Next Generation of Solar Grid EV Coordination Powered by Fuzzy Logic Intelligence and Reconfigurable Converter Control.

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Abstract

Global electric vehicle (EV) sales exceeded 17 million units in 2024, accounting for more than 20% of new passenger vehicle sales worldwide, while renewable energy-based charging infrastructure continues to expand to reduce carbon emissions and grid dependency. However, the intermittent nature of solar photovoltaic (PV) generation and the increasing charging demand create significant challenges in maintaining stable, efficient, and reliable power management in EV charging stations. Solar-integrated EV charging systems are increasingly deployed in residential communities, commercial parking facilities, workplaces, highways, public charging stations, and smart grid applications, where intelligent coordination among renewable energy sources, battery storage, and the utility grid is essential for uninterrupted charging and enhanced energy utilization. Existing coordinated control and power flow management strategies effectively enable bidirectional power exchange among the PV array, battery energy storage system, and utility grid; however, they primarily rely on fixed rule-based control and instantaneous measurements, resulting in limited adaptability to dynamic solar irradiance, battery conditions, and load variations. To address these limitations, this work proposes a Predictive Fuzzy Logic Controlled Coordinated Control and Power Flow Management Strategy (PFLC-CC-PFMS) for a solar-powered bidirectional EV charging system. The proposed framework integrates a predictive state forecaster with a fuzzy logic inference engine to anticipate future photovoltaic generation, battery current, DC-link voltage, and converter operating conditions before determining optimal control actions. The predictive fuzzy controller coordinates the PV boost converter, phase-shifted full-bridge converter, and Totem-Pole PFC converter to achieve adaptive power balancing, intelligent battery charging and discharging, stable DC-link voltage regulation, optimized converter switching, and seamless bidirectional power flow among the PV array, battery storage system, and utility grid. Consequently, the proposed PFLC-CC-PFMS enhances renewable energy utilization, reduces converter losses, improves charging efficiency, strengthens grid support capability, and provides reliable, stable, and energy-efficient EV charging under dynamically changing environmental and loading conditions.

Keywords: Electric Vehicle Charging Systems, Solar Photovoltaic Systems, Predictive Fuzzy Logic Control, Bidirectional Power Flow Management, Battery Energy Storage Systems, Renewable Energy Integration.

1. Introduction

The rapid growth of electric vehicles (EVs) has transformed the global transportation sector, creating an urgent demand for efficient, sustainable, and intelligent charging infrastructure. According to the International Energy Agency (IEA), global EV sales exceeded 17 million units in 2024, representing more than 20% of all new passenger vehicle sales worldwide, while the worldwide EV fleet continues to expand each year due to increasing environmental awareness and government policies promoting clean mobility. Simultaneously, solar photovoltaic (PV) capacity has experienced remarkable growth because of declining installation costs, technological advancements, and supportive renewable energy policies. These developments have encouraged the integration of solar energy into EV charging stations to reduce greenhouse gas emissions, minimize dependence on fossil fuels, and lower electricity costs. As renewable energy becomes a larger component of modern power systems, maintaining reliable and efficient charging operations has become a significant engineering challenge.

The integration of photovoltaic systems, battery energy storage systems, and utility grids has created a new generation of hybrid EV charging stations capable of supporting continuous charging under varying environmental conditions. These charging stations are expected to operate efficiently despite fluctuations in solar irradiance, changing battery charging requirements, varying electricity demand, and dynamic grid conditions. In recent years, governments, utility providers, automobile manufacturers, and renewable energy companies have invested heavily in expanding charging infrastructure to support increasing EV adoption. Consequently, effective coordination among multiple energy resources has become essential for maintaining charging reliability, improving renewable energy utilization, ensuring stable power quality, and supporting future smart grid development. The increasing complexity of modern charging systems highlights the importance of advanced energy management strategies that can efficiently coordinate multiple power sources under continuously changing operating conditions.

