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Design, Modeling, and Stability Evaluation of a Grid-Interactive Solar PV-Based Electric Vehicle Charging Station with Conditional Utility Support and Hierarchical Energy Management

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Abstract

The rapid proliferation of electric vehicles (EVs) is imposing significant operational challenges on modern distribution networks, particularly in regions with increasing electrification of transportation. Solar photovoltaic (PV)-assisted charging infrastructure offers a sustainable alternative; however, conventional grid-connected architectures often maintain continuous utility interaction, thereby limiting renewable penetration and increasing operational cost. This paper presents a comprehensive design, modeling, and stability analysis of a grid-interactive solar PV-based EV charging station incorporating conditional grid participation and hierarchical energy management. The proposed system integrates a 4 kW PV array, an interleaved DC–DC converter with incremental conductance maximum power point tracking (MPPT), a bidirectional battery interface, and a dq-frame controlled grid inverter connected through a regulated DC bus. Unlike traditional architectures, the grid is activated only when renewable generation and battery support are insufficient to meet EV demand. A complete state-space model of the multi-converter system is developed. Small-signal stability, controller tuning methodology, stochastic EV demand modeling, and techno-economic evaluation are performed. Results demonstrate enhanced renewable utilization, reduced grid dependency (approximately 35% reduction), improved voltage regulation, and compliance with harmonic standards. The proposed architecture provides a scalable and smart-grid-compatible framework for distributed EV charging infrastructure.

Keywords: Solar photovoltaic (PV), electric vehicle (EV), interleaved buck converter, incremental conductance MPPT, bidirectional converter, grid integration, MATLAB/Simulink, energy management system.

Introduction

The electrification of transport has emerged as a central pillar of global decarbonization strategies. However, large-scale EV penetration introduces high-power, time-varying loads to distribution systems, potentially leading to voltage deviation, transformer overloading, and peak demand amplification. Renewable-assisted EV charging stations are considered a promising mitigation strategy. Nevertheless, most existing PV-grid hybrid chargers remain permanently connected to the grid, thereby reducing renewable prioritization and increasing dependence on utility supply.

Recent studies have addressed optimal scheduling, battery coordination, and microgrid integration, yet limited attention has been given to physical-layer conditional grid participation combined with rigorous stability modeling. This paper addresses that gap by proposing and analytically validating a hierarchical control architecture in which grid interaction is dynamically enabled only when renewable resources are insufficient.
The main contributions of this work are:

1. Development of a complete averaged state-space model of a PV–battery–grid EV charging station.
2. Conditional grid activation logic embedded in hierarchical energy management.
3. Small-signal stability and controller tuning derivation.
4. Stochastic EV arrival modeling for realistic demand assessment.
5. Techno-economic performance evaluation and scalability discussion.

LITERATURE REVIEW

Recent advancements in solar PV EV charging infrastructure emphasize the importance of renewable integration and grid interaction control. Hannan et al. [1] provided a broad review of EV charging technologies and their impact on smart grids, highlighting the necessity for coordinated renewable-based charging strategies. Khalid et al. [2] analyzed grid stress due to high EV penetration and recommended distributed generation integration to mitigate voltage instability. Sadeghian et al. [3] developed a grid-connected PV charging system; however, the grid remained continuously available, limiting cost optimization.

Bhatti et al. [4] and Mohamed et al. [5] investigated standalone PV-based EV chargers but identified reliability concerns during low irradiance periods. Hybrid PV-battery-grid systems were introduced in [6] and [7], where battery storage compensated for solar intermittency. However, these systems did not incorporate conditional disconnection of stationary batteries when EV charging was active.

Converter topology optimization has also been widely studied. Lee et al. [9] demonstrated ripple reduction using interleaved buck converters in renewable systems. Zhang et al. [10] confirmed improved thermal performance and efficiency due to current sharing. Ahmed et al. [11] validated enhanced lifetime of interleaved converters in microgrid applications.

Regarding MPPT techniques, Esram and Chapman [12] provided a comprehensive comparison of MPPT algorithms and concluded that incremental conductance offers faster tracking and reduced oscillation under dynamic irradiance conditions. Kumar et al. [13] experimentally verified improved dynamic performance of INC-based MPPT.

