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# PV-EV Model Predictive Control- A Review

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***Abstract- The increasing adoption of electric vehicles (EVs) and the growing reliance on renewable energy sources like photovoltaic (PV) systems are transforming the traditional energy landscape. However, integrating these technologies into a unified system presents significant operational challenges, particularly in terms of real-time energy management and power flow optimization. This paper presents a comprehensive solution for managing power distribution in PV-powered EV charging stations through the application of Model Predictive Control (MPC). The proposed method leverages the predictive capabilities of MPC to anticipate future energy demands and PV generation levels, enabling informed, real-time decisions that optimize charging operations while minimizing reliance on the utility grid. The control framework accounts for dynamic variables such as solar irradiance, state-of-charge of connected EVs, and time-varying electricity tariffs. By continuously solving an optimization problem over a moving time horizon, the system adjusts control inputs to achieve efficient power allocation and cost-effective charging. Simulation studies demonstrate that the MPC-based strategy significantly improves system performance compared to traditional rule-based methods. Key benefits include reduced energy losses, enhanced grid stability, and increased utilization of locally generated solar power. Additionally, the system ensures that EVs are charged within required timeframes without overloading the network. The results confirm that MPC offers a flexible and scalable approach for intelligent energy management in smart charging infrastructures. This method contributes to the development of sustainable, grid-friendly EV charging networks that align with future smart grid and decarbonization goals.***

***Indexed Terms—Electric vehicles, Battery energy storage, Photovoltaic panel, Grid, MPPT.***

## I. INTRODUCTION

In recent years, the growing global energy demand, coupled with the depletion of conventional fossil fuel resources and the adverse environmental impacts such as global warming and carbon emissions, has highlighted the urgent need for cleaner and more sustainable energy alternatives. Renewable sources like solar, wind, ocean, and biomass energy have emerged as promising substitutes to traditional energy systems due to their environmental benefits and long-term viability. Electric vehicle (EV) sales are rapidly increasing and could reach 17 million units in 2024, with one in five cars sold being electric. In the first three months of 2024, EV sales grew by 25% compared to the same period in the previous year. With the integration of EVs into the distribution system, the load on feeders will become more complex to predict, potentially impacting power quality . Among all renewable energy sources, the photovoltaic systems have achieved rapid growth in commercial and industrial sectors due to the significant technological advancement in power electronics and solar cell .

The global shift towards sustainable energy and the growing concern over environmental degradation have accelerated the adoption of electric vehicles (EVs). While EVs significantly reduce greenhouse gas emissions compared to internal combustion engine vehicles, the widespread deployment of EV charging infrastructure presents new challenges for existing power systems. High and uncoordinated charging demand can lead to grid overloading, voltage instability, and increased peak load conditions. The proposed system also incorporates a Maximum Power Point Tracking (MPPT) mechanism to enhance the efficiency of solar energy conversion. The effectiveness of the design is validated through simulation studies, demonstrating the system's ability to reduce grid stress, ensure continuous EV charging, and support a more resilient and environmentally friendly power network.

The integration of photovoltaic (PV) systems with electric vehicle (EV) charging infrastructure is gaining traction as a sustainable solution to reduce grid dependency and support the transition to clean energy. However, challenges such as power quality, dynamic load management, and efficient energy utilization require advanced control strategies. The majority of existing electric vehicle (EV) charging stations are directly connected to the conventional power grid. While this approach enables continuous power availability, it also significantly increases the load on the already stressed grid infrastructure, especially during peak charging hours. The escalating demand from widespread EV adoption further exacerbates grid instability and raises concerns about energy sustainability and reliability.

This scenario underscores the urgent need to explore alternative power solutions, particularly those based on renewable energy sources such as solar and wind. Integrating renewable energy into EV charging infrastructure not only helps to alleviate pressure on the electrical grid but also supports global efforts to reduce greenhouse gas emissions and transition toward cleaner energy systems. Moreover, renewable-powered charging stations can offer decentralized and environmentally friendly energy solutions, especially in remote or underserved areas.