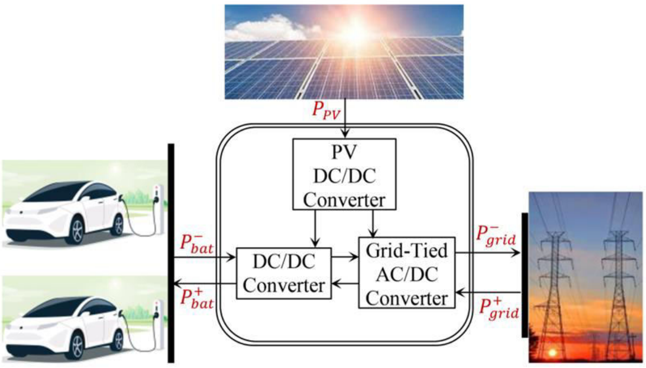

Figure 1: General Architecture of a Solar-Integrated Bidirectional Electric Vehicle Charging System

Figure 1 illustrates the general architecture of a solar-integrated bidirectional electric vehicle (EV) charging system that enables coordinated energy exchange among the photovoltaic (PV) array, battery energy storage system, utility grid, and electric vehicles. The photovoltaic array serves as the primary renewable energy source and supplies electrical power to the PV DC/DC converter, which regulates the PV output before transferring it to the common power conversion stage. A bidirectional DC/DC converter manages the charging and discharging of the EV battery by enabling energy transfer in both directions according to the charging requirements. Simultaneously, the grid-tied AC/DC converter interfaces the charging system with the utility grid, allowing power to be imported from the grid during insufficient solar generation or exported to the grid whenever surplus photovoltaic energy or stored battery energy becomes available. The bidirectional power flow between the battery and the charging station is represented by the charging power and discharging power, while the utility grid also supports bidirectional energy exchange through grid import and export operations. This integrated architecture ensures continuous EV charging under varying solar irradiance and load conditions by intelligently coordinating renewable energy generation, battery storage, and grid support. Consequently, the system improves renewable energy utilization, reduces dependence on conventional electricity sources, supports vehicle-to-grid (V2G) functionality, enhances power system flexibility, and provides a reliable foundation for sustainable electric vehicle charging infrastructure within modern smart grid environments.

2. Literature Survey

Sekhar et al. [1] introduced an Enhanced Hybrid Converter (EHC) architecture to integrate photovoltaic (PV) generation, the utility grid, and electric vehicle (EV) charging within a unified platform. The converter incorporated a coordinated control mechanism capable of extracting maximum solar power, maintaining a regulated DC-link voltage, and supporting bidirectional energy exchange between the PV source, grid, and EV battery. Multiple operating scenarios, including PV-to-EV, PV-to-Grid, EV-to-Grid, and independent PV charging, were successfully accommodated. In addition, a dedicated switching algorithm was implemented to ensure reliable converter performance under no-load conditions. The effectiveness of the proposed system was confirmed through MATLAB/Simulink analysis and experimental verification using a TI F28379D-based hardware controller. García-Triviño et al. [2] presented a supervisory energy management framework for a grid-connected medium-voltage DC microgrid incorporating photovoltaic generation, battery storage, hydrogen energy storage, and electric vehicle charging facilities. Their approach utilized Z-source converter technology to interface multiple energy resources with a common MVDC bus while minimizing the number of required power conversion stages. The supervisory controller coordinated energy flow among all sources and loads, ensuring power balance and improving economic performance through optimized interaction with the utility grid. This architecture demonstrated enhanced operational flexibility and efficient utilization of distributed renewable resources. Sun et al. [3] designed a compact photovoltaic-assisted bidirectional charging system for switched reluctance motor-based electric vehicles. The proposed configuration combined the electric drive and charging circuitry into a single integrated platform capable of supporting Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and Vehicle-to-Load (V2L) operating modes. A bridgeless interleaved boost converter was employed to achieve efficient battery charging while maintaining a high input power factor and enabling smooth bidirectional power transfer among the PV array, battery pack, utility grid, and motor drive. The integrated design reduced hardware complexity while improving charging efficiency. Lenka et al. [4] developed a multifunctional off-board EV charging system powered by photovoltaic energy with enhanced grid support capabilities. An Adaptive Notch Filter (ANF)-based control strategy was incorporated to accurately estimate the fundamental components of grid voltage and current under distorted operating conditions. The charger was designed to function in both standalone and grid-connected modes, allowing simultaneous battery charging, harmonic current compensation, reactive power support, and backup power supply for residential loads. The proposed control methodology significantly improved grid power quality while ensuring reliable charging performance.

