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Power Enhancement of Solar Powered Electric Vehicle Charging with Boost Converter

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Abstract
This research presents the design and simulation of an advanced Battery Management System (BMS) integrated with a solar-powered electric vehicle (EV) fast-charging station, highlighting its potential to revolutionize energy storage and charging technologies. The system architecture was modeled and simulated using MATLAB/SIMULINK (R-2021a) to develop a 40 kW off-grid EV charging station. The proposed solution utilizes solar energy as a standalone source, employing a Perturb and Observe Maximum Power Point Tracking (MPPT) algorithm to optimize the efficiency of photovoltaic (PV) panels under varying irradiation and temperature conditions (1000 W/m² and 25°C–40°C, respectively). A key innovation in this system is the implementation of fast-charging capabilities while maintaining off-grid independence, addressing the critical challenge of grid dependency and power outages common in on-grid PV systems. Simulation results demonstrate significantly reduced EV charging times compared to standard benchmarks, reinforcing the efficacy of the developed system in real-world scenarios. The findings not only fulfill the research objectives but also emphasize the transformative potential of advanced BMS frameworks in supporting the increasing demand for efficient, sustainable, and reliable energy solutions. This study contributes to the ongoing development of next-generation automotive technologies and lays the groundwork for future innovations in renewable- powered infrastructure.
Keywords: *Battery Management System (BMS), Electric Vehicle (EV) Fast Charging, Photovoltaic (PV) Off-Grid System, Maximum Power Point Tracking (MPPT), MATLAB/SIMULINK Simulation, etc.*

1. Introduction
A viable answer to the growing need for environmentally friendly transportation is the incorporation of solar energy into electric vehicle (EV) charging infrastructure. The DC-DC boost converter, a crucial part of this integration, raises the comparatively low voltage from photovoltaic (PV) panels to levels appropriate for charging EV batteries. Conventional boost converters, however, have drawbacks including parasitic effects and switching losses, especially in situations with fluctuating solar irradiation [1], [2]. By improving energy conversion efficiency and dependability in EV charging systems, recent developments in converter topologies and control methodologies seek to address these issues [3],[4]. Improved resilience and efficiency have been the main goals of recent developments in DC-DC boost converters for solar-powered EV charging systems. A Y-source boost converter in conjunction with a phase-shifted full-bridge converter was introduced by Anitha et al. [1], who achieved a notable voltage gain and good efficiency. A high-gain enhanced quasi-Y-source DC–DC step-up converter was proposed by Pandya and Mehta [2], who showed 91.8% efficiency in charging a 60V battery from a

50V solar input. Because they can greatly increase the input voltage, high-gain topologies like the Modified Luo Converter and Modified SEPIC Converter have been investigated as potential high-voltage EV charging solutions [3], [4]. Model Predictive Control (MPC) has been applied to synchronous boost converters, replacing diodes with SiC MOSFETs to minimize switching losses and improve efficiency in Vehicle-to-Grid (V2G) systems [5]. To stabilize DC voltage in solar-powered EV charging stations, a reliable sliding mode control approach has been created. This method provides robustness against changes in system characteristics, outside disturbances, and uncertainties by using a bidirectional DC-DC buck-boost converter to react quickly to power fluctuations [6]. Additionally, the integration of Maximum Power Point Tracking (MPPT) algorithms, such as Incremental Conductance, has been shown to enhance solar efficiency by dynamically adjusting the operating point of the PV system to match optimal power output [7]. Bidirectional converters have been employed in charging stations to facilitate both charging and discharging of EV batteries, supporting grid stability and energy storage [8] Due to their high-power density and bidirectional power flow capabilities, advanced converter topologies including Dual Active Bridge (DAB) and CLLC converters have been investigated as potential candidates for ultra- fast EV charging stations [10], [9]. Recent research has also suggested hybrid solar and battery systems for continuous EV charging during periods of low sunlight [12] and optimized the converter layout for improved thermal performance and smaller size [11]. Lastly, to get over the voltage restrictions placed by PV cells, novel variations of classical converters, like the Cuk and SEPIC topologies, have been improved [13], [14].

