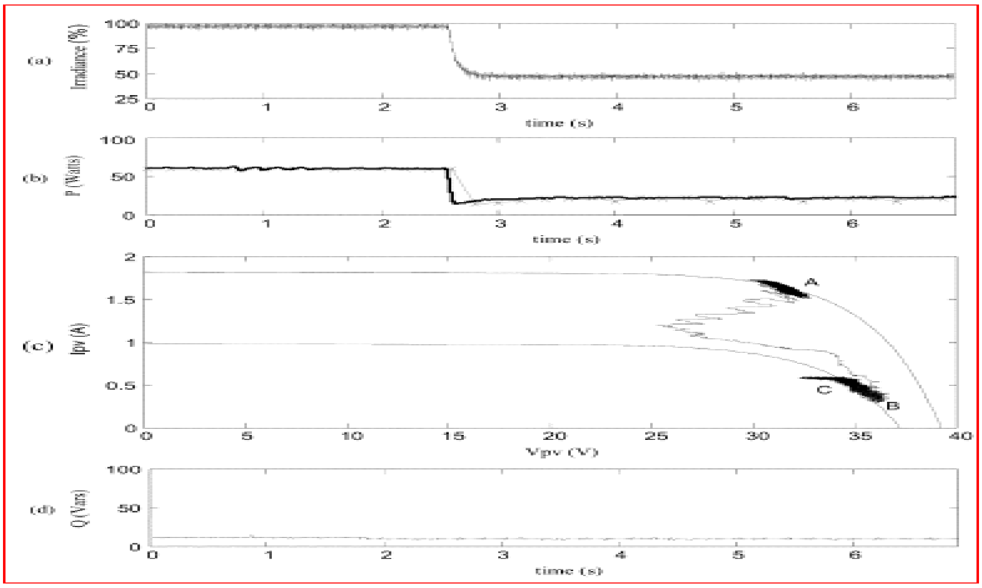
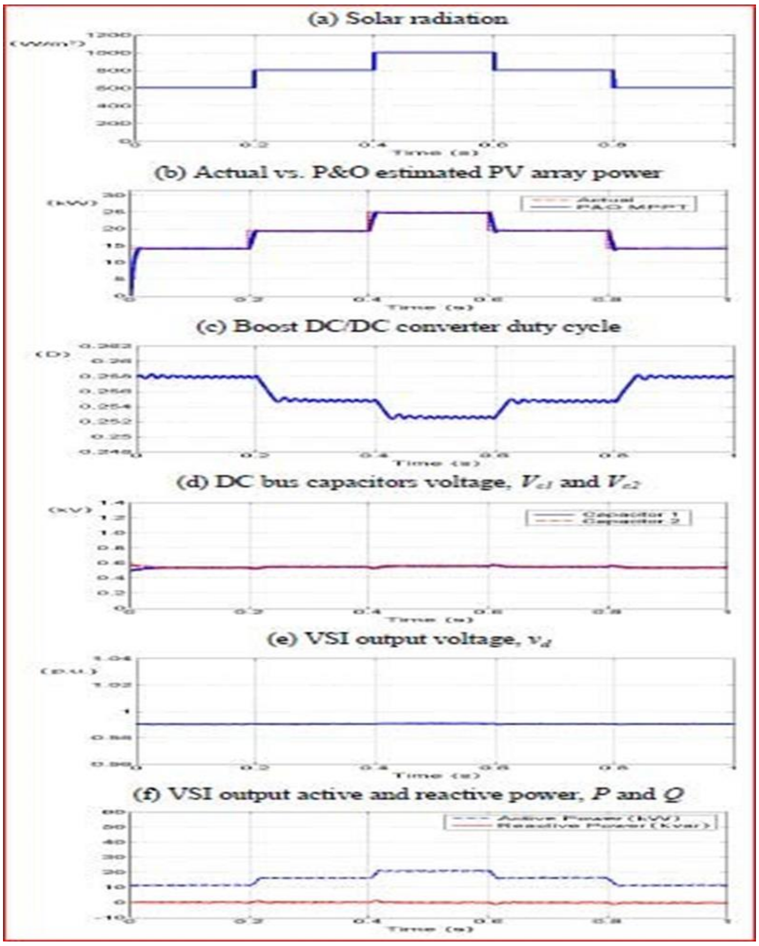