Abeywardana et al. [5] investigated a single-phase boost inverter-based EV charger capable of providing reactive power compensation during Vehicle-to-Grid (V2G) operation. To overcome the adverse effects of second-order harmonic ripple currents on battery performance, the authors incorporated a DC-side capacitor that effectively suppressed ripple propagation into the battery. The charger delivered reactive power support without causing unnecessary battery discharge or excessive current stress. Furthermore, the study examined converter dynamic characteristics, operating mode transitions, capacitor voltage regulation, and appropriate capacitor sizing to ensure stable and efficient system operation. Monteiro et al. [6] introduced a three-port integrated charging architecture that established a common DC-link interface among photovoltaic (PV) generation, electric vehicles (EVs), and the utility grid. The developed converter supported several bidirectional operating modes, including Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), Renewable-to-Vehicle (R2V), and Renewable-to-Grid (R2G), allowing flexible management of energy flow under different operating conditions. To ensure accurate regulation of power transfer, dedicated power management and current control schemes were designed for both the AC and DC interfaces. The integrated configuration demonstrated improved operational flexibility and efficient coordination of renewable energy resources with EV charging infrastructure. Iyer et al. [7] examined the dynamic stability characteristics of a two-stage bidirectional single-phase battery charger employed in grid-connected EV charging applications. Their investigation focused on the influence of the load-dependent small-signal resistance associated with the AC–DC converter on the intermediate DC-link stability during charging and discharging processes. To overcome instability issues, the authors developed an active damping approach based on a virtual resistor, eliminating the need for additional sensing hardware. The proposed controller successfully maintained DC-link stability and ensured reliable converter operation regardless of the direction of energy transfer. Mouli et al. [8] carried out a comprehensive assessment of photovoltaic-integrated electric vehicle charging stations by comparing different converter structures and system configurations. The review considered various design aspects, including converter architecture, galvanic isolation, system flexibility, and Vehicle-to-Grid (V2G) capability, to evaluate their suitability for renewable energy-based charging applications. After analyzing the strengths and limitations of existing solutions in terms of efficiency, implementation complexity, and operational performance, the authors recommended two optimized multi-port converter architectures. In addition, modular charging configurations capable of simultaneously serving multiple electric vehicles were presented to improve charging station scalability. Carli and Williamson [9] investigated the design considerations associated with integrating photovoltaic generation into charging systems for electric and plug-in hybrid electric vehicles. Their analysis examined multiple power converter configurations by comparing energy conversion efficiency, operational characteristics, and compatibility with renewable energy sources. Based on this evaluation, the study identified converter arrangements that maximize solar energy utilization while minimizing conversion losses throughout the charging process. The findings also emphasized that locally generated photovoltaic energy can significantly reduce dependence on utility power while lowering transmission-related energy losses.

