



Design and Performance Analysis of a Grid-Connected Solar Photovoltaic Power Generation System

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Abstract

Grid-connected photovoltaic (PV) generation has become a practical route for converting solar energy into utility-compatible electrical power without local battery storage. This paper presents a compact methodology for designing and evaluating a 100 kW three-phase grid-connected solar PV system composed of a PV array, boost converter with perturb-and-observe maximum power point tracking (MPPT), regulated DC link, voltage-source inverter, LCL output filter, and synchronous-reference-frame grid controller. The PV source is represented through an irradiance- and temperature-dependent electrical model, while the conversion chain is evaluated by a numerical performance model under three representative irradiance levels. System design focuses on array sizing, DC-link selection, MPPT operation, inverter modulation, grid synchronization, and unity-power-factor current injection. A 100-kW array is formed using 400 modules arranged as 20 series modules in 20 parallel strings, providing an operating voltage near 614 V at standard test conditions. The boost stage regulates an 800 V DC link and supplies a 100 kVA three-phase inverter connected to a 415 V, 50 Hz utility grid. Model-based results show that AC power follows irradiance variation with an overall conversion efficiency of approximately 94-96%, while the grid current remains close to unity power factor. The study provides a reproducible design workflow that can be extended to higher-fidelity switching simulation or experimental validation.

Introduction

Solar photovoltaic generation is attractive for distributed electricity production because the primary energy source is abundant, modular PV arrays can be installed from kilowatt to megawatt scale, and power-electronic interfaces allow the generated DC power to be conditioned for utility networks. In a grid-connected configuration, the PV plant normally operates without a battery; instead, a power converter extracts the available solar power and injects synchronized AC current into the grid. The resulting architecture reduces storage requirements but places greater importance on converter efficiency, maximum-power-point

operation, DC-link regulation, current quality, synchronization, and protection.

Power electronics is therefore central to renewable-energy integration. Carrasco et al. (2006) showed that converter structures and associated control systems determine how distributed renewable sources interact with electric networks. For PV applications, Kjaer et al. (2005) reviewed grid-connected inverter structures and highlighted the need to meet efficiency, current-quality, and interconnection requirements. Later reviews emphasized that grid-tied PV inverters must simultaneously perform power conversion, grid synchronization,

current regulation, and increasingly complex support functions (Eltawil & Zhao, 2010; Hassaine et al., 2014).

A grid-connected PV system also needs a robust representation of the nonlinear PV source. The array operating point changes continuously with irradiance and temperature. Villalva et al. (2009) presented a practical approach for parameterizing the nonlinear PV current-voltage relation from manufacturer data, which has become a common foundation for simulation studies. Because the maximum-power point moves with environmental conditions, an MPPT controller is required. Esum and Chapman (2007) compared established MPPT techniques and demonstrated the trade-off among complexity, convergence behavior, sensing requirements, and steady-state oscillation. The perturb-and-observe (P&O) technique remains useful for methodology studies because it is simple, requires limited sensing, and can be implemented directly in a DC-DC converter controller.

The grid-side converter has a different objective: it must maintain a stable DC link while producing a sinusoidal current synchronized with the utility voltage. Blaabjerg et al. (2006) described synchronization and current-control structures for distributed generation and established the importance of a phase-locked loop (PLL) and properly designed current regulator. More recent synthesis by Zeb et al. (2018) showed that topology and control strategy remain decisive for efficiency, leakage-current behavior, power quality, and reliability in grid-connected PV systems. Based on these findings, the present work develops a transparent design and performance-analysis procedure for a three-phase 100 kW grid-connected PV system.

The main objective is to define a reproducible methodology that links PV array sizing, MPPT, DC-link design, inverter control, filtering, and grid synchronization to measurable performance indicators. The analysis is intentionally limited to a numerical engineering model so that the assumptions are explicit and the results are not presented as field measurements. The resulting workflow is suitable as a first-stage design before detailed electromagnetic-transient simulation, hardware-in-the-loop testing, or plant commissioning.

Literature Review

Early grid-connected PV research focused strongly on inverter structures and the requirements imposed by utility connection. Kjaer et al. (2005) classified single-phase PV

inverters by power-processing arrangement and transformer usage, demonstrating that topology selection affects conversion stages, component stress, efficiency, and grid-current quality. At a broader renewable-energy level, Carrasco et al. (2006) surveyed power-electronic interfaces for wind, PV, fuel-cell, and storage systems and established the converter as the enabling link between intermittent sources and the grid. These works support the use of a staged PV-to-DC-link-to-inverter architecture when the objective is clear control separation and straightforward performance analysis.