A new evolutionary called particle swarm optimization (PSO) has been proposed. PSO has been motivated by the behavior of organisms such as fish schooling and bird flocking. Local modes of oscillations are those associated with a single generator or plant, while global ones are related to groups of generators or plants. The term inter-area is used when referring to global modes of oscillations. To mitigate these issues, integrating renewable energy sources with energy storage systems in EV charging stations has emerged as a viable solution. Among the various renewable options, solar photovoltaic (PV) systems are particularly attractive due to their scalability, low maintenance, and abundance in many regions. However, the intermittent nature of solar energy requires support from energy storage systems, such as batteries, to ensure reliable and continuous charging.

This study focuses on the development and analysis of a solar photovoltaic (PV)-based electric vehicle (EV) charging station integrated with a battery energy storage system (BESS). The proposed station design incorporates nine DC fast charging ports to accommodate the energy demands of incoming EVs, which serve as the primary load. To ensure economic viability and operational efficiency, a cost optimization of the BESS is undertaken. The analysis takes into account several factors influencing battery cost, such as initial investment, lifecycle performance, degradation rate, and operational efficiency. To address the complex nature of this multi-variable optimization problem, the Particle Swarm Optimization (PSO) algorithm is employed due to its robustness and convergence capabilities. In addition to cost analysis, accurate forecasting of both solar energy generation and charging demand plays a vital role in the efficient operation of a PV- based charging infrastructure. Given the intermittent nature of solar power and the variable behavior of EV charging demand, predictive modeling becomes essential.

In this context, artificial neural networks (ANNs) are utilized for forecasting tasks, owing to their proficiency in handling non-linear, time-dependent data. Unlike conventional forecasting techniques, neural networks can learn from historical trends and variable inputs, thereby enhancing prediction accuracy for both solar irradiance and load demand. Load forecasting, in particular, relies heavily on historical consumption patterns, environmental conditions, and time-of-use variables. By analyzing and learning from these datasets, the forecasting model can effectively anticipate future energy demands at the station, allowing for better scheduling of energy resources and improved operational planning. The integration of forecasting with optimization not only supports real-time control but also contributes to the long-term sustainability and economic performance of the solar-powered EV charging station.

## II. MODELING AND SIMULATION BLOCK DIAGRAM

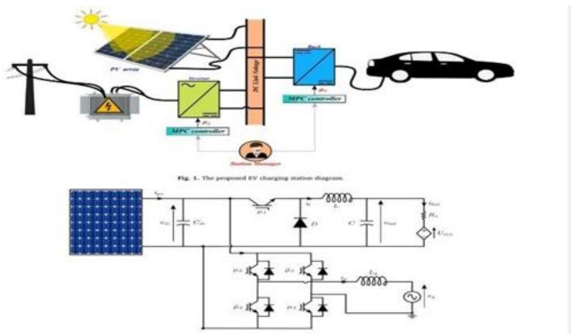

Figure 1. System Block Diagram

The block diagram illustrates a solar-integrated electric vehicle (EV) charging station, incorporating a Battery Energy Storage System (BESS) and intelligent control mechanisms to optimize energy management. The system begins with a photovoltaic (PV) array, which captures solar energy. This energy is regulated through a Maximum Power Point Tracking (MPPT) controller, ensuring that the PV system operates at its highest efficiency under varying environmental conditions. The regulated power is then fed into a DC link, which serves as a common power bus. In parallel, the utility grid is connected to the same DC link through a power electronic interface, allowing bi-directional power flow. This ensures that energy can be drawn from the grid when solar output is insufficient or injected back into the grid during excess generation, depending on system demand.

A Battery Energy Storage System (BESS) is connected to the DC link and managed by a dedicated MPPT controller. This battery stores excess solar energy and supplies power during high demand or low generation periods, helping to flatten peak loads and maintain grid stability. Electric vehicles are charged from the DC link through a smart charging interface that regulates charging based on available energy sources and real-time load conditions. A station manager module supervises the entire system operation, managing source prioritization and load balancing using a control algorithm.

The lower portion of the figure presents a detailed circuit diagram representing the interfacing of the PV system and battery with power electronic converters and filtering components. It includes switches, inductors, and capacitors that condition the DC power, making it suitable for EV charging applications. This configuration ensures smooth power delivery, minimizes ripple, and protects the connected equipment.

This hybrid setup enhances the reliability and efficiency of the EV charging process while mitigating stress on the power grid, particularly during peak demand periods.