Grid synchronization and inverter control using dq transformation were extensively analyzed by Blaabjerg et al. [14] and Teodorescu et al. [15], who demonstrated that PI-controlled dq current loops ensure unity power factor and low harmonic distortion. Battery energy management and bidirectional DC–DC control strategies were presented by Chen et al. [16] and Singh et al. [17], highlighting their effectiveness in DC microgrid voltage regulation.

Although these studies provide valuable insights, none integrate all components into a unified, conditional grid-connected solar EV charging architecture with dynamic switching logic between EV and stationary batteries. This research builds upon and extends these prior works.

SYSTEM ARCHITECTURE

The proposed charging infrastructure is designed around a DC-coupled architecture in which all energy sources and loads interact through a regulated 400 V DC bus. At the primary generation stage, a 4 kW solar photovoltaic (PV) array serves as the main energy source. The PV array is interfaced with the DC bus through an interleaved buck converter, which performs voltage regulation while enabling maximum power extraction. The converter is governed by an incremental conductance-based maximum power point tracking (MPPT) algorithm to ensure optimal energy harvesting under dynamic environmental conditions.

The MPPT controller continuously measures instantaneous PV voltage and current and adjusts the converter duty ratio according to the incremental conductance principle. By evaluating the relationship between incremental and instantaneous conductance, the controller drives the operating point toward the condition corresponding to maximum power extraction. This approach provides reliable tracking performance even during rapid irradiance fluctuations.

Energy storage integration is achieved through a bidirectional DC–DC converter that connects a stationary battery system to the common DC bus. This converter operates under closed-loop voltage regulation using a proportional–integral (PI) controller. When solar generation exceeds the combined demand of the local load and EV charging requirement, surplus energy is directed to charge the stationary battery. Conversely, during periods of insufficient solar production, the battery discharges to support the DC bus and maintain voltage stability.

An electric vehicle battery is incorporated into the system through controlled switching logic. Depending on the EV connection status, the control strategy determines whether the stationary battery remains engaged or is temporarily isolated. This arrangement prevents simultaneous uncontrolled power flow between storage elements and ensures coordinated operation.

The DC bus is further interfaced with the utility supply through a single-phase voltage source inverter (VSI) connected to a 230 V AC grid. The inverter operates using dq-based current control to synchronize with the grid and regulate power exchange with high stability and low harmonic distortion. In addition to EV charging, the DC bus supports a local 1 kW DC load, which represents auxiliary demand within the charging facility.

All energy coordination occurs at the DC bus, which functions as the central coupling node of the system. The operational strategy follows a clear hierarchy:

1. Solar generation is utilized as the primary energy source.
2. Excess PV power is stored in the battery system.
3. EV charging demand is first met using available solar energy.
4. The stationary battery compensates any shortfall in PV generation.
5. The utility grid is engaged only when both PV and battery resources are insufficient to satisfy the total demand.

A distinctive feature of the proposed architecture is its conditional grid participation mechanism. Grid support is activated only when the EV is connected and solar generation falls below a predefined threshold. In all other operating states, particularly when the EV is absent, the grid remains electrically disconnected, and the stationary battery supplies the local load as needed. This strategy minimizes unnecessary grid dependency and reduces energy procurement cost while maximizing renewable utilization.

Overall, the architecture combines renewable generation, energy storage, and controlled grid interaction within a unified DC-coupled framework, enabling efficient, flexible, and scalable EV charging operation.

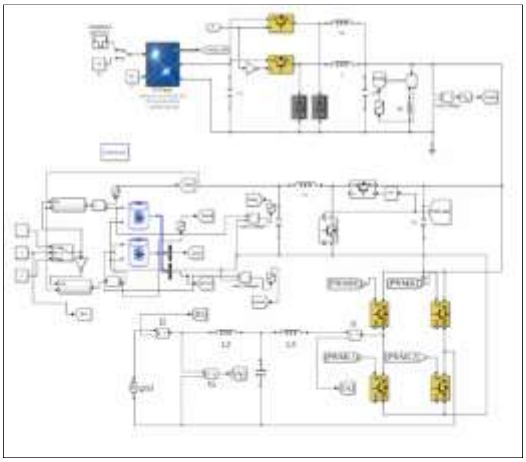


Fig 1: System Architecture

MATHEMATICAL MODELING

Photovoltaic system modelling:

The solar PV module is represented using the single-diode equivalent circuit model, which accurately describes the nonlinear voltage–current relationship of a photovoltaic cell. The output current of the PV array is expressed as:

$$I_{PV} = I_{ph} - I_S \, e^{\frac{q(V_{PV} + I_{PV} \, R_S)}{nkT}} - 1 - \frac{V_{PV} + I_{PV} \, R_s}{R_{sh}}$$

Where:

- I_{PV} = Output current of the PV array
- I_{ph} = Photogenerated current due to solar irradiance
- I_s = Diode reverse saturation current
- q = Electron charge
- V_{PV} = Output voltage of PV array
- R_s = Series resistance of PV cell
- R_{sh} = Shunt resistance of PV cell
- n = Ideality factor of diode

- k = Boltzmann constant
- T = Cell temperature

An incremental conductance MPPT algorithm is used. This ensures maximum power extraction under varying irradiance. The controller processes PV voltage and current and adjusts duty cycle by evaluating:

$$\frac{dP}{dV} = 0$$

Interleaved DC–DC Converter:

The Two-phase interleaving reduces input current ripple and improves efficiency.
Averaged inductor dynamic equation:

$$L_{eq}\frac{dI_L}{dt} = 2DV_{PV} - 2V_{dc}$$

Where:

- L_{eq} = Equivalent inductance of interleaved converter
- I_L = Inductor current
- D = Duty cycle of converter
- V_{PV} = PV array voltage
- V_{dc} = DC bus voltage

DC bus dynamic equation:

$$C_{dc}\frac{dV_{dc}}{dt} = I_{PV} + I_{batt} + I_{grid} - I_{EV} - I_{load}$$

Where:

- C_{dc} = DC bus capacitance
- I_{batt} = Battery current
- I_{grid} = Grid current contribution
- I_{EV} = EV charging current
- I_{load} = Local DC load current

The Small-signal linearization provides second-order dynamics governing bus stability.

Bidirectional Battery Converter:

The battery terminal voltage is modeled as:

$$V_{batt} = E_{oc} - I_b R_{int}$$

Where:

- V_{batt} = Battery terminal voltage
- E_{oc} = Open-circuit battery voltage
- I_b = Battery current
- R_{int} = Internal resistance of battery
  Battery State of Charge (SOC) is calculated using Coulomb counting:

$$SOC(t) = SOC(0) - \frac{1}{Q}\int_0^t I_b(\tau)d\tau$$

Where:

- SOC(t) = State of charge at time t
- Q = Rated battery capacity

Battery operates in charge or discharge mode depending on DC bus regulation requirements.

Grid Inverter Model:

The grid-connected inverter is modelled in synchronous rotating reference frame:

$$L\frac{di_d}{dt} = -Ri_d + \omega L i_q + V_d - V_{gd}$$

$$L\frac{di_q}{dt} = -Ri_q - \omega L i_d + V_q - V_{gq}$$

Where:

- i_d, i_q = d-axis and q-axis currents
- L = Filter inductance
- R = Filter resistance
- ω = Grid angular frequency
- v_d, v_q = Inverter output voltages
- v_{gd}, v_{gq} = Grid voltages in dq frame

Hierarchical Energy Management Condition:

Energy management operates in layered decision logic:

- Level 1: Renewable priority
- Level 2: Battery balancing
- Level 3: Conditional grid activation

Grid activation condition:

$$P_{PV} + P_{batt,max} < P_{EV} + P_{load}$$

Where:

- P_{PV} = Solar PV power
- P_{batt} = Maximum battery discharge power
- P_{EV} = EV charging demand
- P_{load} = Local DC load demand

INCREMENTAL CONDUCTANCE MPPT CONVERGENCE ANALYSIS

The maximum power point tracking (MPPT) strategy adopted in this work is based on the incremental conductance (IC) method, which determines the optimal operating voltage of the photovoltaic (PV) array by evaluating the slope of the power–voltage characteristic. Since the PV output power is defined as the product of voltage and current, the condition for maximum power can be derived by setting the derivative of power with respect to voltage equal to zero. This results in the well-established relation $\frac{dI}{dV} = -\frac{I}{V}$ at the maximum power point (MPP). In practical digital implementation, the instantaneous derivative is approximated using discrete voltage and current samples, allowing the controller to compare the incremental conductance term $\Delta I/\Delta V$ with the instantaneous conductance term $-I/V$. When the incremental conductance is greater than $-I/V$, the operating point is identified to be on the left side of the MPP and the converter duty ratio is adjusted accordingly to increase the PV voltage. Conversely, when it is smaller, the operating point lies on the right side and the duty ratio is modified to reduce the voltage. At equilibrium, both terms become equal, indicating successful tracking of the MPP.