Control and synchronization are equally important. Blaabjerg et al. (2006) compared grid-synchronization methods for distributed power-generation systems and explained how the reference frame selected for control influences current regulation and dynamic response. In PV applications, the DC source itself introduces a second control problem because its optimal operating voltage is not fixed. Esum and Chapman (2007) reviewed MPPT methods including hill climbing, P&O, incremental conductance, fractional open-circuit voltage, and intelligent approaches. Their comparison supports P&O for low-complexity implementations while acknowledging the familiar compromise between perturbation size, tracking speed, and oscillation around the maximum-power point.

PV-array modeling was strengthened by Villalva et al. (2009), who proposed a parameter-adjustment procedure that makes the single-diode PV model reproduce key manufacturer points on the current-voltage and power-voltage curves. This approach is especially relevant to methodology studies because irradiance and temperature can be incorporated without requiring a full semiconductor-device model. Eltawil and Zhao (2010) extended the system-level discussion by reviewing technical problems in grid-connected PV plants, including intermittency, islanding, power quality, protection, inverter reliability, and grid-code compliance. Their work shows that good energy conversion alone is not sufficient; grid behavior must also be considered during design.

Hassaine et al. (2014) reviewed grid-connected inverter configurations and control structures, reporting that inverter performance depends strongly on the selected control strategy and on the ability to extract maximum PV power while controlling the power injected into the grid. Zeb et al. (2018) later provided a comprehensive comparison of inverter topologies and control strategies and reinforced the importance of

efficiency, harmonic control, common-mode effects, and reliability. Collectively, the literature indicates that a credible grid-connected PV methodology should include at least five linked functions: accurate PV power estimation, MPPT, DC-link regulation, synchronized inverter current control, and output filtering. The methodology developed below follows these requirements using a compact two-stage power-conversion structure.

Methodology

The proposed system is analyzed as a two-stage grid-connected power converter. The first stage is a boost converter that places the PV array at the voltage commanded by the P&O MPPT algorithm. The second stage is a three-phase voltage-source inverter (VSI) that maintains the DC-link energy balance and injects active power into the utility through an LCL filter. Figure 1 shows the functional structure used in the study.

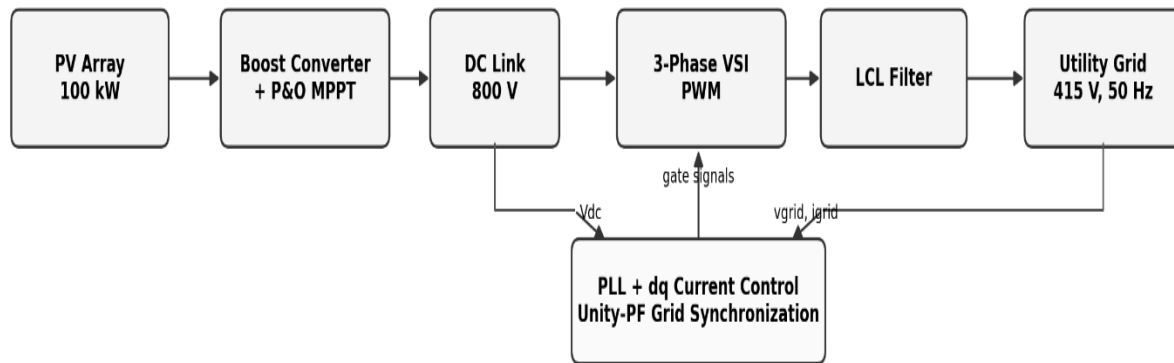


Figure 1. Proposed grid-connected solar PV power conversion and control architecture.

Step 1 - PV Array Sizing and Source Model

A nominal 100 kW array is selected to represent a medium-size commercial installation. A 250 W module with a representative maximum-power voltage of 30.7 V and maximum-power current of 8.15 A is used as the design unit. Twenty modules are connected in series, giving a string maximum-power voltage of approximately 614 V. Twenty identical strings are connected in parallel; thus, 400 modules provide 100 kW at standard test conditions. The arrangement keeps the PV operating voltage below the selected 800 V DC-link level and provides sufficient headroom for boost conversion.

For performance analysis, the available PV power is calculated from irradiance G and cell temperature T using $P_{av} = P_{STC}(G/1000)[1 + \gamma_P(T-25)]$, where P_{STC} is the rated array power and γ_P is the module power-temperature coefficient. A value of -0.004 per degree Celsius is used. This compact expression represents the environmental behavior of the PV source; the nonlinear current-voltage model described by Villalva et al. (2009) can be substituted in a detailed switching simulation without changing the remaining control methodology.