Mouli et al. [10] evaluated the environmental and economic feasibility of employing photovoltaic-powered charging stations for workplace electric vehicle charging in the Netherlands. A detailed analysis of a 10 kW solar-assisted charging facility was performed by comparing the operational costs of conventional gasoline vehicles with electric vehicles charged using either utility electricity or photovoltaic energy. The results demonstrated considerable reductions in fuel expenditure, taxation costs, and carbon dioxide (CO_2) emissions when solar energy was utilized for EV charging. Furthermore, the study compared rooftop photovoltaic installations with solar carport systems to determine their respective energy production capabilities and assessed the influence of feed-in tariff policies on the financial viability of photovoltaic-based charging infrastructure. Mouli et al. [11] presented the design of a photovoltaic-powered electric vehicle charging station intended for workplace environments. The research examined long-term solar irradiance patterns to determine the most effective orientation of photovoltaic panels while assessing seasonal fluctuations in energy production for charging applications. To maximize the direct use of renewable energy, the authors recommended deploying an oversized PV array together with an optimized charging strategy that minimized reliance on the utility grid. A priority-based charging scheme was also introduced to manage multiple vehicles simultaneously, and the incorporation of local battery storage was investigated to enhance system independence and improve overall energy availability. Kumar et al. [12] developed a grid-connected photovoltaic-assisted onboard charging system for electric vehicles with the objective of improving charging performance and grid power quality. Their work introduced a Multilayer Multi-order Generalized Discrete Integrator-based Adaptive Control (MMGDI-AC) technique that effectively reduced harmonics, suppressed measurement noise, and ensured precise synchronization with the utility grid. To improve photovoltaic energy harvesting, a Single-Input Adaptive Fuzzy Logic (SIAFL)-assisted Perturb and Observe (P&O) maximum power point tracking method was incorporated. The complete charging system utilized a two-stage single-phase converter architecture to provide stable operation and efficient power management under varying operating conditions.

3. Proposed System

Figure 2 illustrates the proposed PFLC-CC-PFMS developed for a solar-powered bidirectional EV charging system. Unlike the conventional CC-PFMS, the proposed framework incorporates a predictive state forecaster and a fuzzy logic controller (FLC) to intelligently regulate power flow among the PV array, battery energy storage system (BESS), utility grid, and DC-link. The predictive controller continuously forecasts future operating conditions, including photovoltaic power generation, battery current, DC-link voltage, and converter duty cycle, while the fuzzy inference engine optimizes converter switching decisions based on multiple operating parameters. The coordinated operation of the predictive forecaster and fuzzy logic controller enables adaptive power balancing, enhanced renewable energy utilization, stable DC-link voltage regulation, reduced converter losses, improved battery charging efficiency, and reliable bidirectional energy transfer under varying environmental and loading conditions.

Step 1: Photovoltaic Power Generation Module: The photovoltaic array serves as the primary renewable energy source of the charging station by converting solar irradiance into electrical energy. The generated photovoltaic voltage, current, and output power are continuously measured and supplied to the predictive controller. These measurements provide real-time information regarding solar energy availability and form the primary input for forecasting future photovoltaic generation. The predictive controller utilizes these signals to anticipate variations in solar irradiance and prepares the converter control system accordingly, thereby improving renewable energy utilization and reducing unnecessary dependence on the utility grid.

Step 2: Battery Energy Storage System: The battery energy storage system functions as both an energy storage device and a bidirectional power source for the charging station. It stores surplus photovoltaic energy during periods of high solar generation and supplies stored energy whenever photovoltaic generation becomes insufficient to satisfy EV charging demand. The battery current, battery power, and charging condition are continuously monitored and transmitted to the predictive control system. Based on the predicted battery operating condition and charging requirements, the controller intelligently determines whether the battery should operate in charging mode, discharging mode, or standby mode while ensuring safe operating limits and extending battery lifespan.

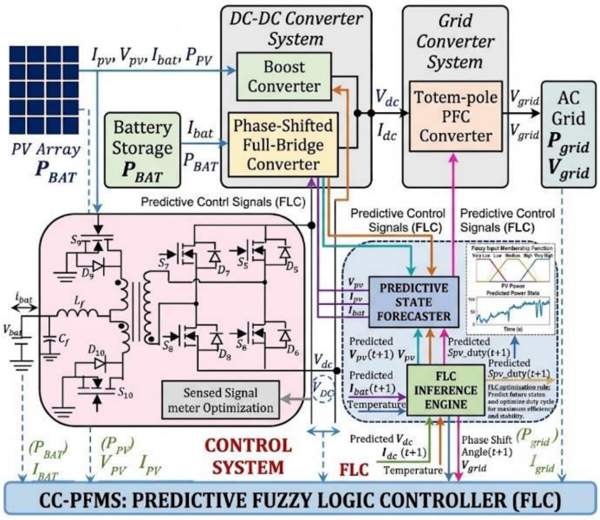

Figure 2: Proposed PFLC-CC-PFMS for a Solar-Powered Bidirectional EV Charging System