1.1 Proposed system

The proposed system as shown in fig. 1 is a hybrid solar-powered electric vehicle (EV) charging solution that integrates photovoltaic (PV) panels with the power grid. The PV array's solar output serves as the main energy source for EV charging. However, in situations where the solar energy is insufficient to meet the charging demand, the grid acts as a supplementary energy source to ensure reliable charging. The energy generated by the PV system is either used directly to charge the EV or is stored in a battery for future use, and any surplus can be injected into the grid. A DC-DC boost converter is used to regulate and enhance the DC output produced by the PV system. A Maximum Power Point Tracking (MPPT) controller then controls the output to guarantee the PV panels run as efficiently as possible. The regulated power is supplied to both a battery storage unit and the EV charging circuit.

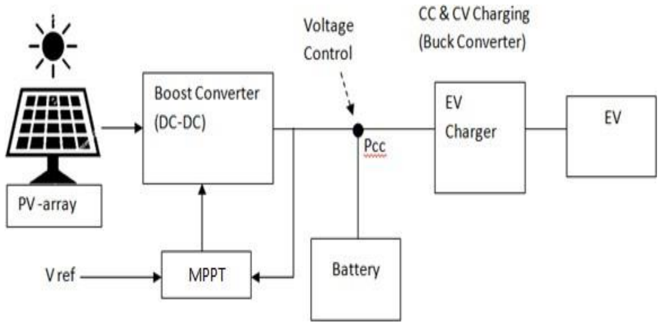

Figure 1 Block Diagram of Proposed System [1]

A buck converter is used to step down voltage where necessary, Figure 1. When solar power is insufficient, the grid provides additional energy to maintain uninterrupted EV charging [15-16]. The following elements make up the suggested system:

- **Solar PV System:** Uses semiconductors to transform sunlight into electricity, producing DC power. Additional components like controllers, converters, and storage ensure consistent power supply and system compatibility.
- **DC-DC Boost Converter:** Increases the low DC voltage from the solar panels to a suitable level for battery charging and EV systems, ensuring efficient power conversion.
- **MPPT Charge Controller:** Keeps track of the maximum power point to maximize solar power production, improving efficiency, and allowing higher voltage PV arrays to charge lower voltage batteries.
- **Battery Charging Circuit:** Manages the charging process, using CC-CV methodology to protect lithium-ion batteries from overcharging and ensuring safe operation.
- **Buck Converter:** Reduces DC voltage to levels

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needed by specific components or devices, crucial for regulating voltage in the EV charging unit and other low-voltage loads.

- **Energy Storage Battery:** Stores excess energy for use during low sunlight or high demand periods. Lithium-ion batteries are typically used due to their high density, long lifecycle, and fast charging.
- **EV Charging Circuit:** Supplies power to the EV battery using a two-phase CC-CV charging process, with duration varying by battery size, vehicle type, and charger capacity.
- **Electric Vehicle Battery:** EVs use lithium-ion batteries (40–100 kWh) that require DC input. Battery capacity impacts the vehicle's range and performance.

2. System Design and Methodology

2.1 PV Array Specifications

Table 1 **PV Array Specifications**

S. No	Component /Parameters	Specifications
1	Maximum Power	213.15 W
2	Cell per module	60
3	Open circuit voltage (VoC)	36.3 V
4	Short circuit current	7.84 A
5	Voltage at maximum power point	29V
6	Current at maximum power point	7.35

2.2 Boost Converter Design

The boost converter (step-up converter) is used when the output voltage must be higher than the input voltage. A DC-DC boost converter (also called a step-up converter) is a type of power converter that increases (boosts) the input voltage to a higher output voltage using inductors, switches (typically MOSFETs), diodes, and capacitors. Here's the mathematical model that governs its behavior.

