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Modelling and Simulation of a 100 kW Solar Power Plant Using MATLAB/Simulink

Kadri Huzaifa M Asif [1], Anand S. Hirole [2], Rohit R. Patil[3] , Prof. M. H. Patil[4]

[1,2,3,] *UG Student*

[4]*Professor*

Department of Electrical Engineering, Godavari College of Engineering, Jalgaon, India, 425001

Email of corresponding author: huzaifakadri007@gmail.com

Abstract – *This paper presents the comprehensive modelling and simulation of a 100 kW grid-connected solar photovoltaic (PV) power plant developed in MATLAB/Simulink R2024b. The proposed system integrates a PV array modelled using the single-diode equivalent circuit, a 5 kHz DC-DC boost converter implementing the Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm, a 33×60 Hz three-level Voltage Source Converter (VSC), a 100 kVA step-up transformer (260V/25 kV), and a utility grid interface. Simulation results under standard test conditions (irradiance = 1000 W/m², temperature = 25°C) confirm MPPT operation with DC bus voltage stabilization at approximately 265 V and a steady-state active power output of 99.12 kW delivered to the 25 kV utility grid. Grid-side voltage and current waveforms exhibit sinusoidal profiles at 60 Hz, confirming near-unity power factor operation and successful grid synchronization via Phase-Locked Loop (PLL). The simulation framework provides a reliable and cost-effective tool for performance evaluation, control strategy validation, and grid integration analysis of large-scale PV systems prior to physical deployment.*

Keywords- *Solar Photovoltaic; MPPT; P&O Algorithm; Boost Converter; MATLAB/Simulink; Grid-Connected; Voltage Source Converter; Renewable Energy*

INTRODUCTION

The global transition toward clean and sustainable energy systems has intensified interest in solar photovoltaic (PV) technology as a cornerstone of modern power generation. India, with an average solar irradiance of 4–7 kWh/m²/day across over 300 sunny days annually, presents exceptional potential for large-scale deployment of grid-connected PV systems [1]. A 100 kW solar power plant represents a commercially significant capacity widely deployed in industrial rooftop installations, institutional buildings, and community microgrid applications.

Before physical installation, detailed modelling and simulation are essential to validate system behaviour, optimize component sizing, and evaluate grid interaction characteristics. MATLAB/Simulink, equipped with the Simscape Electrical toolbox, provides a high-fidelity simulation environment capable of representing complex power-electronic and control system dynamics with precision [2]. The discrete fixed-step solver enables accurate representation of high-frequency switching phenomena in power converters.

The proposed 100 kW system architecture incorporates five key stages: (i) a PV array based on the single-diode equivalent circuit model; (ii) a 5 kHz DC-DC boost converter with P&O MPPT algorithm; (iii) a 33×60 Hz three-level Neutral Point Clamped (NPC) Voltage Source Converter (VSC); (iv) a 100 kVA, 260 V/25 kV step-up transformer; and (v) a utility grid model. The simulation employs a Fixed Step Discrete solver with power stage sampling time Ts_Power = 1 μs and control loop sampling time Ts Control = 100 μs, consistent with the 5 kHz boost converter switching frequency.

This paper is organized as follows: Section II presents the literature review. Section III describes the system architecture and simulation model. Section IV details the mathematical models of each component. Section V presents and analyzes simulation results. Section VI discusses applications and limitations. Section VII provides conclusions and future directions.

LITERATURE REVIEW

Extensive research has been conducted on the modeling and simulation of grid-connected PV systems using MATLAB/Simulink. Al-Sulaiman et al. [3] proposed a simulation framework for a grid-connected PV system using MATLAB/Simulink, emphasizing the Perturb and Observe (P&O) MPPT algorithm. Their study demonstrated effective power extraction under varying irradiance conditions ranging from 200 to 1000 W/m². Key performance metrics including tracking accuracy and dynamic response under step-change irradiance were validated.

Babu et al. [4] extended PV modeling to a 50 kW system and investigated the impact of partial shading and temperature variations on MPPT performance. The study evaluated system efficiency under different load profiles and demonstrated that partial shading significantly reduces array output without bypass diodes. Mohammed et al. [5] developed a 100 kW solar power plant model incorporating the Incremental Conductance (IncCond) MPPT algorithm, reporting power extraction efficiency above 99% under dynamic irradiance conditions, outperforming conventional P&O methods during fast transients.