Step 3: DC–DC Converter System: The DC–DC converter subsystem consists of a photovoltaic boost converter and a PSFB bidirectional converter connected to a common DC bus. The boost converter regulates the photovoltaic output voltage and transfers the maximum available renewable energy to the DC-link, whereas the PSFB converter controls bidirectional energy exchange between the battery and the DC bus. Both converters receive optimized predictive control signals generated by the fuzzy logic controller. Consequently, the converter switching operation continuously adapts to predicted operating conditions, resulting in faster dynamic response, lower switching losses, and higher conversion efficiency compared to conventional fixed-control strategies.

Step 4: DC-Link Energy Management: The common DC-link serves as the central energy exchange platform connecting the photovoltaic system, battery storage system, and utility grid. The DC-link voltage and current are continuously monitored to ensure stable operation despite rapid variations in solar irradiance, battery charging demand, or grid loading conditions. The predictive controller estimates future DC-link voltage behavior and proactively adjusts converter control signals before significant voltage deviations occur. This predictive regulation significantly improves DC-link stability and minimizes transient disturbances throughout the charging process.

Step 5: Grid Converter System: The grid converter employs a Totem-Pole PFC converter to establish bidirectional power exchange between the DC bus and the utility grid. During grid-to-vehicle operation, the converter imports electrical energy from the utility grid whenever renewable energy becomes insufficient. During vehicle-to-grid operation, surplus battery or photovoltaic energy is exported back to the utility grid. The predictive fuzzy controller continuously regulates converter switching to maintain unity power factor, reduce current harmonics, improve converter efficiency, and ensure seamless synchronization with the utility grid under varying operating conditions.

Step 6: Predictive State Forecaster: The predictive state forecaster represents the primary enhancement introduced in the proposed charging strategy. Rather than relying solely on present operating measurements, the forecaster continuously predicts future photovoltaic voltage, photovoltaic current, battery current, DC-link voltage, converter duty cycle, and other system variables. These predicted operating states provide advance information regarding future power availability and charging demand, enabling the controller to perform proactive decision-making instead of conventional reactive control. As a result, the charging station responds more rapidly to sudden environmental changes while maintaining stable power flow and improved overall system performance.

Step 7: Fuzzy Logic Inference Engine: The fuzzy logic inference engine functions as the intelligent decision-making unit of the proposed PFLC-CC-PFMS. It receives both real-time measurements and predicted operating variables from the predictive state forecaster. Using predefined fuzzy membership functions and inference rules, the controller evaluates multiple operating conditions simultaneously, including photovoltaic generation, battery charging state, DC-link voltage stability, converter loading, and grid power demand. Based on this comprehensive analysis, the fuzzy controller generates optimized converter control signals that achieve efficient power balancing while minimizing converter stress and switching losses. The intelligent reasoning capability of fuzzy logic significantly enhances adaptability under uncertain operating conditions.

Step 8: Predictive Converter Control Signals: The optimized outputs generated by the fuzzy inference engine are supplied as predictive control signals to both the photovoltaic boost converter and the phase-shifted full-bridge converter. These predictive control signals regulate the converter duty cycle, phase-shift angle, switching sequence, and operating mode before significant system disturbances occur. Consequently, converter operation remains smooth and highly efficient even during rapid changes in solar irradiance, battery charging demand, or utility grid conditions. This predictive control approach substantially improves transient response and converter reliability compared to conventional control techniques.