## II. COMPONENTS USED

A solar-based electric vehicle charging station typically comprises several key components, including photovoltaic (PV) panels, a battery energy storage system (BESS), power conditioning units, and multiple charging ports. Each component plays a critical role in ensuring efficient energy conversion, storage, and delivery to meet the dynamic charging demands of electric vehicles.

i. Photovoltaic (PV) Array:

the Photovoltaic (PV) array serves as the fundamental energy generation unit. It comprises a series of solar panels configured to harvest solar energy and convert it into direct current (DC) electricity through the photovoltaic effect. The energy generated by the PV array directly supports the charging demand of EVs while also supplying power to the battery storage system and, when necessary, exporting excess energy to the grid. Given the variable nature of solar irradiance, the output of the PV array is inherently intermittent and non-linear, necessitating the integration of control strategies such as Maximum Power Point Tracking (MPPT) to maximize energy harvest. Within the framework of Model Predictive Control (MPC), real-time forecasting of solar power plays a vital role in predicting available PV output and optimizing power flow. As a result, the PV array not only acts as a sustainable power source but also plays a critical role in the control-oriented architecture of intelligent EV charging systems, contributing to reduced grid dependency and enhanced energy autonomy.

ii. MPPT Controllers (Maximum Power Point Tracking): Maximum Power Point Tracking

(MPPT) controllers are essential components in solar photovoltaic (PV) systems, designed to continuously extract the maximum available power from the PV array under varying environmental conditions. In a solar-powered EV charging station, the output of the PV array fluctuates due to changes in solar irradiance and temperature, which affects the operating point of the system. MPPT controllers dynamically adjust the voltage and current of the PV array to operate at the point where power output is maximized. This is achieved through advanced algorithms that track the nonlinear characteristics of PV modules in real time. Integrating MPPT with Model Predictive Control (MPC) further enhances overall system efficiency by providing predictive adjustments based on anticipated solar generation. The use of MPPT is particularly critical in ensuring that the solar energy harvested is optimally utilized for charging electric vehicles or storing in the battery energy storage system (BESS). As a result, MPPT controllers significantly improve energy yield, system reliability, and economic performance of PV-EV charging infrastructures.

iii. DC Link (DC Bus):

The DC link, also referred to as the DC bus, serves as a central electrical interconnection within a solar-powered electric vehicle (EV) charging station. It acts as a common pathway that connects multiple power electronic components, such as the output of the photovoltaic (PV) array, battery energy storage system (BESS), and DC-DC or DC-AC converters. The primary function of the DC link is to stabilize and distribute the direct current (DC) power collected from the PV array or discharged from the battery, ensuring a consistent voltage level for downstream components. It also facilitates bidirectional power flow, allowing energy to be directed either toward EV charging or back to the grid, depending on system demands. The voltage regulation and energy buffering capabilities of the DC link are critical in managing transient variations and maintaining system stability. In a system governed by Model Predictive Control (MPC), the DC link serves as a pivotal control point, enabling coordinated real- time power management across all subsystems. Its efficient design and operation are essential for ensuring reliable, flexible, and efficient performance in modern smart charging infrastructure.

iv. Battery Energy Storage System (BESS):

The Battery Energy Storage System (BESS) plays a pivotal role in enhancing the reliability, flexibility, and efficiency of photovoltaic (PV)-based electric vehicle (EV) charging stations. Acting as an energy buffer, the BESS stores excess solar energy generated during periods of high irradiance and supplies power during times of low generation or peak EV charging demand. This capability significantly reduces dependence on the utility grid and contributes to better load balancing. The integration of BESS allows for time-shifting of energy usage, improving the economic viability of the charging station by enabling energy arbitrage and minimizing energy wastage. In a control-oriented framework such as Model Predictive Control (MPC), the BESS is managed proactively, with real-time decisions optimizing charging and discharging cycles based on forecasted solar output, load demand, and energy prices. Efficient operation of the BESS depends on factors such as battery type, state of charge, degradation rate, and power conversion efficiency. Through intelligent coordination with other system components, the BESS enhances overall system stability, reduces operational costs, and supports the transition to sustainable, grid-independent EV charging infrastructure.

v. Bidirectional Grid Interface:

The bidirectional grid interface is a crucial component in modern photovoltaic (PV)-based electric vehicle (EV) charging stations, enabling dynamic interaction between the charging infrastructure and the utility grid. Unlike conventional unidirectional systems, this interface allows for both importing electricity from the grid during periods of insufficient solar generation and exporting excess power back to the grid when generation exceeds local demand. Such flexibility enhances the overall resilience and operational efficiency of the charging station. In systems governed by Model Predictive Control (MPC), the bidirectional grid interface is intelligently managed to optimize power exchange based on forecasted load, solar production, and grid pricing signals. This not only helps in reducing peak demand charges but also supports grid stability by contributing to ancillary services like voltage regulation and frequency control. The interface typically includes power electronic converters capable of seamless bidirectional operation, ensuring synchronized and safe power flow.

By integrating this feature, PV-EV charging stations can operate more economically and sustainably, contributing to the development of smart, grid-responsive energy ecosystems.

vi. Station Manager / Control Algorithm:

The Station Manager, supported by a robust control algorithm, serves as the central intelligence unit of a photovoltaic (PV)- based electric vehicle (EV) charging station. It is responsible for coordinating the operation of all major subsystems, including the photovoltaic array, battery energy storage system (BESS), power converters, grid interface, and EV charging ports. The control algorithm continuously monitors real-time data such as solar power availability, energy storage levels, EV charging demand, and grid conditions to make optimized decisions. In advanced systems, Model Predictive Control (MPC) is employed as the core algorithm, enabling predictive and adaptive energy management by solving optimization problems over a rolling time horizon. This approach ensures that the charging station operates efficiently, maintains energy balance, and minimizes operational costs while satisfying user charging requirements. The Station Manager also facilitates demand forecasting, energy scheduling, and fault handling, contributing to the station's reliability and responsiveness. By integrating data-driven control with predictive modeling, the Station Manager plays a vital role in transforming conventional charging stations into intelligent, grid-aware energy hubs.

vii. Power Electronic Converter (DC-DC and DC-AC Converters):

Power electronic converters, including DC-DC and DC-AC types, are essential components in solar-powered electric vehicle (EV) charging stations, facilitating efficient energy conversion and management across different subsystems. The DC-DC converter is primarily used to regulate voltage levels between the photovoltaic (PV) array, battery energy storage system (BESS), and EV chargers. It enables bidirectional energy flow in cases where power must be either drawn from or supplied to the battery, optimizing charge and discharge operations based on system demands. On the other hand, the DC-AC converter, or inverter, is responsible for interfacing the station with the utility grid, converting DC electricity into grid-compatible alternating current (AC). These converters play a crucial role in maintaining voltage stability, controlling current flow, and ensuring high conversion efficiency. In an optimized control framework such as Model Predictive Control (MPC), the operation of these converters is dynamically adjusted based on real-time forecasts of solar irradiance and charging demand, allowing for coordinated and predictive power flow management. Their proper design and control are fundamental to achieving high- performance, low-loss, and flexible operation in smart EV charging infrastructure.

viii. Inductors and Capacitors:

Inductors and capacitors are fundamental passive components used extensively in the power electronic circuitry of photovoltaic (PV)-based electric vehicle (EV) charging stations. These components play a critical role in filtering, energy storage, voltage regulation, and the overall stability of the power conversion process. Inductors are primarily used to control the rate of change of current and to store energy temporarily in magnetic fields, which is particularly important in DC-DC converters to ensure smooth energy transfer and minimize ripple currents. Capacitors, on the other hand, store energy in electric fields and are vital for filtering voltage fluctuations, maintaining a stable DC bus voltage, and supporting transient load conditions. When integrated into converter circuits, the coordinated operation of inductors and capacitors ensures efficient and reliable power delivery by mitigating harmonics and reducing electromagnetic interference (EMI). In systems utilizing Model Predictive Control (MPC), the performance and behavior of these passive components are factored into the control model to enhance dynamic response and optimize the power flow between PV arrays, batteries, and EV loads. Their correct sizing and placement are crucial for achieving high efficiency and stability in modern power electronic systems.

ix. Switches (MOSFETs or IGBTs):