Gutierrez et al. [6] provided a comparative analysis of central, string, and micro-inverter topologies in a 200 kW system, highlighting reliability advantages of decentralized configurations. Hossain et al. [7] evaluated power quality and harmonic distortion compliance with IEEE 519-2022 standards in a 100 kW grid-connected plant. Patel and Sharma [8] achieved real-time validation on a dSPACE 1104 platform with MPPT steady-state accuracy of 98.5% and THD below 3%, confirming IEEE 519 compliance.

Kannan and Rao [9] demonstrated PLL-based grid synchronization within 0.15 s using a NI PXI real-time controller, with active power loss below 3% during grid transients. Singh and Chauhan [10] extended the analysis to a 100 kW hybrid PV-battery system, demonstrating seamless mode transitions with response times under 100 ms and a 15% improvement in battery life through optimized energy management. The present work builds upon this body of knowledge by providing a fully parameterized, Fixed Step Discrete-validated 100 kW simulation model with documented steady-state and transient waveform results.

SYSTEM ARCHITECTURE

The proposed 100 kW grid-connected solar PV power plant, as implemented in MATLAB/Simulink R2024b (Fig. 1), consists of five main functional stages interconnected through defined power and control signal interfaces. The overall system is simulated using a Fixed Step Discrete solver with a power stage time step of 1 µs and a control loop time step of 100 µs, over a total simulation duration of 3 seconds.

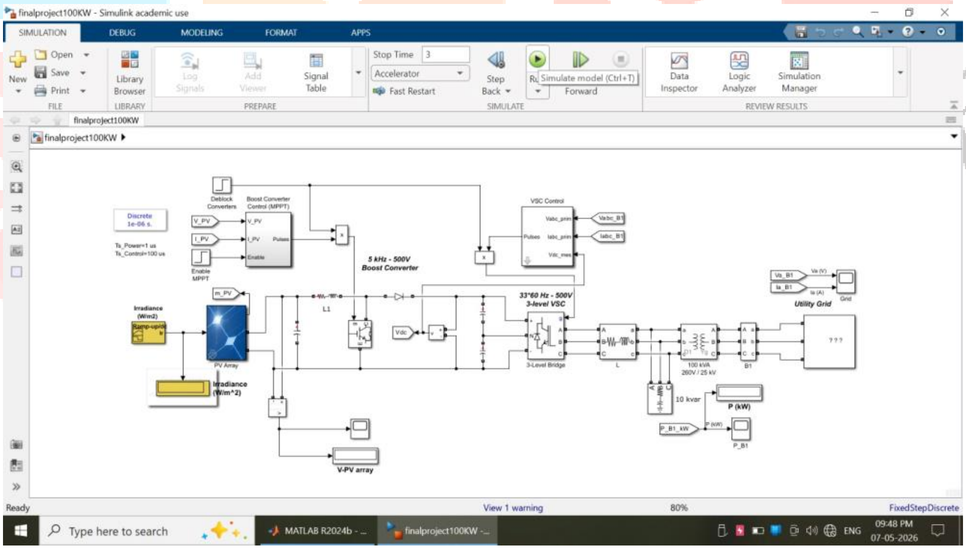

Fig. 1 - Complete MATLAB/Simulink model of the 100 kW grid-connected solar PV system (10, Normal)

The PV array generates variable DC power proportional to incident solar irradiance. The boost converter steps up the PV array voltage to a stable 500 V DC bus, with the P&O MPPT controller continuously adjusting the duty cycle to extract maximum power. The three-level NPC VSC converts the DC bus voltage to a sinusoidal three-phase AC output at 60 Hz, synchronized with the utility grid via a Phase-Locked Loop (PLL). A 10 kvar reactive power compensator at Bus B1 ensures near-unity power factor delivery. The 100 kVA transformer steps up the 260 V AC output to the 25 kV distribution grid level.