Step 9: Sensed Signal Meter Optimization: The proposed framework incorporates a sensed signal optimization block that continuously acquires measurements from the photovoltaic array, battery system, DC-link, and utility grid. These measured signals undergo filtering, validation, and optimization before being supplied to the predictive controller. Accurate signal conditioning minimizes measurement noise and sensor uncertainty, thereby improving prediction accuracy and enhancing the overall reliability of the fuzzy decision-making process. This optimization stage ensures that the controller operates using high-quality real-time system information.

The proposed PFLC-CC-PFMS integrates photovoltaic power generation, battery energy storage, bidirectional converter control, predictive forecasting, fuzzy intelligence, and utility grid interaction into a unified energy management framework. The predictive state forecaster anticipates future operating conditions, while the fuzzy inference engine determines the optimal converter switching actions required to maintain balanced power flow among all energy sources. The coordinated operation of these intelligent modules enables adaptive power management, maximum renewable energy utilization, improved battery charging efficiency, enhanced DC-link voltage stability, reduced converter losses, faster transient response, superior grid power quality, and highly reliable bidirectional EV charging under dynamic environmental and load variations. Compared with the existing CC-PFMS, the proposed PFLC-CC-PFMS provides a more intelligent, predictive, and adaptive control architecture capable of significantly improving overall charging system efficiency, stability, and operational reliability.

3.1 Front-End Power Converter Architecture

Figure 3 illustrates the proposed front-end power converter architecture employed in the PFLC-CC-PFMS for the solar-integrated bidirectional EV charging system. The front-end stage comprises a PV boost converter, a Totem-Pole PFC converter, a common DC-link capacitor, and the connected load. The photovoltaic boost converter extracts and regulates the maximum available solar energy before supplying it to the DC-link, whereas the Totem-Pole PFC converter facilitates bidirectional power exchange between the utility grid and the DC bus while maintaining high power factor and low harmonic distortion. The DC-link capacitor stabilizes the intermediate DC voltage by compensating transient power fluctuations between the renewable source, utility grid, and load. The proposed predictive fuzzy logic controller continuously supervises the operation of both converters to ensure adaptive power balancing, improved conversion efficiency, enhanced DC-link voltage regulation, and reliable energy transfer under dynamic operating conditions.

Step 1: Utility Grid Input Stage: The utility grid serves as an auxiliary electrical power source for the charging station whenever the available photovoltaic power becomes insufficient to satisfy the load demand. The grid voltage is supplied to the Totem-Pole PFC converter through an input filter inductor, which smooths the grid current and minimizes high-frequency switching harmonics. The grid-side current is continuously monitored by the predictive fuzzy controller to maintain synchronized operation, achieve near-unity power factor, and ensure compliance with grid power quality standards. During vehicle-to-grid operation, the same converter enables surplus energy to be exported back to the utility grid in a controlled manner.

Step 2: Totem-Pole PFC Converter: The Totem-Pole PFC converter forms the primary AC–DC conversion stage between the utility grid and the common DC bus. It consists of four actively controlled semiconductor switches arranged in a Totem-Pole topology, enabling efficient bidirectional power transfer with significantly reduced conduction losses compared to conventional bridge rectifiers. The predictive fuzzy logic controller dynamically regulates the switching sequence according to the instantaneous grid voltage, current demand, and DC-link voltage conditions. This intelligent control strategy maintains stable DC output voltage, minimizes switching losses, improves converter efficiency, and substantially reduces input current harmonics during both charging and discharging operations.

Step 3: Photovoltaic Boost Converter: The photovoltaic boost converter interfaces the PV array with the common DC bus by increasing the relatively low photovoltaic output voltage to the desired DC-link voltage. The converter consists of an input capacitor, boost inductor, semiconductor switch, and output diode that collectively regulate photovoltaic power delivery. The predictive fuzzy controller continuously monitors the photovoltaic voltage and current while adjusting the converter switching duty cycle to maximize renewable energy extraction. As a result, the boost converter maintains efficient operation over a wide range of solar irradiance and temperature variations while ensuring stable DC bus voltage.