Semiconductor switches, such as Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) and Insulated Gate Bipolar Transistors (IGBTs), are integral components in the power electronic converters used within photovoltaic (PV)-based electric vehicle (EV) charging stations. These devices are responsible for controlling the flow of electrical energy by rapidly switching power on and off in response to control signals. MOSFETs are typically used in low- to medium-voltage applications due to their high switching speed and efficiency, making them ideal for DC-DC converter stages. IGBTs, on the other hand, are preferred in higher voltage and power applications, such as DC-AC inverters and bidirectional grid interfaces, because of their ability to handle large currents with relatively low conduction losses. The selection between MOSFETs and IGBTs depends on system voltage levels, switching frequency requirements, and thermal management considerations. In advanced control strategies like Model Predictive Control (MPC), the operation of these switches is optimized to achieve precise voltage and current regulation, minimize switching losses, and enhance overall system performance. Their reliable operation is critical to ensuring efficient power conversion, reduced electromagnetic interference, and extended lifespan of the charging station components.

## III. METHODOLOGY

This research develops an advanced control framework for a solar photovoltaic (PV)-based electric vehicle (EV) charging station integrated with a Battery Energy Storage System (BESS). The system architecture includes a PV array, MPPT controllers, power electronic converters (both DC-DC and DC-AC), a bidirectional grid interface, and multiple fast-charging ports for EVs. The main aim is to optimize real-time power management by coordinating energy flows among the PV array, battery, grid, and EV loads to enhance system efficiency, reliability, and economic performance. Model Predictive Control (MPC) is employed as the core strategy due to its capability to handle system constraints and predict future operating conditions for optimal decision making.

The initial stage involves detailed modeling of the PV-EV charging station components. The PV array model accounts for variations in solar irradiance and temperature, enabling realistic simulation of power output. MPPT controllers are integrated to continuously track the maximum power point of the PV array under changing environmental conditions. The battery model includes critical parameters such as state of charge (SOC), capacity, charging/discharging efficiencies, and degradation factors. Additionally, power electronic converters are modeled to represent the dynamics of voltage and current conversion between the different subsystems. A bidirectional grid interface model is developed to allow controlled import and export of power, supporting grid stability and energy balancing.

Accurate forecasting of solar power generation and EV charging load demand forms the next critical step. A neural network-based approach is utilized for predicting short-term solar irradiance and PV output, leveraging historical weather data and real-time measurements. Load forecasting incorporates analysis of historical charging behavior, time-dependent usage patterns, and EV arrival rates to estimate future power demands. These predictive models provide essential inputs to the MPC algorithm, enabling proactive energy management that anticipates fluctuations rather than reacting solely to current conditions.

The core of the methodology lies in the design and implementation of the Model Predictive Control algorithm. MPC formulates a constrained optimization problem over a finite prediction horizon, aiming to minimize a cost function that includes energy costs, battery degradation penalties, and grid interaction charges. The constraints encompass battery operational limits (such as SOC thresholds), converter power ratings, and grid capacity restrictions. By solving this optimization at each control interval, the MPC controller determines optimal power setpoints for the PV array, BESS, and grid interface. This predictive, rolling horizon approach allows the system to adapt dynamically to uncertainties while respecting physical and operational constraints.

To implement the control strategy, power electronic converters are managed to follow the MPC-generated setpoints. DC-DC converters regulate the power exchange between the PV array, battery, and DC bus, ensuring efficient energy flow and voltage stabilization. The DC-AC inverter facilitates bidirectional power transfer between the DC bus and the grid, allowing excess energy to be fed back to the utility or supplemental power to be drawn when necessary. Fast charging ports for EVs receive controlled power delivery based on real-time station load and available renewable energy, optimizing user satisfaction and energy utilization.

The proposed system and control algorithm are rigorously tested using comprehensive simulation studies. Various scenarios incorporating different solar irradiance profiles, EV arrival patterns, and grid conditions are analyzed to evaluate performance metrics such as energy efficiency, cost savings, battery cycling, and grid dependency reduction. The MPC-based control is compared against conventional rule-based methods to demonstrate its superior ability to handle uncertainties and improve overall station operation. These simulations validate the effectiveness of the methodology in real-time applications and highlight potential for practical deployment.

1. Solar PV Integration with MPPT
The system begins with a PV array that captures solar irradiance and converts it into DC electrical energy. An MPPT (Maximum Power Point Tracking) controller is employed to ensure that the PV system operates at its highest efficiency, regardless of variations in sunlight and temperature. This improves the overall energy yield from the PV system.