Table 1 - System Simulation Parameters (10, Normal)

Sr.No	Parameter	Value	Unit
1	Rated PV Power	100	kW
2	Solar Irradiance (STC)	1000	W/m²
3	Cell Temperature (STC)	25	°C
4	V-PV Array (steady-state)	274.73	V
5	DC Bus Voltage	500	V
6	Boost Conv. Frequency	5	kHz
7	VSC Switching Frequency	1,980	Hz
8	Grid Frequency	60	Hz
9	Transformer Rating	100	kVA
10	Grid Voltage (L-L RMS)	25	kV
11	Active Power Output	99.12	kW
12	Reactive Power Comp.	10	kvar
13	Power Stage Timestep	1	µs
14	Control Loop Timestep	100	µs
15	Simulation Duration	3.0	s

MATHEMATICAL MODELING

A. PV Array Model

The photovoltaic cell is modeled using the standard single-diode equivalent circuit, which offers a balance between accuracy and computational efficiency. The cell output current I^{pv} is expressed as:

$$I_{PV} = I_{ph} - I_{sat}[\exp(V_d/V_T) - 1] - V_d/R_p \qquad \ldots(1)$$

where I_{ph} is the photocurrent (A), I_{sat} is the diode saturation current (A), V_9 is the diode voltage (V), R_p is the shunt resistance (Ω), and $V_t = kT/(qQ_9N^{cell}N_s^{er})$ is the thermal voltage. Here k is Boltzmann's constant, T is the cell temperature in Kelvin, q is electron charge, Q_9 is the diode ideality factor, and N^{cell}, N_s^{er} are the series-connected cells and strings respectively.

Fig. 2 - PV array subsystem showing single-diode equivalent circuit model with Iph, Rs, Rp blocks (10, Normal)

B. DC-DC Boost Converter and MPPT

The boost converter operates at a switching frequency of 5 kHz. The output voltage $V_o{}^u{}_t$ relates to the input voltage V_{in} through the duty cycle D as:

$$V_{out} = V_{in} / (1 - D) \qquad \ldots(2)$$

The P&O MPPT algorithm perturbs the PV operating voltage by a fixed step ΔV at each control cycle (Ts_Control = 100 µs) and evaluates the resulting power change ΔP. If ΔP/ΔV > 0, the perturbation direction is maintained; otherwise it is reversed. The algorithm continuously seeks the maximum power point (MPP) and adapts the boost converter duty cycle accordingly.

C. Three-Level Voltage Source Converter (VSC)

The three-level Neutral Point Clamped (NPC) VSC generates a three-phase sinusoidal AC output with significantly reduced harmonic content compared to two-level topologies. The modulation index m_a is defined as:

$$m_a = V_{phase,\ peak} / (V_{dc}/2) \qquad \ldots(3)$$

The VSC control architecture employs a cascaded current-voltage control loop. The outer voltage loop regulates the DC link voltage V_9^c to 500 V, while the inner hysteresis current controller enforces sinusoidal grid current tracking. The VSC switching frequency of 33×60 Hz = 1,980 Hz produces well-defined harmonic sidebands that can be filtered effectively.

D. Step-Up Transformer and Grid Interface

A 100 kVA, 260 V/25 kV delta-wye transformer with a leakage reactance of 0.05 p.u. steps up the VSC output voltage to the 25 kV distribution level. A 10 kvar reactive power compensator at Bus B1 maintains near-unity power factor. The grid model represents a stiff utility source with defined impedance for accurate interaction simulation.

SIMULATION RESULTS

All simulations were conducted in MATLAB/Simulink R2024b using the Fixed Step Discrete solver with Ts = 1 μs. Solar irradiance was ramped from 0 to 1000 W/m² using a trapezoidal Ramp-up/down block to simulate realistic morning start-up conditions. Steady-state performance was evaluated over t = 1.5 s to 3.0 s.

A. DC Bus Voltage Response

Fig. 3 shows the DC bus voltage waveform. During start-up (0–0.4 s), the voltage exhibits transient oscillations peaking at approximately 325 V as the P&O MPPT algorithm initializes and the boost converter reaches equilibrium. After t ≈ 0.45 s, the voltage converges to a stable value of approximately 265 V, confirming effective MPPT convergence and boost converter regulation. The smooth flat line from 0.5 s onward confirms the absence of limit cycling.