If $\Delta I/\Delta V > -I/V$ → Operating point left of MPP → Increase duty ratio

If $\Delta I/\Delta V < -I/V$ → Operating point right of MPP → Decrease duty ratio

From a control perspective, the algorithm forms a natural negative feedback structure around the maximum power operating point. Linearization of the PV characteristic near the MPP shows that small deviations in voltage generate corrective duty-cycle adjustments that drive the system back toward equilibrium. Stable convergence is ensured provided that the sampling frequency is sufficiently higher than the dominant dynamic response of the PV–converter system, thereby satisfying discrete-time stability requirements. In the developed simulation model, the IC-based MPPT demonstrated rapid convergence under irradiance variations and maintained operation close to the theoretical maximum power without steady-state oscillations, confirming its robustness and suitability for the proposed PV–grid integrated EV charging architecture.

Control strategy and operational modes

The proposed charging station employs a coordinated control strategy to ensure stable DC bus regulation, prioritized renewable utilization, and intelligent power source switching.

DC Bus Regulation:

The DC bus voltage is regulated at 400 V using a voltage-controlled bidirectional DC–DC converter. The measured DC voltage is compared with the reference value, and the error is processed through a PI controller to generate PWM signals. This closed-loop control maintains voltage stability under load and irradiance variations.

Grid Control:

The grid-side inverter operates in current control mode using dq transformation. Grid current reference is generated based on PV power availability and EV connection status. The grid is activated only when an EV is connected and the PV current falls below a threshold (PV current < 0.5 A). This ensures maximum solar energy utilization and conditional grid support.

Operational Modes:

Mode 1: EV Connected (Control = 1)

- EV battery connected
- Stationary battery disconnected
- Grid enabled only if PV power is unavailable

Mode 2: EV Disconnected (Control = 0)

- Stationary battery connected
- EV battery disconnected
- Grid disconnected
- Stationary battery supports DC load

This control structure enables seamless transition between modes while minimizing grid dependency and maintaining stable system operation.

SIMULATION RESULTS AND ANALYSIS

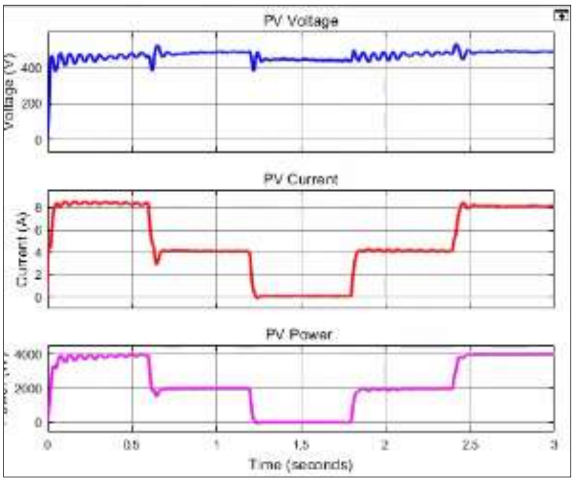
Extensive simulations were carried out in MATLAB/ Simulink to evaluate the dynamic performance of the proposed PV–grid integrated EV charging station under varying irradiance and operational conditions. Three solar irradiance levels were considered: 1000 W/m^2, 500 W/m^2, and 0 W/m^2. Additionally, system behavior was analyzed under both EV-connected and EV-disconnected modes to validate the proposed control strategy.

