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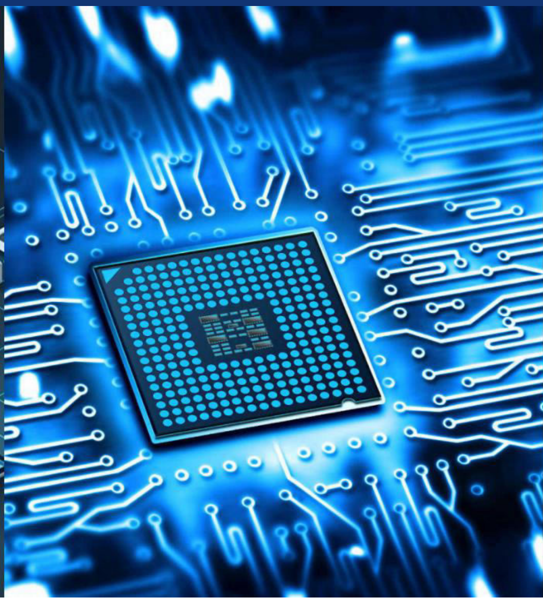

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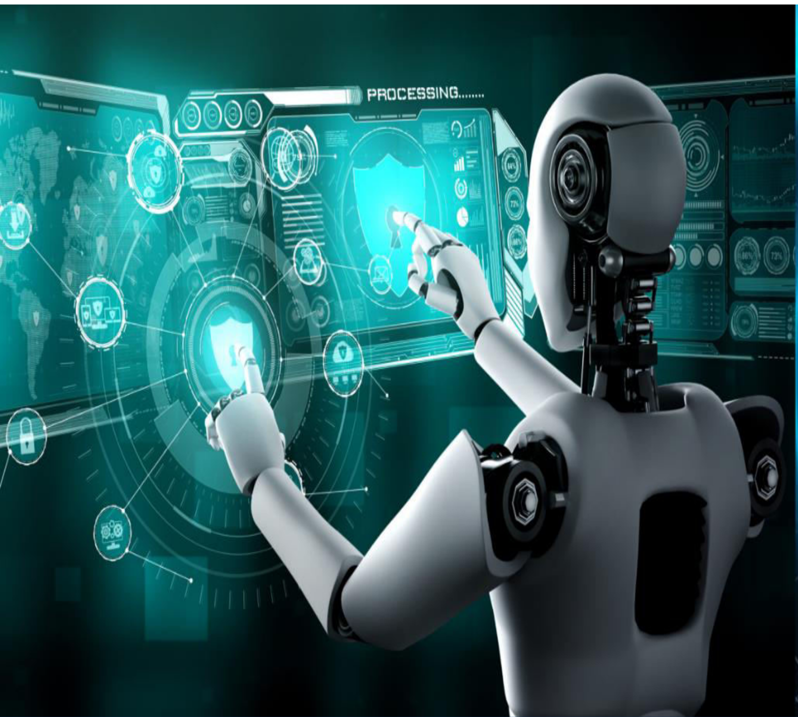