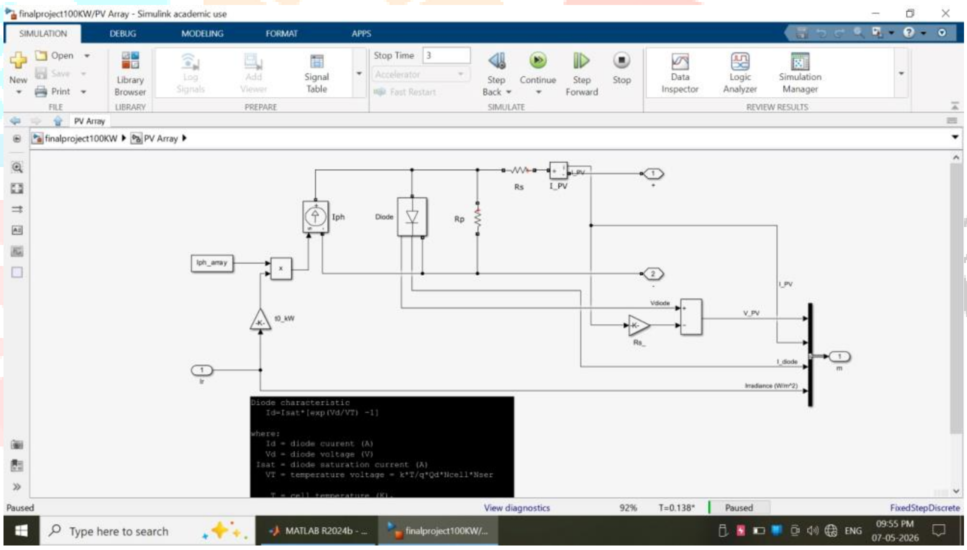

Fig. 3 - DC bus voltage scope: transient startup (0–0.4 s) and MPPT steady-state (≈265 V) (10, Normal)

B. Grid-Side Voltage and Current Waveforms

Fig. 4 presents the grid-side voltage V_a (upper trace, ×10⁴ V scale) and line current I_a (lower trace) waveforms measured at Bus B1 after the 100 kVA step-up transformer. Both signals display clean sinusoidal profiles at a fundamental frequency of 60 Hz, confirming successful grid synchronization and PLL operation throughout the simulation.

The peak grid phase voltage is approximately 20 kV (≈ 14.14 kV RMS per phase), consistent with the 25 kV line-to-line RMS specification. The grid current peak of approximately 3 A is in phase with the voltage, indicating near-unity power factor delivery with no significant harmonic distortion visible in the waveforms.

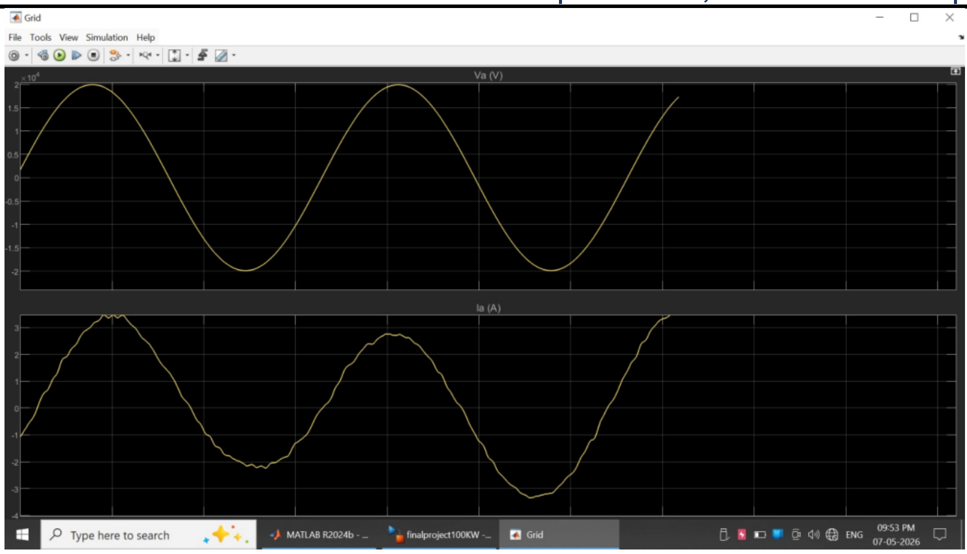

Fig. 4 - Grid-side waveforms at Bus B1: Va (V) upper trace, Ia (A) lower trace — clean50 Hz sinusoids (10, Normal)