2.3 Duty Cycle D

D= (Vout-Vin+V)/(Vout+VD) -----(1)

Where,

Input voltage: V_{in} =29.75V

Output voltage: V_{out} = 75.51 V

Forward voltage rectifier diode: V_D = 0.5 V

Putting values in equation (1)

Duty Cycle

D= (75.51-29.75+0.4)/ (75.51+0.4) =0.608

The mathematical relationship for the output voltage (Vout) of an ideal boost converter compared to the input voltage (Vin) is given by

D=Vin/(1-D) ------ (2)

Where,

Input voltage: V_{in} = 29.75 V

Duty Cycle: D = 0.608

Putting values in equation (2)

Vout=29.75/ (1-0.608) =75.91 V

2.4 Boost Converter Design Values

Table 2 **Boost Converter Design Values**

S. No	Component/Parameters	Specifications
1	Duty Cycle, D	0.608
2	Resistance, R	0.1Ω
3	Inductor, L	5 mH
4	Capacitor, C_a	100 µF
5	Capacitor, C_b	3300 µF

2.5 P&O MPPT Algorithm Flowchart

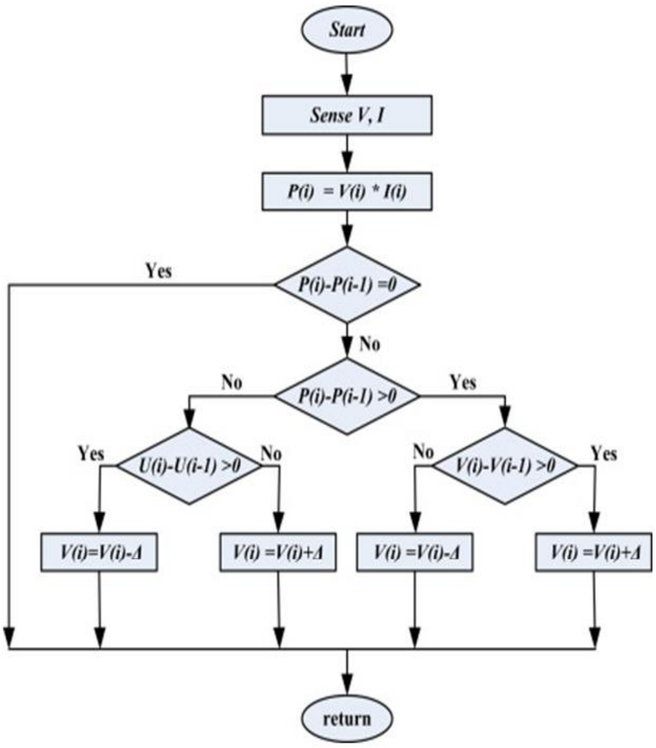

Figure 2 **P&O MPPT Algorithm Flowchart [2]**

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2.6 Buck Converter

A buck converter is a type of DC-DC converter that steps down voltage from its input to its output using switching elements (typically a transistor and diode), Figure 2, an inductor, and a capacitor. To understand its behavior, we derive a mathematical model based on its operation during different switching intervals. The output voltage (V_{out}) of a buck converter is directly proportional to the duty cycle (D) of the switching device and the input voltage (V_{in}), expressed as

$$Vout = D * Vin \text{-----} (3)$$

Where,
Input voltage: V_{in} = 75.91 V
Duty Cycle: D = 0.608
Putting values in equation (3)
Vout=75.91 x 0.608 = 46.15 V

2.7 Buck Converter Design Values

Table 3 Buck Converter Design Values

S. No	Component/Parameters	Specifications
1	Duty cycle	0.608
2	Inductor(L)	1mH
3	Capacitor(C1)	10µF
4	Capacitor(C2)	10µF

2.8 Storage Battery Specifications

Table 4 Storage Battery Specifications

S. No	Component/Parameters	Specifications
1	Nominal Voltage	70V
2	Rated Capacity	5.4Ah
3	Initial State of Charge (SOC)	50%
4	Response time	30s

The energy stored in a battery (Storage Capacity) is calculated by multiplying its voltage (V) by its capacity (Ah)
E=(V*Q)/1000
Were,
V is the voltage in volts = 70V
Q is the capacity in amp-hours (Ah) =5.4Ah
Energy E=70*5.4/1000 = 3.15KWh