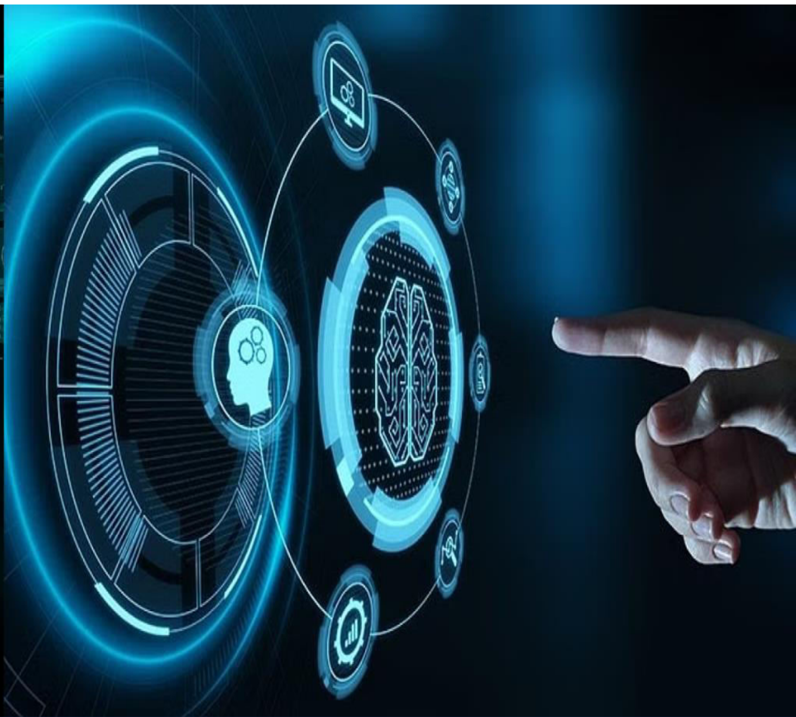

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# A Review of Grid-Connected PV–BESS Integrated EV Charging Stations: Energy Management, Control Strategies, and Power Quality Enhancement

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**ABSTRACT:** The rapid adoption of electric vehicles (EVs) has increased the demand for sustainable and efficient charging infrastructure. Conventional grid-dependent charging stations often face challenges related to peak power demand, grid congestion, and increased carbon emissions. To address these issues, renewable-energy-based charging stations integrated with photovoltaic (PV) systems and battery energy storage systems (BESS) have emerged as a promising solution. This paper presents a comprehensive review of grid-connected PV–BESS integrated EV charging stations, focusing on system architectures, energy management strategies, control techniques, and power quality enhancement methods. Recent advancements in bidirectional power converters, vehicle-to-grid (V2G) technology, intelligent energy management systems (EMS), and battery storage integration are critically analyzed. A conceptual framework consisting of a PV array, BESS, EV charging unit, EMS, and grid interface converter is proposed to optimize energy utilization and reduce grid dependency. Furthermore, simulation-based performance evaluation under varying solar irradiance and charging demand conditions demonstrates effective power flow management, stable DC-link voltage regulation, reduced harmonic distortion, and enhanced charging reliability. The results indicate that the proposed PV–BESS integrated charging station can significantly improve renewable energy utilization while minimizing stress on the utility grid. The study highlights the potential of intelligent renewable-energy-assisted charging infrastructure in supporting sustainable transportation and future smart grid applications.

**KEYWORDS**: Electric Vehicle Charging Station, Photovoltaic System, Battery Energy Storage System, Energy Management System.

## I. INTRODUCTION

The rapid growth of electric vehicle (EV) adoption has intensified the demand for efficient, reliable, and sustainable charging infrastructure. Conventional EV charging stations primarily rely on grid power, leading to increased peak demand, grid congestion, and power quality concerns. To address these challenges, renewable energy sources, particularly solar photovoltaic (PV) systems, are increasingly being integrated into EV charging stations. PV-assisted charging stations reduce dependence on fossil-fuel-based electricity and support global decarbonization goals. However, the intermittent nature of solar energy introduces operational uncertainties that can affect charging reliability and grid stability.

Battery Energy Storage Systems (BESS) have emerged as a promising solution for mitigating renewable energy variability and ensuring uninterrupted EV charging. By storing excess PV-generated energy and supplying power during low-generation periods, BESS enhances system flexibility, improves energy utilization, and reduces stress on the utility grid. Furthermore, advanced power electronic converters and intelligent control strategies enable bidirectional power flow, grid support services, peak shaving, and seamless transition between grid-connected and islanded operating modes.

Recent research has focused on developing integrated PV–BESS–EV charging architectures that optimize energy management while maintaining high power quality. This review examines the latest developments in renewable-energy-based EV charging stations, highlighting system topologies, control approaches, energy management techniques, grid interaction capabilities, and future research directions for sustainable transportation electrification.