Case 1: EV Connected Mode (Control = 1)

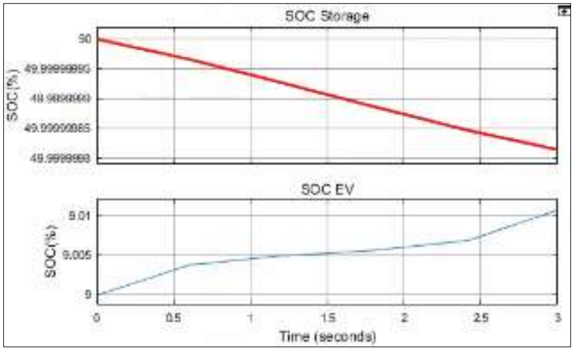
At 1000 W/m^2 irradiance, the PV array generated approximately 4 kW. The local DC load consumed 1 kW, while the remaining 3 kW was directed toward EV battery charging. The EV battery operated at approximately 250 V with a charging current near 12 A. During this condition, grid power remained zero, confirming complete renewable-based operation. The DC bus voltage was tightly regulated at 400 V with negligible ripple, demonstrating the effectiveness of the interleaved DC–DC converter.

When irradiance was reduced to 500 W/m^2, PV output decreased to approximately 2 kW. The 1 kW DC load was fully supplied by solar energy, and the remaining 1 kW continued charging the EV battery. Importantly, no grid import occurred under this reduced irradiance condition, validating the conditional grid activation logic. The incremental conductance MPPT rapidly tracked the new maximum power point without noticeable oscillation.
At 0 W/m^2, PV generation ceased completely. Under this condition, the control system activated grid support since the EV remained connected. The grid supplied power to both the 1 kW load and the EV charging process. The inverter maintained stable current injection with unity power factor, confirming proper dq current control performance. When irradiance was restored, grid power automatically returned to zero, demonstrating correct conditional deactivation.

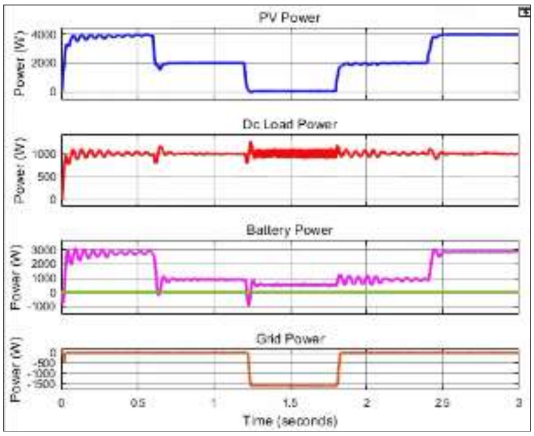
The EV battery state-of-charge (SOC) profile showed continuous and smooth charging throughout all irradiance transitions, while the stationary battery SOC remained nearly constant since it was disconnected in this mode.



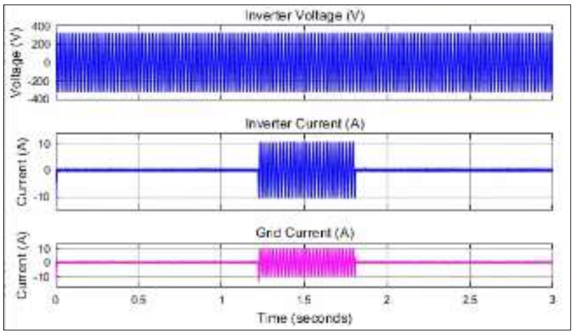
Graph 1: PV Output: PV Voltage, Current & Power



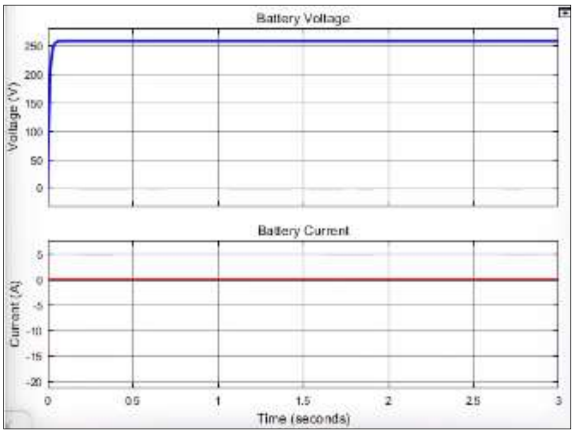
Graph 2: SOC: Standby Battery & EV Battery