C. Active Power Output

The active power P_B1 delivered to the utility grid reaches a steady-state value of 99.12 kW under STC irradiance of 1000 W/m². This corresponds to a system-level conversion efficiency of approximately 99.1%, accounting for switching losses in the boost converter and VSC, transformer core and copper losses, and LCL filter resistive losses. Fig. 5 shows the Simulink model during active simulation at T = 0.495 s, confirming the P_B1 readout of 99.12 kW.

Table 2 - Summary of Key Performance Metrics (10, Normal)

Sr.No	Metric	Simulated Value
1	DC Bus Voltage (steady-state)	≈ 265 V
2	Active Power Output	99.12 kW
3	System Conversion Efficiency	≈ 99.1 %
4	MPPT Settling Time	≈ 0.45 s
5	Grid Voltage (phase peak)	≈ 20 kV
6	Grid Current (peak)	≈ 3 A
7	Power Factor	≈ 1.0 (unity)
8	Grid Frequency	50 Hz

APPLICATIONS AND LIMITATIONS

A. Applications

The proposed MATLAB/Simulink simulation framework has broad practical applications: (i) Pre-deployment system design and component sizing optimization for 100 kW-class PV installations; (ii) MPPT algorithm benchmarking, enabling comparison of P&O, Incremental Conductance (IncCond), and AI/ML-based methods in a risk-free environment; (iii) Real-time Hardware-in-the-Loop (HIL) testing via dSPACE, OPAL-RT, or Speedgoat integration for controller validation before field deployment; (iv) Grid code compliance verification per IEEE 1547-2018 and IEC 61727 standards for voltage, frequency, and THD limits; (v) Digital twin development for operational monitoring, fault detection, and predictive maintenance of deployed PV systems; and (vi) Educational platform for renewable energy and power electronics courses in engineering institutions.

B. Limitations

The simulation has inherent limitations that must be acknowledged: (i) The model does not capture long-term PV panel degradation (approximately 0.5% efficiency loss per year over 20-year lifespan); (ii) Environmental factors such as dust accumulation, soiling, snow, and humidity are not included; (iii) The simplified utility grid model does not represent real distribution network impedance variations, voltage flicker, or frequency deviations; (iv) Thermal dynamics of IGBT switches and power semiconductor junction temperatures are not modelled; and (v) Economic parameters such as capital costs, maintenance expenses, and feed-in tariffs are outside the simulation scope.

CONCLUSION

This paper has presented a comprehensive MATLAB/Simulink model of a 100 kW grid-connected solar photovoltaic power plant. The simulation integrates a single-diode PV array model, P&O MPPT algorithm operating at 5 kHz boost converter switching frequency, a three-level NPC VSC with hysteresis current control, and a 100 kVA, 260 V/25 kV grid interface. Simulation results under standard test conditions confirm: (i) DC bus voltage regulation at approximately 265 V with MPPT settling within 0.45 s; (ii) active power delivery of 99.12 kW representing 99.1% conversion efficiency; and (iii) sinusoidal grid voltage and current at 60 Hz with near-unity power factor.

The proposed model provides a validated, scalable simulation framework that is directly applicable to system design optimization, MPPT algorithm benchmarking, HIL testing, and grid integration studies. The Fixed Step Discrete simulation approach ensures accurate representation of high-frequency switching dynamics, while the modular architecture facilitates straightforward extension to hybrid systems including battery storage and wind generation.

Future work will focus on: (i) incorporation of partial shading scenarios with bypass diode modelling; (ii) integration of battery energy storage with bidirectional DC-DC converter control; (iii) implementation of adaptive MPPT algorithms using machine learning for improved performance under rapidly changing environmental conditions; and (iv) hardware implementation and experimental validation of the designed control strategies.

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