Step 4: Photovoltaic Energy Conversion: The photovoltaic array functions as the primary renewable energy source of the charging system by converting solar irradiance into electrical energy. The generated photovoltaic voltage and current are continuously sensed and supplied to the predictive fuzzy controller for real-time analysis. Based on anticipated environmental conditions and load demand, the controller optimizes converter operation to maximize renewable energy utilization while minimizing unnecessary power exchange with the utility grid. This intelligent energy management significantly improves overall charging station efficiency and reduces dependence on conventional electrical energy sources.

Step 5: DC-Link Capacitor: The DC-link capacitor serves as the central energy storage element connecting the photovoltaic boost converter and the Totem-Pole PFC converter. Its primary function is to stabilize the DC bus voltage by absorbing temporary energy surplus and supplying energy whenever transient load variations occur. The capacitor effectively suppresses voltage ripple and minimizes sudden voltage fluctuations caused by rapid changes in solar generation, grid power, or load demand. The predictive fuzzy controller continuously monitors the DC-link voltage and proactively adjusts converter switching actions to maintain a constant operating voltage under all operating conditions.

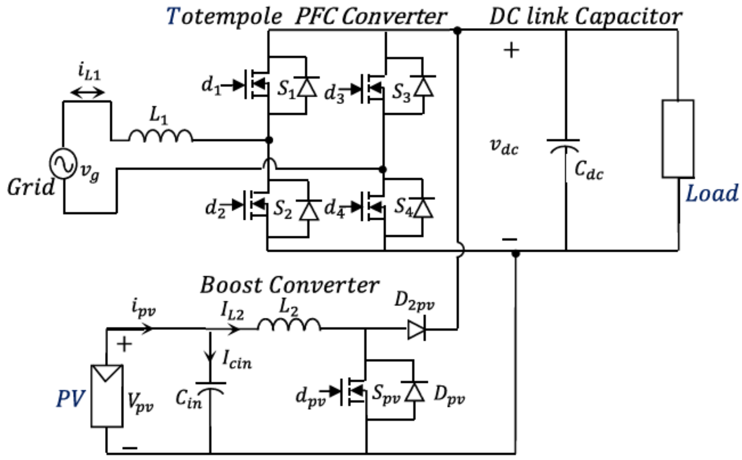

Figure 3: Proposed Front-End Power Converter Architecture.

Step 6: Load Interface: The regulated DC-link supplies electrical energy to the connected charging load, representing the electric vehicle charging system or any associated DC load. Depending on renewable energy availability and charging requirements, the load receives power from the photovoltaic system, the utility grid, or a combination of both. The predictive fuzzy logic controller continuously coordinates power sharing among all available energy sources to ensure uninterrupted charging, stable voltage regulation, and efficient energy utilization even during rapidly changing operating conditions.

Step 7: Predictive Fuzzy Logic-Based Converter Coordination: Unlike conventional converter control methods, the proposed architecture employs a predictive fuzzy logic controller to coordinate the operation of both the photovoltaic boost converter and the Totem-Pole PFC converter simultaneously. The controller continuously acquires measurements of photovoltaic voltage, photovoltaic current, grid voltage, grid current, and DC-link voltage, while predicting future operating conditions using intelligent forecasting techniques. The fuzzy inference mechanism processes these predicted system states and generates optimized converter switching commands that improve dynamic response, minimize converter stress, reduce switching losses, and maintain balanced power flow between the renewable energy source, utility grid, and charging load.

3.2 Proposed PSFB Bidirectional DC–DC Converter

Figure 4 illustrates the proposed PSFB bidirectional DC–DC converter employed in the PFLC-CC-PFMS for the solar-powered electric vehicle charging system. The converter establishes bidirectional energy transfer between the battery energy storage system and the common DC-link while providing high-frequency galvanic isolation through an isolation transformer. The converter consists of a full-bridge switching network, an isolation transformer, battery-side filter components, and bidirectional switching devices that collectively enable controlled charging and discharging of the battery. The proposed predictive fuzzy logic controller continuously regulates the converter switching sequence by adjusting the phase shift between bridge switches, thereby improving power conversion efficiency, minimizing switching losses, reducing converter stress, and ensuring smooth bidirectional power flow under varying operating conditions.