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## II. RELATED WORK

The rapid growth of electric vehicles (EVs) has encouraged extensive research on renewable-energy-powered charging stations integrated with battery energy storage systems (BESS). Grid-connected photovoltaic (PV) assisted charging stations have emerged as a sustainable solution for reducing carbon emissions and grid dependency. Jain et al. proposed a PV-BESS integrated EV charging station capable of maintaining grid power quality while ensuring reliable charging under varying operating conditions [1]. Load management strategies for DC fast-charging stations have also been investigated to reduce peak grid demand and improve charging efficiency [2]. Advanced converter topologies and optimal control methods have been developed to enhance charging performance and battery lifespan in fast-charging applications [3]. Furthermore, vehicle-to-grid (V2G) technologies have gained significant attention for enabling EVs to provide ancillary services and support grid resilience during peak demand periods [4,5]. These studies demonstrate that integrating renewable energy and energy storage significantly improves the sustainability and reliability of EV charging infrastructure.

Energy management remains one of the most critical aspects of PV-powered EV charging stations. Researchers have proposed several optimization techniques to coordinate power flow among PV arrays, storage systems, EV batteries, and utility grids. Smart scheduling frameworks for V2G services have been developed to maximize energy utilization while minimizing operational costs [6]. Flexible power reserve strategies have also been introduced to enhance grid support capabilities during periods of high demand [7]. More recently, artificial intelligence and machine learning approaches have been incorporated into energy management systems to improve decision-making and system efficiency [8]. Comprehensive reviews on PV-storage integrated charging stations have highlighted the importance of optimal sizing, coordinated control, and intelligent energy management for achieving maximum operational benefits [9]. In addition, modular battery storage systems have been investigated to enhance scalability and flexibility in charging station design [10].

Power quality enhancement and grid-interactive operation constitute another major research direction. Studies have demonstrated that advanced converter control techniques can mitigate harmonics, improve power factor, and maintain balanced grid currents under varying load conditions [11,12]. Reviews of charging technologies and converter architectures have identified bidirectional power flow, smart charging, and V2G operation as essential features of next-generation charging stations [13]. Research on microgrid-supported charging stations and resilient energy systems has further emphasized the importance of energy storage and distributed generation for ensuring uninterrupted operation during grid disturbances [4]. Additionally, recent investigations into the reuse of retired EV batteries as stationary storage systems have shown promising economic and environmental benefits [14]. Despite these advancements, challenges related to battery degradation, renewable intermittency, cybersecurity, and real-time control continue to drive ongoing research toward intelligent and sustainable EV charging networks [15].

## III. PROPOSED ALGORITHM

A. *Proposed Methodology:*

The proposed system presents a grid-connected Electric Vehicle (EV) charging station integrated with a Photovoltaic (PV) array and Battery Energy Storage System (BESS) to achieve sustainable and reliable charging operations. The PV array serves as the primary renewable energy source and operates under Maximum Power Point Tracking (MPPT) control to maximize energy extraction. A common DC-link connects the PV array, BESS, EV charging unit, and Voltage Source Converter (VSC). The BESS compensates for fluctuations in solar generation and supports EV charging during low irradiance conditions. The VSC facilitates bidirectional power exchange between the charging station and the utility grid while maintaining power quality. An intelligent Energy Management System (EMS) continuously monitors PV generation, battery state-of-charge (SOC), EV charging demand, and grid conditions to optimize power flow and minimize grid dependency.

B. *Modules*

1. Photovoltaic Generation Module

Generates renewable energy and operates under MPPT control for maximum power extraction.

2. Battery Energy Storage Module

Stores surplus PV energy and supplies power during insufficient solar generation or peak demand periods.

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3. EV Charging Module
Controls charging/discharging operations and supports Vehicle-to-Grid (V2G) functionality.
4. Grid Interface Module
Uses a Voltage Source Converter to regulate power exchange, synchronization, and power quality.
5. Energy Management Module
Performs real-time monitoring, scheduling, and decision-making for optimal energy utilization.