2. DC Link and Power Distribution
The output from the PV system is fed into a DC link, which serves as the main power hub. The DC link connects the PV system, battery storage, grid interface, and EV charger, enabling seamless energy exchange among these components.

3. Battery Energy Storage System (BESS) Operation
A battery system is connected to the DC link to store excess energy generated by the PV panels. This stored energy is used to charge EVs during low generation periods or peak demand times, reducing reliance on the grid. The battery is also managed by a separate MPPT-based controller to regulate charging and discharging efficiently.

4. Grid Integration
The grid interface provides bi-directional power flow. When solar generation and battery capacity are insufficient to meet EV charging demand, power is drawn from the grid. Conversely, during periods of excess generation, surplus energy can be fed back into the grid, depending on regulatory permissions and technical configurations.

6. Central Control Unit (Station Manager)
A central controller or station manager oversees the entire system. It continuously monitors load demand, source availability, and system parameters. Using a decision-making algorithm, it determines the most efficient source for EV charging at any given time, thereby ensuring optimal load management and improving voltage stability across the grid.

7. Power Electronics and Circuit Configuration
The system employs power electronic converters (DC-DC and possibly DC-AC) to regulate voltage levels and ensure efficient energy transfer. The circuit includes inductors, capacitors, and semiconductor switches (e.g., MOSFETs or IGBTs) to filter out ripples and enhance power quality.

As the adoption of electric vehicles (EVs) continues to grow rapidly, the demand for charging infrastructure is increasing proportionally. Conventional EV charging stations, when connected solely to the utility grid, contribute to peak demand and may cause power quality issues, voltage instability, and network congestion. Integrating renewable energy sources—particularly solar photovoltaic (PV) systems—with battery energy storage provides a viable solution to mitigate these effects. The proposed hybrid system not only ensures a sustainable energy supply but also contributes to decarbonization goals.

This methodology integrates forecasting, modeling, and advanced control to achieve an optimized power management system for PV-EV charging stations. The use of Model Predictive Control enables real-time, predictive decision making that balances energy sources, minimizes costs, and prolongs battery life. By coordinating renewable generation, storage, and grid interaction, the approach supports sustainable and efficient electric vehicle charging infrastructure, contributing to the broader goals of clean energy transition and smart grid development.

## V. ALGORITHM [MATLAB\SIMULINK]

The control algorithm is developed to manage energy flow within the proposed EV charging station by dynamically selecting the optimal power source—solar PV, battery storage, or the utility grid—based on real-time operating conditions. The algorithm is implemented as a state-based controller using MATLAB/Simulink and follows the steps outlined below:

1. Input Parameters

PPV : Real-time power generated by the PV array. SOC: State of charge of the battery.

PEV : Power demand from the EV(s). Vgrid : Grid voltage level.

Pgrid_max : Maximum allowable grid power draw. SOCmin, SOCmax : Battery charge limits.

2. Initialization

Set the system to idle mode if no EV is connected. Initialize SOC monitoring for battery.

Establish default priority: PV → Battery → Grid.

3. Mode Selection Logic
4. Battery Management Subroutine
5. Grid Voltage Monitoring
6. Output Signals

The core of the proposed real-time power control strategy for the PV-EV charging station is based on the Model Predictive Control (MPC) algorithm. MPC is an advanced control technique that optimizes system performance by solving a finite horizon optimization problem at every control step, using a predictive model of the system dynamics. The control logic is modelled using MATLAB's State flow for decision-making and Simulink for system-level integration. The power electronic converters are modelled using standard Simulink blocks or Simscape Electrical toolbox. SOC estimation uses a coulomb counting method for simplicity.

The algorithm begins by collecting real-time data, including current solar power output from the photovoltaic (PV) array, the state of charge (SOC) of the battery energy storage system (BESS), the grid power availability, and the electric vehicle (EV) charging demand. Additionally, it incorporates forecasts of solar irradiance and EV load for a future prediction horizon, typically spanning several minutes to hours depending on system requirements.

Using this information, the MPC formulates an objective function that aims to minimize the total operational cost, which typically includes the cost of electricity purchased from the grid, degradation cost of the battery due to cycling, and any penalties associated with energy export or grid constraints. The function also ensures that the system meets the EV charging demand while respecting the physical and operational limits of the components, such as battery SOC boundaries, converter power ratings, and grid import/export limits.