2.9 EV Battery Specifications

Table 5 EV Battery Specifications

S. No	Component/Parameters	Specifications
1	Battery Type	Lithium-Ion
2	Nominal Voltage	45V
3	Rated Capacity	5.4Ah
4	Initial State of Charge (SOC)	21%
5	Response time	30s

The energy stored in a battery (Storage Capacity) is calculated by multiplying its voltage (V) by its capacity (Ah)
E= (V * Q)/1000
Where,
V is the voltage in volts = 45V
Q is the capacity in amp-hours (Ah) =5.4Ah
Energy E= (45 * 5.4)/1000= 0.243 KW

3. Simulation Implementation

The suggested solar-powered electric vehicle (EV) charging system's MATLAB/Simulink-based implementation is described in this section. Every subsystem is included in the simulation, including the EV charging interface, battery storage, buck converter, MPPT control, boost converter, and PV array. A system that satisfied the minimal specifications listed in Table 1 was used to construct and run the simulation, shown in Table 1 to Table 5.

Table 6 System Specifications

S. No	Component/Parameters	Specifications
1	Processor	Intel Core i5 or above
2	RAM	8 GB
3	Graphics Card	Minimum 2 GB VRAM
4	Storage	20 GB free HDD space
5	Software	MATLAB R2021a or above
6	Toolboxes	Simulink, Simscape, Simscape Electrical

The PV Array block replicates solar panels composed of modules connected in series and

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parallel, which may adapt dynamically to temperature and irradiance. Table 7 below lists the input and output signals for the PV array.

Table 7 PV Array Input & Output Signals

Signal	Type	Description
Ir	Input	Solar irradiance in W/m² (range: 0–1000)
T	Input	Cell temperature in °C
V_PV	Output	PV array voltage (V)
I_PV	Output	PV array current (A)
I_diode	Output	Diode current (A)
Irradiance	Output	Irradiance (W/m²)
Temperature	Output	Temperature (°C)

Two types of battery systems are implemented: a storage battery and an EV battery, both modeled using MATLAB's generic battery block. Discharge behavior and state of charge (SOC) are continuously observed. Table 8 displays the parameters of the battery configurations.

Table 8 Battery Configuration Parameters

Parameter	Storage Battery	EV Battery
Type	Lithium-Ion	Lithium-Ion
Initial SOC (%)	50%	21%
Nominal Voltage (V)	48	48–54
Capacity (Ah)	100	100

The PV array's voltage is raised by the Boost Converter to the necessary level for battery charging. The MPPT controller generates a PWM signal that powers it. When needed, the Buck Converter lowers voltage to securely charge the EV battery. When the boost converter output above the battery's charge threshold, this is quite helpful. The best duty cycle, which modifies the boost converter's output for maximum solar power tracking, is calculated using MATLAB's Perturb and Observe (P&O) MPPT method. The duty cycle from the MPPT controller is used by the PWM Generator block to generate switching signals. The MOSFET in the boost converter is driven by this signal to control the voltage. The entire simulation incorporates all of the essential elements: EV load, battery charging system, buck converter, MPPT controller, boost converter, and PV array. In situations with low solar, grid support can be emulated as an auxiliary input. Table 9 shows the parameters of the simulation.

Table 9 Simulation Environment Conditions

S. No	Component/ Parameters	Specifications
1	Irradiance	1000 W/m²
2	Temperature	25 °C
3	Boost Output	~60 V
4	Battery SOC	Initial: 50% (storage), 21% (EV)

Figure 3 to 5 illustrates the complete Simulink simulation. The PV array is set to 1000 W/m² irradiance and a temperature of 25°C. The duty cycle produced by the MPPT and PWM controllers is sent as input to the boost converter, which receives the output from the PV array. The boost converter's output is then supplied to both the storage battery and the buck converter, which charges the EV battery [3].