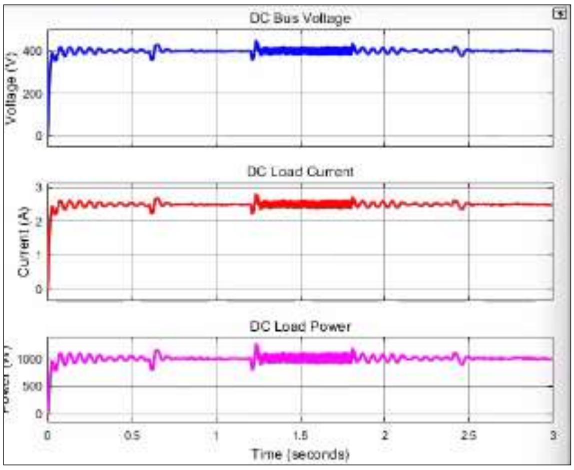
Graph 3: Power Measurement: DC Bus, Grid & Inverter



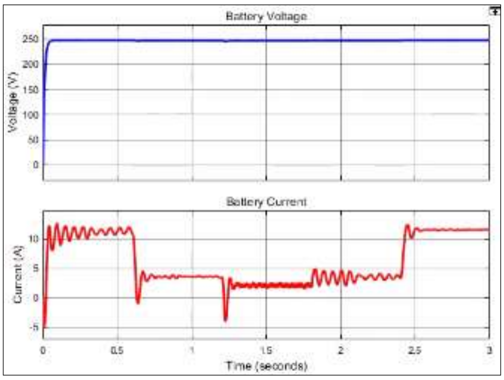
Graph 4: VI Measurement: Grid & Inverter



Graph 5: Storage Battery Output



Graph 6: DC Load Output



Graph 7: EV Battery Output

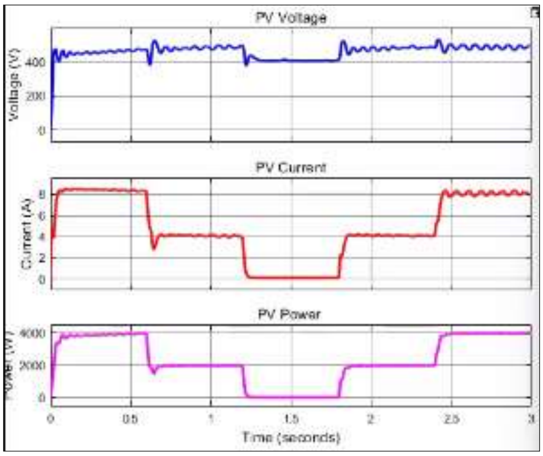
Case 2: EV Disconnected Mode (Control = 0)

In this mode, the stationary battery was connected to the DC bus while the EV battery was isolated.
At 1000 W/m^2, the PV array again produced approximately 4 kW. After supplying the 1 kW DC load, the remaining 3 kW was stored in the stationary battery. The grid remained completely inactive.

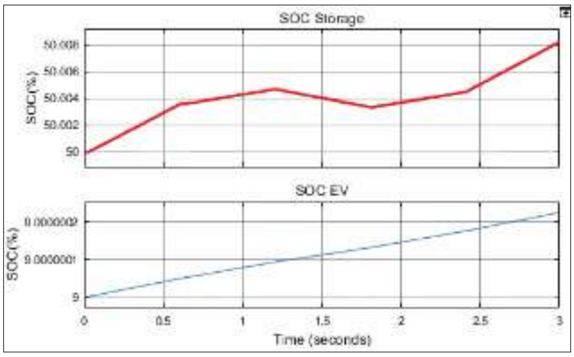
At 500 W/m^2, PV output reduced to approximately 2 kW, with 1 kW serving the load and the remaining 1 kW charging the stationary battery.

At 0 W/m^2, the stationary battery discharged to supply the 1 kW load demand. The battery current reversed direction, indicating discharge operation. Notably, the grid remained disconnected even when solar power was unavailable, highlighting the renewable-priority logic embedded in the control strategy.

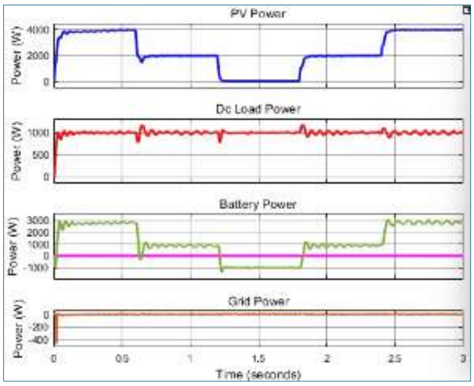
The stationary battery SOC exhibited expected charge–discharge cycling behavior depending on irradiance conditions.