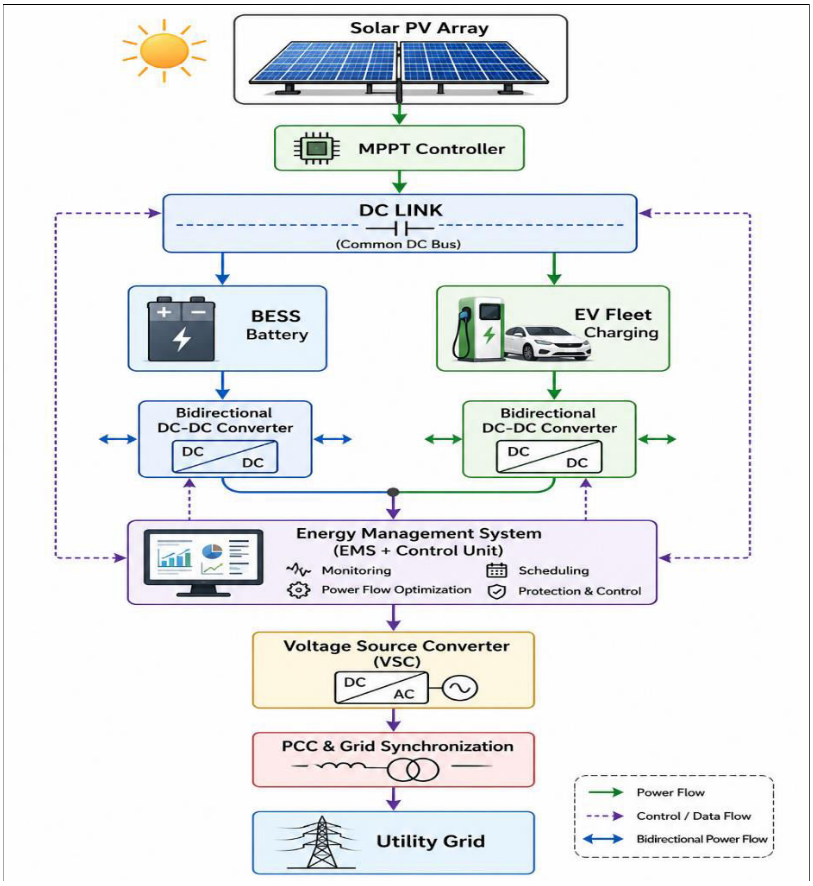


Fig1: Proposed Architecture

## IV. PSEUDO CODE

Step 1: Measure PV power, BESS SOC, EV charging demand, and grid status.
Step 2: If PV generation ≥ EV demand, supply EV load using PV energy and store excess power in BESS.
Step 3: If PV generation < EV demand, discharge BESS to meet the deficit.
Step 4: If both PV and BESS are insufficient, import power from the utility grid.
Step 5: During peak demand or V2G operation, allow controlled discharge from EV and BESS to support the grid.
Step 6: Maintain DC-link voltage, power factor, and harmonic limits using VSC control.
Step 7: Continuously update energy management decisions based on real-time operating conditions.
Step 8: End.

## V. SIMULATION RESULTS

The proposed grid-connected PV–BESS integrated EV charging station was simulated under varying solar irradiance and charging demand conditions using MATLAB/Simulink. The performance of the Energy Management System (EMS),

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Battery Energy Storage System (BESS), and Voltage Source Converter (VSC) was evaluated in terms of power flow management, DC-link voltage regulation, battery state-of-charge (SOC), and power quality improvement.