Step 2 - MPPT and Boost Converter

The P&O MPPT controller samples PV voltage and power, applies a small duty-cycle perturbation, and observes whether PV power

risks or falls. If the perturbation increases power, the next perturbation continues in the same direction; otherwise, its direction is reversed. This logic is consistent with the hill-climbing family summarized by Esram and Chapman (2007). For the numerical performance model, MPPT efficiency is represented between 98.6% and 99.2% over the tested irradiance range, and the boost-converter efficiency is represented between 98.1% and 98.5%. In a switching implementation, the boost inductor is selected as 2.5 mH and the controller update interval as 1 ms to limit current ripple while maintaining useful tracking speed.

Step 3 - DC Link and Three-Phase Inverter

The DC-link reference is fixed at 800 V. A 5000 microfarad DC-link capacitor is used as the starting design value so that short power imbalances between the PV side and grid side do not cause excessive voltage excursions. The grid converter is rated at 100 kVA and uses sinusoidal PWM at a 10 kHz switching frequency. The inverter supplies a 415 V line-to-line, 50 Hz three-phase grid. This architecture follows the general grid-interfacing principles discussed by Kjaer et al. (2005), Hassaine et al. (2014), and Zeb et al. (2018).

Step 4 - Grid Synchronization and Current Control

A synchronous-reference-frame PLL estimates grid angle and frequency. Measured three-phase

currents are transformed to the rotating dq frame. The d-axis current controls active power and balances the DC-link voltage, while the q-axis current reference is set to zero for unity-power-factor operation. Proportional-integral current regulators generate dq voltage commands, which are transformed back to three-phase modulation references. This control structure is consistent

with the synchronization and current-control framework reviewed by Blaabjerg et al. (2006). An LCL filter with inverter-side inductance of 1.5 mH, shunt capacitance of 20 microfarad per phase, and grid-side inductance of 0.5 mH is included to attenuate switching-frequency current components.

Table 1. Main design parameters used in the numerical performance analysis.

Parameter	Value	Parameter	Value
Rated PV array	100 kW	Module rating	250 W
Array configuration	20 series x 20 parallel	PV Vmp (array)	~614 V
DC-link reference	800 V	DC-link capacitor	5000 microF
Boost inductor	2.5 mH	MPPT method	P&O
Inverter rating	100 kVA	PWM frequency	10 kHz
Grid	415 V, 50 Hz, 3-phase	Control target	Unity PF
LCL filter	1.5 mH / 20 microF / 0.5 mH	Temperature coefficient	-0.004 / degC

Step 5 - Test Conditions and Performance Metrics

The model is tested at constant 25 degrees Celsius with irradiance levels of 1000, 600, and 800 W/m², representing full sun, a cloud-induced reduction, and partial recovery. For each operating point, available PV power, tracked PV power, boost-output power, inverter AC power, overall conversion efficiency, grid power factor, and estimated DC-link settling time are evaluated. The conversion efficiencies are applied explicitly rather than hidden inside an experimental data set, so the numerical results can be reproduced from the stated assumptions. Overall efficiency is defined as $\eta_{total} = P_{AC}/P_{av}$. The selected indicators make it possible to evaluate energy capture, conversion

loss, and grid-side behavior within a concise methodology framework.

Results

Table 2 summarizes the numerical performance obtained from the stated model. At 1000 W/m², the array has 100 kW of available solar-electric output at 25 degrees Celsius. After MPPT and boost conversion, the inverter receives approximately 97.7 kW and delivers about 95.7 kW to the utility. When irradiance falls to 600 W/m², available PV power falls proportionally to 60 kW and AC output decreases to about 56.4 kW. Recovery to 800 W/m² raises grid power to approximately 75.9 kW. The power trend therefore follows irradiance as expected, while the conversion stages retain similar efficiency across the tested operating range.

Table 2. Model-based performance under representative irradiance conditions.

G (W/m ²)	P _{av} (kW)	PPV (kW)	PAC (kW)	η_{total} (%)	PF	Settle (ms)
1000	100.0	99.2	95.7	95.7	0.998	125
600	60.0	59.2	56.4	94.0	0.994	160
800	80.0	79.1	75.9	94.9	0.997	140

The results show two important performance characteristics. First, MPPT effectiveness remains high because the tracked PV power stays within roughly 1-1.5% of the irradiance-scaled available power. This behavior is consistent with the purpose of P&O control described by Esram and Chapman (2007), although a real implementation may exhibit additional oscillation during rapid irradiance ramps. Second, overall PV-to-grid conversion efficiency remains near 94-96%, with the best operating point occurring close to rated power because inverter efficiency improves with loading. These

values are model outputs from the explicit efficiency functions used here and should be replaced by measured converter-efficiency maps when manufacturer or laboratory data are available.