At each control interval, the MPC algorithm solves this constrained optimization problem using numerical optimization techniques, generating an optimal sequence of control inputs— such as power setpoints for the PV array, battery charge/discharge rates, and grid power exchange. However, only the first control input in this sequence is implemented in the system. At the next time step, the algorithm updates its predictions and measurements, and the optimization is solved again, forming a rolling horizon approach. This feedback mechanism allows the controller to continuously adjust its decisions based on updated system states and external conditions, effectively handling uncertainties in solar power and EV charging load.

By proactively anticipating future changes and making optimized decisions accordingly, the MPC algorithm enhances the efficiency, reliability, and economic performance of the PV- EV charging station. This approach leads to improved utilization of renewable energy, reduced grid dependency, and prolonged battery lifespan, contributing to sustainable and intelligent energy management.

## VI. FORMULAS

1. Photovoltaic (PV) Power Output

The output power of a PV array is calculated as: $PPV=VPV \times IPV$

Where:

VPV : Output voltage of PV array IPV : Output current of PV array

2. Maximum Power Point Tracking= $dV/dP=0$

$\Rightarrow dV/dI=-I/V$

3. Battery Charging/ Discharging $Pbat=Vbat \times Ibat \times \eta bat$
4. DC link Power Balance $PPV + Pgrid + P\ bat = PEV$
5. Grid Power Control $Pgrid = PEV - (PPV + Pbat)$

## CONCLUSION

The proposed system presents an effective solution to address the increasing energy demands posed by the growth of electric vehicles (EVs), while minimizing stress on the utility grid. By integrating a photovoltaic (PV) array with a battery energy storage system (BESS), the charging station is capable of operating independently from the grid during peak periods and utilizing renewable energy efficiently. The incorporation of Maximum Power Point Tracking (MPPT) significantly enhances the energy extraction from the solar panels under varying environmental conditions. Through intelligent control algorithms implemented in MATLAB/Simulink, the system dynamically switches between energy sources—PV, battery, and grid—based on real-time load and source conditions. This ensures uninterrupted and optimized EV charging, improves voltage stability, and promotes efficient energy utilization. The control strategy also protects the battery from overcharging or deep discharging, thereby extending its operational lifespan.

This research develops and demonstrates an optimized real- time power control strategy for a photovoltaic (PV)-based electric vehicle (EV) charging station integrated with a battery energy storage system (BESS). The application of Model Predictive Control (MPC) allows for dynamic coordination of power flows among the PV array, battery, grid, and EV loads, effectively balancing energy supply and demand in the presence of uncertainties such as fluctuating solar generation and variable charging demands. The proposed control approach not only reduces operational costs by minimizing reliance on grid energy during peak pricing periods but also extends battery life by avoiding excessive cycling through intelligent charge/discharge management. Simulation results highlight significant improvements in renewable energy utilization, grid interaction reduction, and overall system efficiency compared to conventional rule-based control methods.

Moreover, the integration of accurate forecasting models for solar irradiance and EV load demand into the MPC framework enables proactive and adaptive decision-making. This predictive capability is crucial for handling the inherent variability and intermittency of renewable energy sources and dynamic EV charging patterns. By continuously updating control inputs based on rolling horizon optimization, the system maintains operational flexibility and robustness, ensuring user charging requirements are met without compromising system stability. The comprehensive control framework thus offers a scalable and practical solution for managing complex energy flows in emerging smart charging infrastructures.

It can focus on extending the proposed control framework by incorporating vehicle-to-grid (V2G) capabilities, allowing EVs to act as distributed energy resources that can supply power back to the grid during peak demand. Additionally, integration with smart grid communication protocols can enable more dynamic interaction with grid operators, facilitating demand response and ancillary services. Further improvements can be made by enhancing the forecasting accuracy through advanced machine learning techniques and incorporating real-time pricing models to optimize energy costs more effectively. Moreover, experimental validation using hardware-in-the-loop (HIL) setups or pilot deployments would provide valuable insights into practical challenges and performance under real-world conditions. These advancements would support the widespread adoption of intelligent, renewable-powered EV charging stations, contributing to a cleaner and more resilient energy ecosystem.

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