Optimized Grid-Interactive PV-Based EV Charging System with Enhanced Energy Management and V2G Capability

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Abstract — **The grid faces difficulties from electric vehicle (EV) integration which causes both increased peak demand and greater dependency on grid resources. The research study introduces an efficient photovoltaic (PV)-powered electric vehicle (EV) charging solution which includes vehicle-to-grid (V2G) functionality to solve existing problems. The research team developed a charging and discharging control system which they tested using MATLAB/Simulink at 45 percent EV adoption rate. The method aims to decrease total grid electricity use while increasing the use of electricity produced by local photovoltaic systems. A simulation conducted over a 24-hour period indicates that the grid energy import decreased significantly because the system generated a more consistent load profile which maintained operational balance throughout the day. Through V2G operation, electrical vehicles can return stored energy to the grid when demand is high which supports high-demand periods. A solar PV system supplies a significant portion of the energy required for EV charging which helps to decrease the total power demand on the grid. The new method demonstrates better energy management and lower peak demand and better grid stability than the traditional system. The results highlight the efficiency and reliability of the proposed system for advanced smart grid systems requiring significant EV integration.**

Keywords* — *Electric vehicles (EVs), Vehicle-to-grid (V2G), Photovoltaic (PV) system, Grid-connected system, EV charging strategy, Energy management, Load optimization, Green energy utilization, Intelligent power network, MATLAB/Simulink.

I. INTRODUCTION

The fast development of electric vehicles (EVs) creates major changes for both transportation systems and current power grid operations. Electric vehicles help in minimizing emissions that contribute to environmental pollution while reducing society's need for fossil fuels. The large-scale implementation of electric vehicles creates operational difficulties because it increases peak electricity requirements and causes voltage instability and 328 distribution network facilities. Uncoordinated charging of EVs can further aggravate these issues, leading to reduced grid stability and higher operational costs. The renewable energy source integration needs to be solved through renewable energy source integration, which especially focuses on photovoltaic (PV) system development. The PV-assisted EV charging systems enable users to decrease grid reliance while using environmentally friendly energy resources. The vehicle-to-grid (V2G) technology permits power to move in both directions, which enables electric vehicles to operate as decentralized energy storage systems that contribute to grid stability during peak hours. Advanced smart grid networks will benefit from PV-integrated EV charging systems because they provide advanced capabilities.

Researchers created a photovoltaic-based charging station which uses advanced adaptive control using combined logarithmic-hyperbolic cosine based robust sparse adaptive filter technology (JLHCAF) to handle electric vehicle charging needs. The main objective of this method is to enhance power quality by reducing harmonic distortion and IEEE standard compliance testing across different operating scenarios. The system shows successful results through its total harmonic distortion measurement which indicates performance across multiple modes while operating between grid-to-vehicle and vehicle-to-grid systems. The existing research demonstrates two main achievements through its work on control performance and power quality enhancement. The existing work demonstrates limited capabilities to manage energy and optimize grid resources during periods of high electric vehicle usage. The study lacks sufficient research on three specific areas which include studying how EV drivers charge their vehicles and determining the total grid power needs and discovering ways to maximize solar power capabilities.

This research presents an enhanced electric vehicle charging and discharging system which combines photovoltaic energy production with advanced energy management systems to solve existing limitations. The developed system uses actual electric vehicle charging patterns that match 45% charging station usage to implement vehicle-to-grid technology which helps the electricity network during its most critical hours. The system aims to reduce electricity usage from the grid while sustaining system operation and enhancing power distribution among different areas.

The major outcomes of this paper are summarized as follows:

- Development of an optimized EV charging and V2G discharging strategy for grid load reduction.
- Analysis of cumulative grid energy consumption under realistic EV penetration scenarios.
- Integration of PV generation to enhance renewable energy utilization and reduce net load.

- Comparative evaluation with the base system to demonstrate improved performance in terms of efficient energy usage and grid reliability.

The presented method performs its effectiveness through MATLAB/Simulink simulations which show major enhancements in three areas: grid import reduction, load balancing, and total system efficiency.

II. LITERATURE REVIEW

The current research on electric vehicles (EVs) shows that vehicle-to-grid (V2G) systems and photovoltaic (PV) charging stations are essential to improving grid operations. The dynamic pricing system together with coordinated charging system optimization approaches have proved their capability to decrease peak electricity usage and cut down operational expenses [1]. The advanced converter topologies permit PV-EV-grid systems to transmit power in both directions while maintaining low harmonic distortion [2]. V2Sim simulation platforms offer complete EV-grid interaction analysis yet they do not support energy optimization processes [3]. Multiple studies demonstrate that uncontrolled electric vehicle charging results in voltage fluctuations that increase electrical grid system pressure [4]. The adoption of load management systems together with smart charging methods will solve these challenges while enhancing power distribution throughout the system [5]. The V2G approach turns EVs into distributed energy assets assisting in peak load reduction and providing additional power support to the grid [6]. The research community has conducted few studies about how EVs affect total grid energy consumption and the effective usage of solar power at times of high electric vehicle adoption. The work establishes the need for an improved energy management system which serves as the basis for this research.