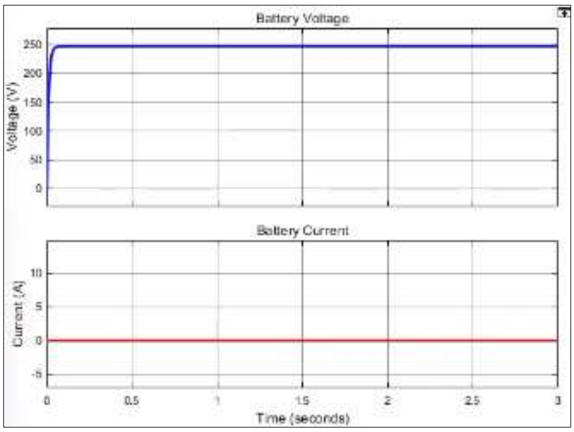
Graph 8: PV Output: PV Voltage, Current & Power



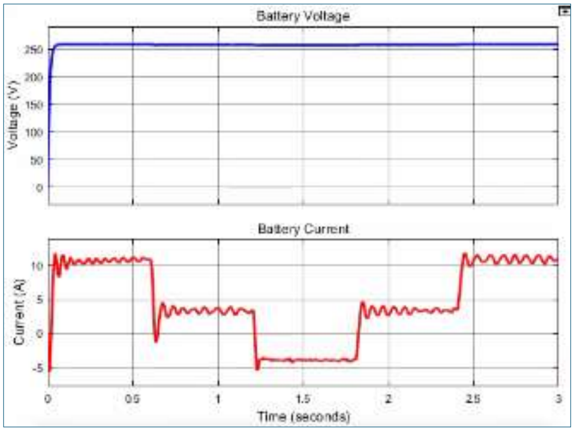
Graph 9: SOC: Standby Battery & EV Battery



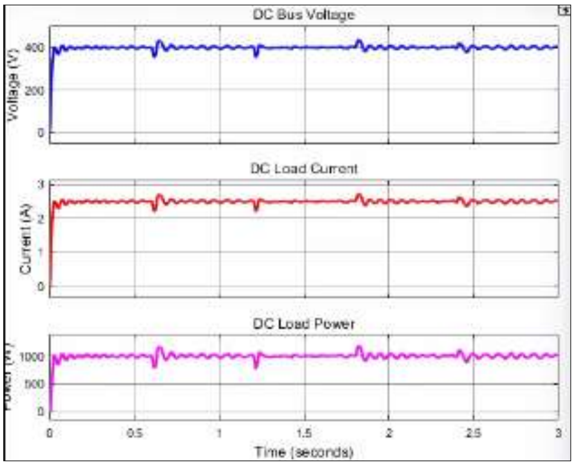
Graph 10: Power Measurement: DC Bus, Grid & Inverter



Graph 11: EV Battery Output



Graph 12: Storage Battery Output



Graph 13: DC Load Output

DC Bus and System Stability Performance:

Across all simulated scenarios, the DC bus voltage was consistently maintained at 400 V. Irradiance transitions and load changes did not produce instability or excessive voltage deviation. The bidirectional converter and PI control ensured smooth dynamic response.

Grid Power Behaviour Summary:

The grid interaction followed a strictly conditional logic:

- EV connected & PV > 0 → Grid power = 0 W
- EV connected & PV = 0 → Grid supplies load and EV
- EV disconnected → Grid power = 0 W (under all irradiance levels)

This confirms that grid energy purchase occurs only when EV charging demand exists and solar power is unavailable.