Figure 10: PV Generator Performance During Sudden AC Voltage Collapse [1]

The renewable energy-based distributed generation (RES-DG) model in reference [2] features high complexity with multiple states and nonlinear components. To minimize computational load, the electrical system employs fixed-step discretization. This approach maintains simulation accuracy comparable to continuous variable-step integration methods while significantly improving computational efficiency.



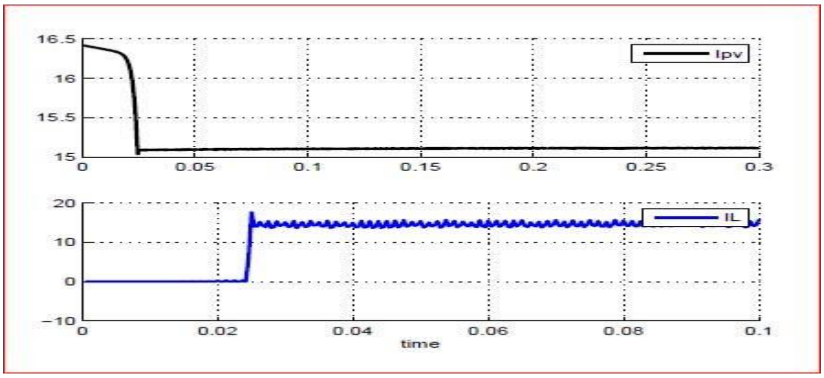


Figure 7: : Responce of the PV array current i_{pv} and the DC to DC output inductor current i_L [6]

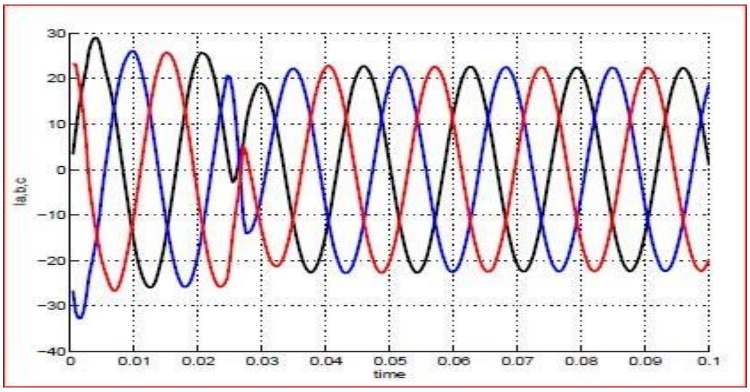


Figure 13: Three-Phase Grid Current Injection from DC-AC Inverter [8]

As established in [9], the developed models accurately characterize the dynamic performance of the purpose-built PV buck converter. This performance is validated through the converter's open-loop transfer functions, frequency response, and time-domain behavior. Results demonstrate close alignment between frequency-domain and time-domain analyses. The study confirms that the designed compensators enable rapid and precise input voltage (Vin) regulation in the DC-DC buck converter powered by a PV solar array.

Conclusion

This review paper outlines the modeling and control strategies of grid-connected converters used in photovoltaic (PV) systems. The control methods integrate a Maximum Power Point Tracking (MPPT) algorithm to optimize active power output while also supporting reactive power compensation on the distribution side. Experimental results highlight the crucial role of the MPPT in enhancing the active performance of the PV system. The dynamic system simulations demonstrate the effectiveness of the proposed multi-level control strategy and the accuracy of the detailed models developed. A small-scale PV experimental setup is utilized to validate the precision of the proposed approach.

The model effectively responds to both significant and minor variations in solar irradiance. Its performance is evaluated by comparing simulation results with experimental outcomes.