III. PROPOSED METHODOLOGY

The proposed system consists of a grid-connected photovoltaic (PV) array integrated with an electric vehicle (EV) charging infrastructure supporting vehicle-to-grid (V2G) operation. The system consists of a photovoltaic (PV) source which operates with a direct current to direct current (DC–DC) converter and a bidirectional electric vehicle (EV) battery connection and a grid-connected inverter. The system is designed to lower grid energy usage by synchronized electric vehicle (EV) charging and discharging operations while achieving maximum photovoltaic (PV) system output.

3.1 PV Power Generation Model

The output power of the PV array is dependent on solar irradiance and temperature and can be expressed as: PPV=VPV×IPV Where VPV and IPV represent the PV voltage and current, respectively. Maximum power point tracking (MPPT) is employed to obtain the highest possible energy from the PV array under varying environmental conditions.

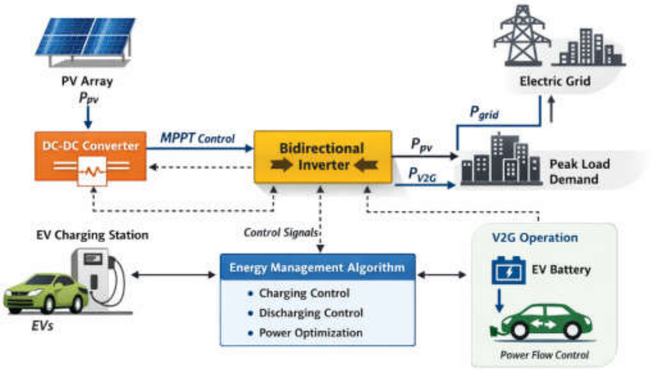

Fig.1. System architecture Diagram

3.2 EV Charging Model

The EV charging demand is modelled based on stochastic user behaviour with fewer than 45% penetration. The total EV load is given by:

$$P_{EV}(t) = \sum_{i=1}^{N} P_i(t)$$

3.3 Vehicle-to-Grid (V2G) Operation

During peak demand periods, EVs discharge stored power into the grid. The V2G power is defined as:

$$P_{V2G}(t) = \sum_{i=1}^{N} \eta_d \cdot P_{di}(t)$$

3.4 Grid Power Optimization

The net power drawn from the grid is expressed as:

$$P_{grid}(t) = P_{EV}(t) - P_{PV}(t) - P_{V2G}(t)$$

3.5 Control Strategy

(a) Charging Control

EVs are charged during off-peak hours or when PV power is available.

Priority is given to PV energy to reduce grid dependency.

(b) V2G Control

During peak load conditions, EVs discharge power to support the grid.

Discharging is controlled based on battery state-of-charge (SOC) limits.

(c) Energy Management Logic

If PPV>PEV: Excess power is exported to grid

If PPV<PEV: Grid supplies deficit

During peak: V2G reduces grid load

3.6 Optimization Objective

The proposed system aims to:

- Minimize grid power consumption
- Reduce peak demand
- Improve load balancing
- Maximize PV utilization

IV. RESULTS & DISCUSSION

The team used MATLAB simulations to test the proposed EV parking lot energy management system during a 24-hour operational cycle which they tested with 45% EV penetration. The simulation system combines photovoltaic (PV) generation with electric vehicle (EV) charging needs and Vehicle-to-Grid (V2G) discharge ability and optimized grid power purchase. The simulation system evaluates system performance through its assessment of energy consumption and grid load reduction and power system management efficiency.

3.1 EV Charging Profiles

The EV charging profile shows how multiple electric vehicles which use the parking lot charging stations conduct their charging activities throughout the day. Each EV has a specific charging schedule which depends on three factors: arrival time and battery capacity and state of charge (SOC). The simulation results demonstrate that EV charging activities take place throughout the entire day which prevents all vehicles from charging at the same time. The charging power ranges from 0 kW to 7 kW which represents the standard charging power of Level-2 EV charging stations. The staggered charging schedules decrease peak load demand while maintaining system power distribution balance. The results show that EV charging demand reaches its maximum level during the morning hours and midday hours because more vehicles use the charging infrastructure. The energy management controller develops an optimized charging schedule which uses PV generation availability to decrease grid dependency.