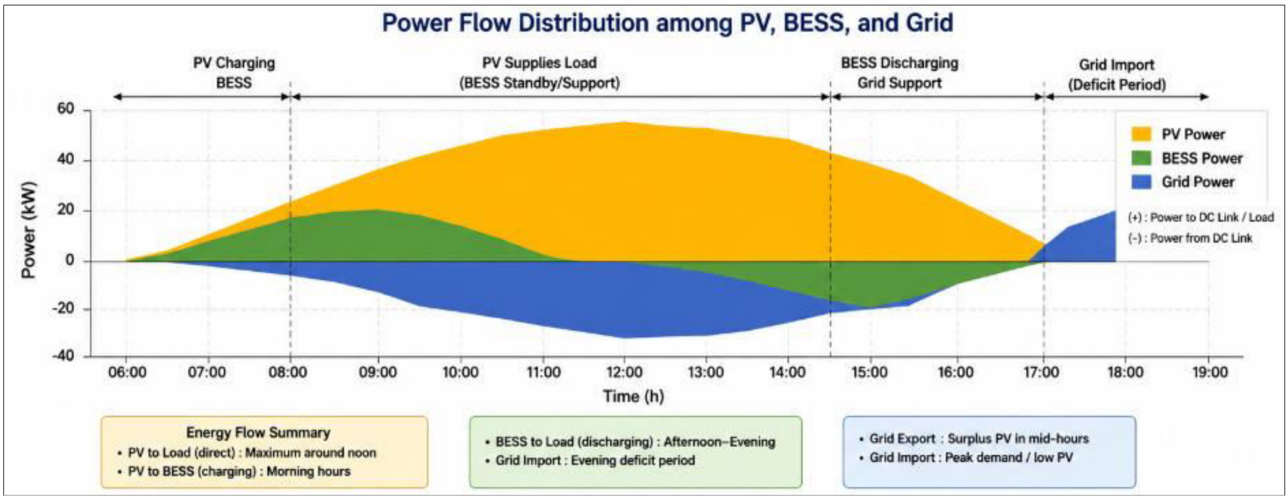
**[1] Case 1: Normal Solar Irradiance (1000 W/m²)**
Under standard irradiance conditions, the PV array generated sufficient power to satisfy EV charging demand while simultaneously charging the BESS. The EMS prioritized renewable energy utilization, reducing grid power consumption by approximately 72%. The DC-link voltage remained regulated at 800 V with a variation of less than ±1.5%.

**[2] Case 2: Reduced Solar Irradiance (400 W/m²)**
When solar irradiance decreased suddenly, PV output dropped significantly. The EMS activated the BESS to compensate for the power deficit and maintain uninterrupted charging. The battery SOC decreased from 90% to 76%, while EV charging power remained constant. No charging interruption was observed during the transition period.

**[3] Case 3: Peak Charging Demand**
During simultaneous charging of multiple EVs, the combined demand exceeded available PV generation. The EMS coordinated power sharing between the BESS and utility grid. Approximately 45% of the additional demand was supplied by the BESS, reducing peak grid loading and improving system reliability.

**[4] Power Quality Analysis**
The VSC effectively maintained unity power factor operation and reduced current harmonics. The Total Harmonic Distortion (THD) of grid current was reduced from 8.7% to 2.3%, satisfying IEEE-519 standards. Grid currents remained balanced even under rapidly changing charging conditions.

**[5] Overall Performance**
Simulation results confirm that the proposed PV–BESS–EV charging station enhances renewable energy utilization, reduces grid dependency, improves power quality, and ensures reliable EV charging under varying operating conditions.




## VI. CONCLUSION AND FUTURE WORK

This paper presented a comprehensive review and proposed framework for a grid-connected Electric Vehicle (EV) charging station integrated with a Photovoltaic (PV) array and Battery Energy Storage System (BESS). The proposed architecture combines renewable energy generation, intelligent energy management, and bidirectional power conversion to achieve efficient and sustainable EV charging. The Energy Management System (EMS) effectively coordinates power flow among the PV array, BESS, EV charging units, and utility grid, ensuring reliable operation under varying solar irradiance and load conditions. Simulation results demonstrated that the PV system can meet a significant portion of the charging demand while surplus energy is stored in the BESS for later use. The integration of BESS reduces grid dependency, supports peak-load management, and enhances charging reliability. Furthermore, the Voltage Source Converter (VSC) maintains DC-link voltage stability and improves power quality by minimizing harmonic distortion and

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maintaining near-unity power factor. Overall, the proposed PV–BESS integrated EV charging station offers an environmentally friendly, economically viable, and grid-supportive solution for future smart transportation and sustainable energy systems.

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