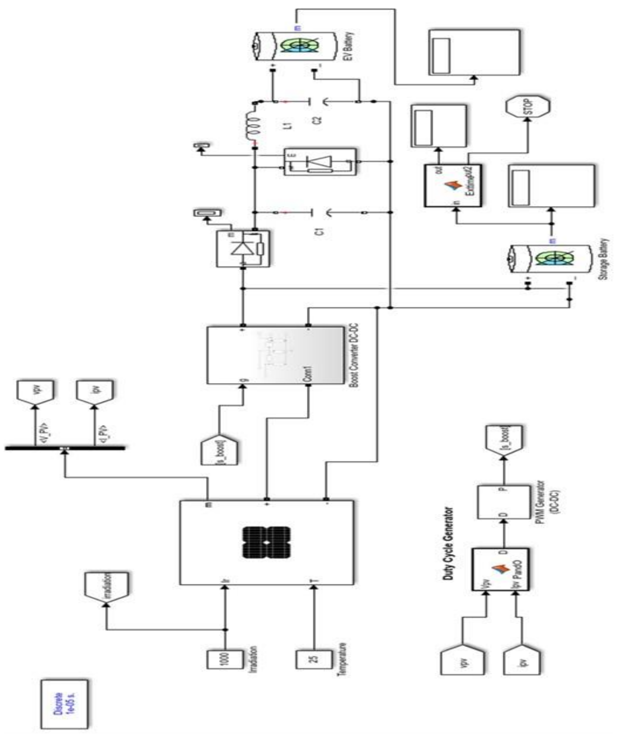

Figure 3 Simulink Simulation Circuit Diagram

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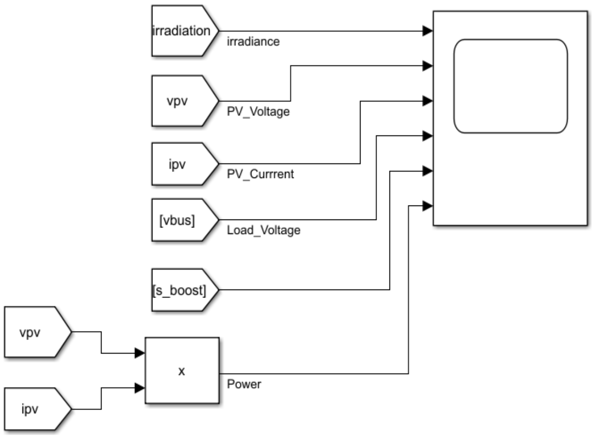

Figure 4 **Plotting Inputs and Outputs [4]**

4. Simulation Results

Scope blocks (shown in Fig. 3) are used to visualize important signals, including PV output voltage, battery voltage, charging current, and duty cycle, in order to track system performance over time. This simulation focuses on optimizing energy generation and storage from a photovoltaic (PV) system for electric vehicle (EV) charging. The PV array generates DC power, which is stepped up to a higher voltage by a boost converter to charge both the storage battery and EV battery. Maximum Power Point Tracking (MPPT) ensures the PV system operates at peak efficiency by adjusting for varying irradiance and temperature. The system performance is analyzed by measuring the impact of irradiance on battery charging time, voltage levels, and overall efficiency. Table 10 presents the time taken to charge the storage battery by 0.1% at various irradiance levels, with the EV charger turned OFF. The results show a clear inverse relationship-as irradiance increases, charging time decreases due to greater solar power availability.