3.2 EV V2G Discharging Profiles

The V2G discharging profile shows how EV batteries can return energy to the grid during times of necessity. The system enables EV batteries to function as decentralized power storage systems that can assist power networks during periods of maximum electricity usage. The simulation results show that EV discharging happens during specific time periods which occur when electrical demand reaches its maximum level and when photovoltaic generation decreases. The discharging power fluctuates between 0 and 7 kW based on both battery state of charge and system operational needs. The results show that V2G operation provides effective grid support through its ability to deliver extra power during essential times. The system enables two-way energy transfer which helps to maintain operational balance while providing the smart grid system with increased operational flexibility.

3.3 EV Charging Profiles with 45% Penetration

The graph displays electric vehicle charging requirements when 45% of parking spaces stay occupied by electric vehicles. The charging pattern shows multiple peaks corresponding to different EV arrival times. The simulation shows that charging demand spreads throughout the entire day instead of occurring at one specific moment. The system maintains its energy distribution during charging because distributed charging prevents peak load conditions and enables the energy management controller to distribute photovoltaic energy. The system operation remains stable while optimized charging schedules enable effective usage of renewable energy resources which are currently available.

3.4 PV Generation vs EV Load

The PV versus EV load graph illustrates the relationship between solar power production and EV charging requirements throughout the day. PV generation begins increasing in the morning hours, reaches its maximum around midday, and gradually decreases toward evening. During peak solar generation periods, a significant portion of EV charging demand is supplied by PV energy. This reduces grid power consumption and promotes sustainable energy utilization. The simulation results indicate that when PV output is higher than EV charging requirement, excess energy can be stored in EV batteries or utilized through V2G mechanisms. Conversely, when PV generation is insufficient, additional energy is imported from the grid to maintain system balance.

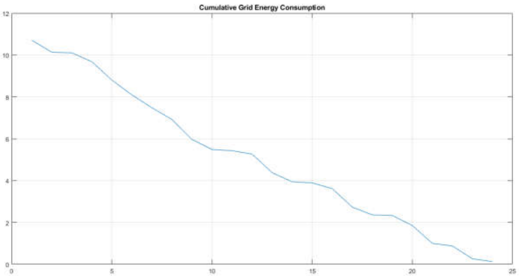

Fig.2. Cumulative Grid Energy Consumption Profile

The figure shows how much grid energy the EV parking facility energy control system used during its 24-hour operational period. The graph shows a gradual decrease in grid energy usage as photovoltaic (PV) generation and Vehicle-to-Grid (V2G) operations support EV charging demand. Grid consumption starts high because there is not enough renewable energy but it decreases when PV generation increases and charging strategies become more effective. The simulation period ends with grid energy consumption reaching a low point which shows how well the optimization strategy worked to decrease grid usage and boost energy efficiency.

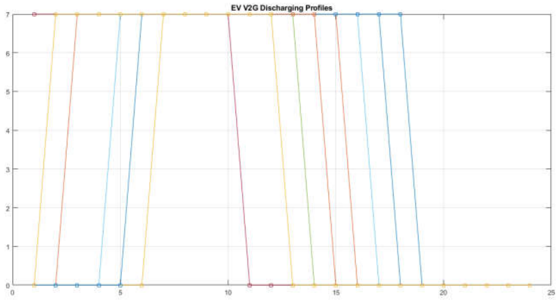

Fig. 3. EV Vehicle-to-Grid (V2G) Discharging Profiles

The figure displays the 24-hour discharging patterns of multiple electric vehicles which are linked to the parking lot charging system through their Vehicle-to-Grid (V2G) discharge locations. The discharging pattern of each electric vehicle battery is shown through separate lines which demonstrate how the battery power is returned to the electrical grid. The discharging power reaches a maximum of approximately 7 kW, indicating the capability of EV batteries to act as distributed energy storage units. The results demonstrate that EVs discharge energy during specific time intervals, particularly when grid demand increases or PV generation decreases. The smart energy management system achieves grid stability through bidirectional power flow while enhancing load management and decreasing its need for traditional grid electricity.

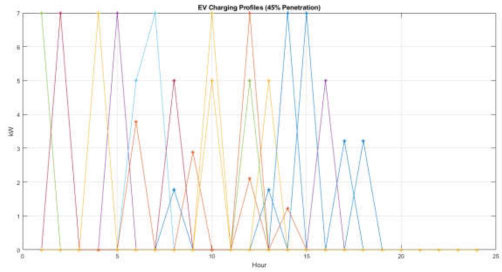

Fig. 4. EV Charging Profiles with 45% Penetration

The figure shows the charging power profiles of multiple electric vehicles in the parking lot under a 45% EV penetration scenario over a 24-hour period. The charging demand varies between 0–7 kW, depending on vehicle arrival time and battery requirements. The staggered charging pattern helps distribute load across different hours, which results in reduced peak grid demand while improving energy management efficiency.