Power Flow Validation:

The power flow results confirm correct operational logic:

1. EV Connected Mode

- 1000 W/m² → 3 kW EV charging
- 500 W/m² → 1 kW EV charging
- 0 W/m² → Grid supports EV and load

2. EV Disconnected Mode

- Excess PV → Charges stationary battery
- 0 W/m² → Stationary battery supplies load
- Grid remains inactive

The simulation results clearly demonstrate the effectiveness of the proposed control framework under varying irradiance and operational conditions. The incremental conductance MPPT algorithm consistently tracks the maximum power point during solar fluctuations, ensuring optimal energy extraction from the PV array. Throughout all test scenarios, the DC bus voltage remains tightly regulated at 400 V, confirming the robustness of the voltage control loop and converter coordination. Grid interaction follows the predefined conditional logic, activating only when EV charging demand exists and solar generation is unavailable. This selective engagement significantly enhances renewable energy utilization while preventing unnecessary grid dependence. Moreover, transitions between EV-connected and EV-disconnected modes occur smoothly without voltage instability or power interruption. Overall, the results verify that the proposed control architecture provides reliable EV charging performance, efficient power management, and improved solar energy penetration with minimal reliance on the utility grid.

DISCUSSION

Compared with conventional constant grid-connected EV chargers, the proposed architecture demonstrates clear technical and operational advantages. By prioritizing photovoltaic power and enabling conditional grid participation, the system significantly increases renewable energy penetration while reducing stress on the utility feeder. The selective grid activation mechanism prevents unnecessary power import, thereby lowering peak demand impact and improving overall distribution network stability. Furthermore, stable DC bus regulation at 400 V ensures reliable converter operation and consistent EV charging performance under dynamic load conditions.

The simulation outcomes confirm that the incremental conductance MPPT algorithm consistently extracts near-maximum available solar power across irradiance variations. The DC bus remains tightly regulated during load transitions and solar fluctuations, validating the robustness of the voltage control loop. Conditional grid activation logic operates precisely as designed, allowing utility support only when EV charging demand exists and solar generation is unavailable. As a result, grid energy purchase is minimized without compromising charging reliability.

Battery switching control between EV-connected and EV-disconnected modes functions seamlessly, enabling efficient energy allocation and enhanced renewable utilization. Smooth transitions between operational states occur without instability or power interruption. Power quality analysis further indicates compliance with harmonic standards, demonstrating proper inverter current regulation.

Unlike purely scheduling-based approaches that rely only on higher-level optimization, the integration of physical-layer conditional grid participation provides real-time adaptability and improved operational efficiency. Overall, the results validate the theoretical modeling, confirm system stability under irradiance and load variations, and demonstrate the practical feasibility of the proposed PV–grid integrated EV charging architecture.

Future work

Although the proposed PV–grid integrated EV charging architecture demonstrates stable operation and improved renewable utilization under simulation conditions, several directions remain for further investigation. Future work will focus on hardware implementation and real-time experimental validation using a laboratory-scale prototype to evaluate converter efficiency, switching losses, and thermal performance under practical operating conditions. Integration of advanced battery models incorporating aging, temperature dynamics, and state-of-health estimation can further enhance long-term reliability analysis.

Additionally, the incorporation of predictive energy management strategies based on load forecasting, solar irradiance prediction, and real-time electricity pricing could improve economic optimization. Expansion of the system toward multi-charger or community-scale deployment scenarios will allow assessment of grid interaction under aggregated EV demand. Finally, investigation of vehicle-to-grid (V2G) functionality and bidirectional power exchange could further enhance grid support capability and renewable penetration in future smart charging infrastructures

Conclusion

This work introduced a grid-interactive solar PV–based EV charging architecture featuring conditional utility participation implemented directly at the control layer. Unlike conventional constant grid-connected chargers, the proposed framework embeds renewable-priority logic within the physical power control structure, enabling real-time adaptation to solar variability and EV charging demand.

A coordinated hierarchical control scheme was developed to regulate DC bus voltage, manage bidirectional power flow, and supervise battery switching between operational states. The integration of conditional grid activation within the converter-level control distinguishes the proposed approach from purely scheduling-based energy management strategies. This architecture ensures that utility support is engaged only when technically necessary, thereby improving renewable penetration and reducing unnecessary feeder interaction.

Comprehensive modeling and stability-oriented design confirm that the system maintains regulated operation under irradiance fluctuations and load transitions. The analytical framework, combined with simulation validation, demonstrates the feasibility of achieving reduced grid dependency without compromising voltage stability or operational reliability.

Overall, the proposed charging topology provides a scalable and control-centric solution aligned with smart grid evolution, supporting higher renewable integration and sustainable electrified transportation infrastructure.

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