Table 10 **Irradiation vs Time When EV Charger is OFF**

S. No	Irradiation (W/m^2)	Time (sec)
1	200	111.4
2	400	45.6
3	600	31.21
4	800	23.45
5	1000	20.24

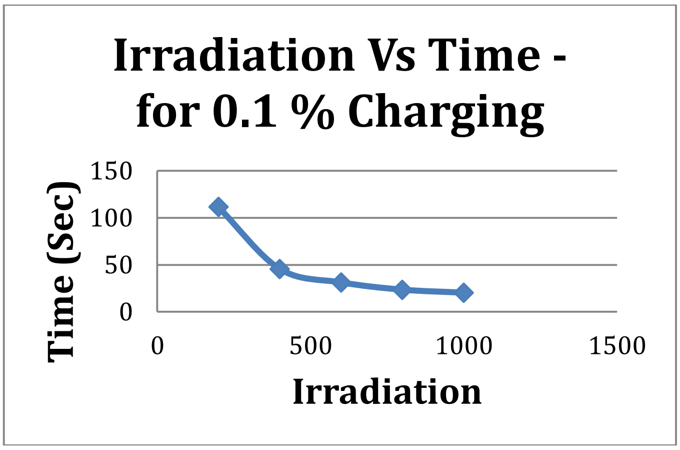

Figure 5 **Irradiation Vs Time Graph of storage battery when EV charger OFF [4]**

Table 11 shows the time taken to charge the storage battery by 0.1% when the EV charger is active. Compared to Table 5, the charging times are longer at each irradiance level due to the additional energy load from the EV battery.

Table 11 **Irradiation vs Time When EV Charger is ON**

S. No	Irradiation (W/m^2)	Time (sec)
1	400	153.4
2	600	87.63
3	800	61.07
4	1000	48.03
5	1200	40.44

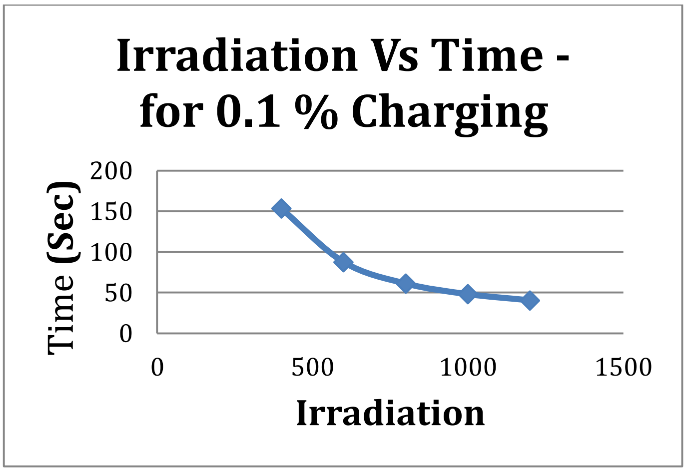

Figure 6 **Irradiation Vs Time Graph of Storage Battery When EV Charger ON [4]**

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Table 12 compares the charging time of the storage battery at different irradiance levels in two scenarios: when the EV charger is OFF and ON. The data clearly illustrates the increase in charging duration when additional power is consumed by the EV charging circuit.

Table 12 Irradiation vs Time for Battery Charging (EV Charger OFF/ON)

Irradiation (W/m^2)	Time (sec) EV OFF	Time (sec) EV ON
200	111.4	153.4
400	45.6	87.63
600	31.21	61.07
800	23.45	48.03
1000	20.24	40.44

The bar graph in Fig. 7 clearly illustrates that battery charging time is significantly shorter when the EV charger is OFF compared to when it is ON, due to the absence of additional power demand from the EV.