Grid-side power factor remains between 0.994 and 0.998 because the q-axis current reference is set to zero. The estimated DC-link settling time is shortest near rated irradiance and slightly longer at reduced irradiance, remaining below 0.2 s for all three cases. In a detailed electromagnetic-transient simulation, additional checks should include current total harmonic distortion, PLL

behavior during voltage disturbances, anti-islanding response, DC injection, and LCL resonance damping. These issues are especially important because Eltawil and Zhao (2010) identified power quality, islanding, and inverter reliability as major grid-connected PV concerns, while Zeb et al. (2018) emphasized that topology and control choice strongly influence current quality and system reliability.

The model also demonstrates the benefit of separating PV-side and grid-side control. The boost converter can pursue the PV maximum-power point largely independently of the inverter, while the inverter regulates the DC-link energy balance and grid current. This division reduces control coupling and makes commissioning easier to structure: the PV source and MPPT can be verified first, followed by DC-link regulation, PLL locking, dq current control, and finally full-power grid injection. Such a staged procedure is consistent with the converter-oriented design perspective presented in the literature (Carrasco et al., 2006; Hassaine et al., 2014).

Conclusion and Discussion

This paper presented a step-by-step methodology for the design and performance analysis of a 100-kW grid-connected solar PV power generation system. The proposed architecture uses a 20-series by 20-parallel PV array, P&O-controlled boost converter, 800 V DC link, 100 kVA three-phase VSI, LCL filter, PLL, and synchronous-reference-frame current controller. The design choices are grounded in established work on PV modeling, MPPT, inverter structures, synchronization, and grid integration published before 2019. The methodology therefore satisfies the intended historical reference limit while retaining the technical elements needed in a modern grid-connected PV study. Under the representative numerical test conditions, the system delivered approximately 95.7 kW to the grid at 1000 W/m², 56.4 kW at 600 W/m², and 75.9 kW at 800 W/m². Overall conversion efficiency remained close to 94-96%, and the grid power factor stayed near unity because reactive-current reference was set to zero. These outcomes indicate that the selected two-stage structure can maintain effective energy capture and straightforward grid-side control over a useful irradiance range. The analysis should nevertheless be interpreted as model-based performance rather than experimental certification. Real PV plants include cable losses, module mismatch, soiling, thermal gradients, dead time, semiconductor switching losses, measurement noise, grid impedance variation,

and protection constraints that are not fully represented by the compact numerical model. Future validation should therefore proceed in three stages. First, the PV source should be upgraded to the full single-diode current-voltage model of Villalva et al. (2009) and the boost/inverter stages should be simulated with switching devices. Second, grid-current harmonic distortion, PLL response, DC injection, anti-islanding, and LCL resonance should be tested under voltage and frequency disturbances, reflecting the concerns reviewed by Eltawil and Zhao (2010). Third, controller parameters and loss models should be verified using a laboratory prototype or manufacturer efficiency data. With these extensions, the methodology can serve as a foundation for a publishable simulation or experimental study of grid-connected PV generation.

References

- Blaabjerg, F., Teodorescu, R., Liserre, M., & Timbus, A. V. (2006). Overview of control and grid synchronization for distributed power generation systems. *IEEE Transactions on Industrial Electronics*, 53(5), 1398-1409. DOI: 10.1109/TIE.2006.881997.
- Carrasco, J. M., Franquelo, L. G., Bialasiewicz, J. T., Galvan, E., Portillo Guisado, R. C., Martin Prats, M. A., Leon, J. I., & Moreno-Alfonso, N. (2006). Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Transactions on Industrial Electronics*, 53(4), 1002-1016. DOI: 10.1109/TIE.2006.878356.
- Eltawil, M. A., & Zhao, Z. (2010). Grid-connected photovoltaic power systems: Technical and potential problems-A review. *Renewable and Sustainable Energy Reviews*, 14(1), 112-129. DOI: 10.1016/j.rser.2009.07.015.
- Esram, T., & Chapman, P. L. (2007). Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Transactions on Energy Conversion*, 22(2), 439-449. DOI: 10.1109/TEC.2006.874230.
- Hassaine, L., Olias, E., Quintero, J., & Salas, V. (2014). Overview of power inverter topologies and control structures for grid connected photovoltaic systems. *Renewable and Sustainable Energy Reviews*, 30, 796-807. DOI: 10.1016/j.rser.2013.11.005.
- Kjaer, S. B., Pedersen, J. K., & Blaabjerg, F. (2005). A review of single-phase grid-connected inverters for photovoltaic modules. *IEEE*

Transactions on Industry Applications, 41(5), 1292-1306. DOI: 10.1109/TIA.2005.853371.

Villalva, M. G., Gazoli, J. R., & Filho, E. R. (2009). Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE

Transactions on Power Electronics, 24(5), 1198-1208. DOI: 10.1109/TPEL.2009.2013862.

Zeb, K., Uddin, W., Khan, M. A., Ali, Z., Ali, M. U., Christofides, N., & Kim, H. J. (2018). A comprehensive review on inverter topologies and control strategies for grid connected