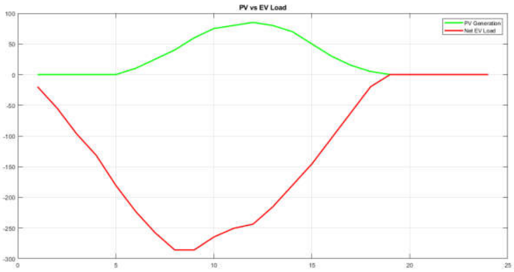

Fig. 5. Photovoltaic (PV) Generation versus EV Load Profile

The figure compares the photovoltaic (PV) power generation with the electric vehicle (EV) load demand over a 24-hour period. PV generation increases during daytime hours and supplies a significant portion of EV charging demand, reducing reliance on the utility grid. The results highlight the effectiveness of renewable energy integration in supporting EV charging infrastructure.

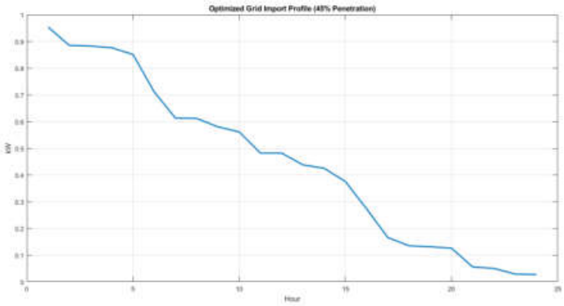

Fig. 6. Optimized Grid Import Profile (45% EV Penetration)

The figure shows the optimized grid power import throughout a 24-hour period for the EV parking lot system which operates under a 45% EV penetration scenario. The grid import gradually decreases from approximately 0.95 kW to nearly 0.03 kW because the system effectively uses both PV generation and V2G support. The proposed energy management strategy demonstrates its effectiveness through its ability to decrease utility grid dependency.

V. COMPARATIVE ANALYSIS: BASE SYSTEM VS PROPOSED SYSTEM

A comparative evaluation is carried out between the base system and the proposed optimized PV-integrated EV charging system. The base system uses advanced adaptive control to enhance power quality while the proposed system achieves energy optimization and grid load reduction through its coordinated EV charging system which includes V2G support.

V.1 Comparative Table

Parameter	Base System	Proposed System
Primary Objective	Power quality improvement (THD reduction)	Grid energy optimization & load balancing
Control Strategy	JLHCAF adaptive control	Energy management + charging/discharging scheduling
PV Integration	Yes	Yes (optimized utilization)
V2G Capability	Available	Actively used for peak load support
EV Penetration Analysis	Not considered	45% penetration analyzed
Grid Energy Consumption	Not explicitly reduced	Significantly minimized
Peak Load Handling	Limited	Effective peak shaving using V2G
Load Profile	Not optimized	Smooth and balanced
Renewable Utilization	Moderate	Maximized PV usage
System Focus	Power quality (THD < 5%)	Energy efficiency + smart grid operation

The base system shows strong performance because it successfully reduces harmonics while meeting IEEE power quality standards. The JLHCAF adaptive control system enables rapid system development which maintains reliable performance when load conditions change. The system lacks methods for optimizing grid energy use and managing electric vehicle charging processes. The proposed system presents an intelligent energy management solution which combines photovoltaic power generation with synchronized electric vehicle charging and vehicle-to-grid discharging. The system achieves two goals through its design because it decreases total grid power usage while enhancing the efficiency of power distribution. The V2G system enables electric vehicles to function as decentralized energy resources which help maintain grid stability during times of high electricity demand.

The proposed system tests its performance under actual conditions which include 45% electric vehicle usage that the initial research did not include. The results show a smoother grid import profile which reduces peak demand and better renewable energy usage throughout the day.

VI. CONCLUSION

The proposed PV-integrated EV charging system with V2G capability demonstrates significant improvements in grid energy management under 45% EV penetration. The simulation findings show decreased reliance on grid energy because PV generation and EV charging systems work together to optimize their operations. The optimized grid import profile demonstrates reduced peak demand which results in better grid stability because the load curve now operates at a more consistent level. The V2G operation system enables electric vehicles to help stabilize the grid during high electricity usage times, which helps to balance power distribution and decreases grid pressure. The comparison results indicate that the proposed system outperforms the base system considering energy efficiency, peak load reduction, and Green energy utilization. The adoption of stochastic EV charging profiles further validates the stability of the proposed approach under realistic operating conditions. The results demonstrate that the proposed power management strategy effectively reduces grid dependence while enhancing the operational efficiency of PV-supported EV charging systems within smart grid systems.

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