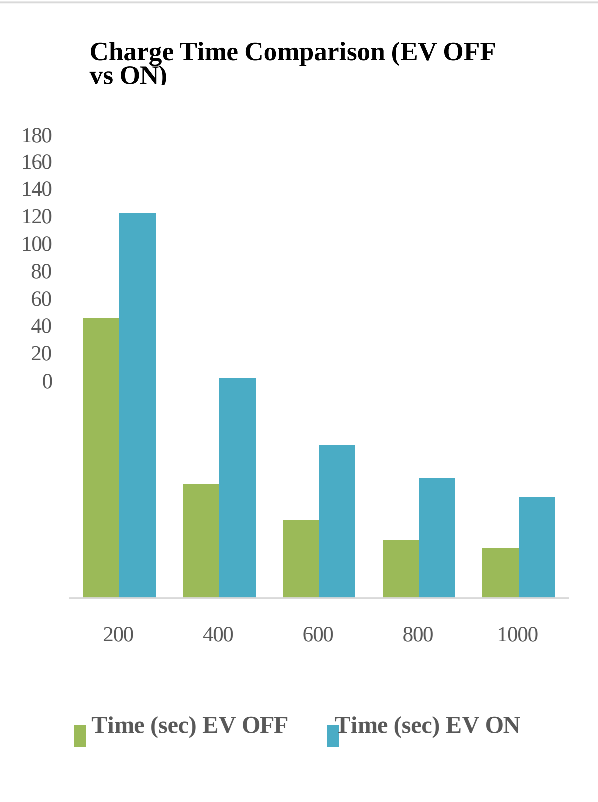

Figure 7 Storage Battery Charging Time Comparison When EV Charger OFF/ON [4]

Table 13 shows the output voltage of the boost converter under varying irradiance conditions. The voltage slightly increases with irradiance, showing that the boost converter maintains a relatively stable and elevated voltage to match charging. requirements, thus confirming its effective operation.

Table 13 Irradiation vs Boost Voltage

S. No	Irradiation (W/m^2)	Boost Voltage (V)
1	200	75.3
2	400	75.6
3	600	76.12
4	800	76.22
5	1000	76.31

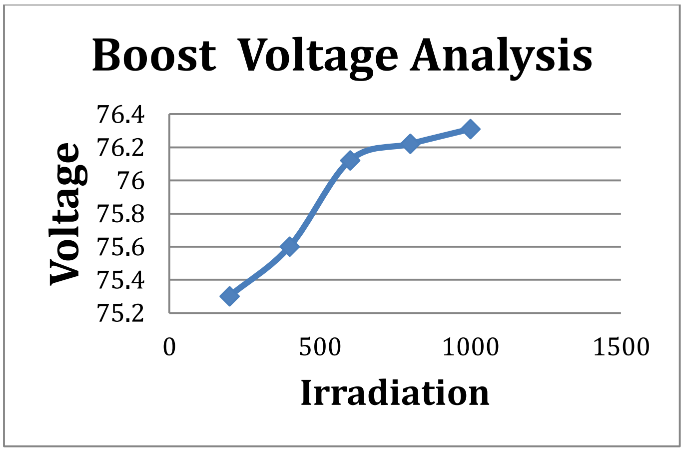

Figure 8 Illustrates That with an Increase in Solar Irradiation

Conclusion

A photovoltaic (PV)-powered electric vehicle (EV) charging system that incorporates a boost converter and Maximum Power Point Tracking (MPPT) for optimal energy management is shown to be effective in this study. Effective energy harvesting and utilization are ensured by the system's ability to function well under a range of temperature and irradiance situations. The findings demonstrate that when solar irradiation rises, battery charging time dramatically drops. When the EV charger is OFF, the time to charge the storage battery by 0.1% drops from 111.4 seconds at 200 W/m^2 to just 20.24 seconds at 1000 W/m^2, illustrating a clear inverse relationship between irradiance and charging duration. In contrast, with the EV charger ON, the same charging takes 153.4 seconds at 400 W/m² and decreases to 40.44 seconds at 1200 W/m². This highlights the added energy demand from the EV and its impact on charging performance. A comparative analysis confirms that charging times are consistently shorter when the EV charger is inactive. For example, at 600 W/m², charging takes 31.21 seconds with the EV charger OFF, compared to 61.07 seconds when it is ON—nearly double the duration. This emphasizes the importance of load management in dual-function systems to maintain charging efficiency. The boost converter also shows reliable performance, with output voltage increasing slightly from 75.3 V at 200 W/m² to 76.31 V at 1000 W/m², effectively stepping up the voltage from the PV array to meet battery charging requirements. In conclusion, the simulation validates that a solar- powered EV charging station equipped with MPPT and a boost converter can provide an efficient, reliable, and environmentally sustainable solution. The system supports both fast charging and energy storage while minimizing reliance on the electrical grid, making it a promising model for future green mobility infrastructure, shown in Figure 6 to 8.

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