REFERENCES :

[1] N. A. Kamarzaman, C. W. J. R. Tan, and S. E. Reviews, "A comprehensive review of maximum power point tracking algorithms for photovoltaic systems," Renewable and Sustainable Energy Reviews, vol. 37, pp. 585-598, 2014.

[2] S.-K. Kim, J.-H. Jeon, C.-H. Cho, J.-B. Ahn, and S.-H. J. I. t. o. i. e. Kwon, "Dynamic modeling and control of a grid-connected hybrid generation system with versatile power transfer," IEEE transactions on industrial electronics, vol. 55, no. 4, pp. 1677-1688, 2008.

[3] Z. Shuai, Y. Li, W. Wu, C. Tu, A. Luo, and Z. J. J. I. T. o. I. E. Shen, "Divided DQ small-signal model: A new perspective for the stability analysis of three-phase grid-tied inverters," vol. 66, no. 8, pp. 6493-6504, 2018.

[4] D. G. Photovoltaics and E. J. I. s. Storage, "IEEE standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces," vol. 1547, no. 1547, p. 2018, 2018.

[5] A. Bag, B. Subudhi, and P. K. J. I. J. o. E. E. P. S. Ray, "Comparative analysis of sliding mode controller and hysteresis controller for active power filtering in a grid connected PV system," vol. 19, no. 1, p. 20170044, 2018.

[6] R. Boopathi and V. J. S. R. Indragandhi, "Enhancement of power quality in grid-connected systems using a predictive direct power controlled based PV-interfaced with multilevel inverter shunt active power filter," vol. 15, no. 1, p. 7967, 2025.

[7] Y. T. Tan, D. S. Kirschen, and N. J. I. T. o. e. c. Jenkins, "A model of PV generation suitable for stability analysis," vol. 19, no. 4, pp. 748-755, 2004.

[8] O. Wasynczuk and N. J. I. P. E. R. Anwah, "Modeling and dynamic performance of a self-commutated photovoltaic inverter system," IEEE Power Engineering Review, vol. 9, no. 9, pp. 33-34, 2007.

[9] L. Wang and Y.-H. Lin, "Dynamic stability analyses of a photovoltaic array connected to a large utility grid," in 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 00CH37077), 2000, vol. 1, pp. 476-480: IEEE.

[10] N. H. Baharudin, T. Mansur, F. A. Hamid, R. Ali, M. I. J. I. J. o. E. E. Misrun, and C. Science, "Topologies of DC-DC converter in solar PV applications," Indonesian Journal of Electrical Engineering and Computer Science vol. 8, no. 2, pp. 368-374, 2017.

[11] M. G. Molina and L. E. Juanico, "Dynamic modelling and control design of advanced photovoltaic solar system for distributed generation applications," 2010.

[12] N. Karania, M. A. AlalI, S. Di Gennaro, and J.-P. J. I. O. J. o. t. I. E. S. Barbot, "Developed AC/DC/AC converter structure based on shunt active filter and advanced modulation approach for asymmetrical cascade H-bridge multilevel inverters," vol. 4, pp. 583-602, 2023.

[13] A. Sangwongwanich, A. Abdelhakim, Y. Yang, and K. Zhou, "Control of single-phase and three-phase DC/AC converters," in Control of Power Electronic Converters and Systems: Elsevier, 2018, pp. 153-173.

[14] C. Guo, Z. Xin, J. Han, L. Hu, and B. J. F. i. E. R. Lu, "Review of the calculation of DC-link capacitor current," vol. 11, p. 1240755, 2023.

[15] P. Alemi, Y.-C. Jeung, and D.-C. J. I. T. o. I. E. Lee, "DC-link capacitance minimization in T-type three-level AC/DC/AC PWM converters," vol. 62, no. 3, pp. 1382-1391, 2014.

[16] A. F. Murtaza, M. Chiaberge, F. Spertino, J. Ahmad, and A. J. I. T. o. E. C. Ciocia, "A direct PWM voltage controller of MPPT & sizing of DC loads for photovoltaic system," vol. 33, no. 3, pp. 991-1001, 2018.