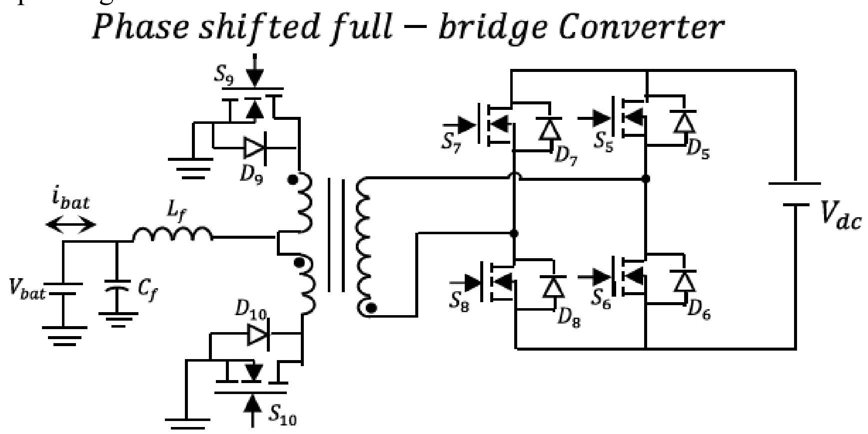

Figure 4: Proposed PSFB Bidirectional DC–DC Converter.

Step 1: Battery Energy Storage Interface: The battery energy storage system is connected to the primary side of the converter and functions as both an energy storage unit and a bidirectional power source. During charging operation, electrical energy flows from the DC-link to the battery, whereas during discharging operation, stored battery energy is transferred back to the DC-link for supplying the electric vehicle load or the utility grid. The battery voltage and current are continuously monitored by the predictive fuzzy controller to determine the appropriate operating mode while maintaining safe charging and discharging limits. This continuous supervision improves battery utilization and extends its operational lifetime.

Step 2: Battery-Side Filter Circuit: The battery-side filter comprises an inductor and capacitor connected between the battery and the converter. This filtering network smooths the battery current by suppressing high-frequency switching ripple generated during converter operation. The reduced current ripple minimizes battery heating, improves charging quality, and decreases electrical stress on the battery cells. The predictive fuzzy controller further enhances current regulation by dynamically adapting converter switching according to the battery operating condition and load requirements.

Step 3: Primary-Side Bidirectional Switching Network: The primary side of the converter incorporates bidirectional semiconductor switches that regulate energy transfer between the battery and the high-frequency transformer. During charging operation, the switches conduct in a sequence that transfers energy from the DC-link to the battery. During discharging operation, the switching sequence is automatically reversed to enable battery energy delivery back to the DC-link. The predictive fuzzy logic controller continuously determines the optimum switching pattern based on predicted battery current, charging demand, and converter operating conditions, thereby improving conversion efficiency and reducing switching losses.

Step 4: High-Frequency Isolation Transformer: A high-frequency transformer is positioned between the primary and secondary converter stages to provide galvanic isolation between the battery and the DC-link. This transformer enhances electrical safety by preventing direct electrical connection while simultaneously enabling voltage matching between both sides of the converter. The high-frequency operation significantly reduces transformer size and weight compared with conventional low-frequency transformers, resulting in a compact and highly efficient converter suitable for electric vehicle charging applications.

Step 5: Full-Bridge Switching Circuit: The secondary side consists of a full-bridge converter composed of four actively controlled semiconductor switches. These switches alternately generate high-frequency alternating voltage across the transformer winding, enabling controlled bidirectional energy transfer. The predictive fuzzy controller determines the appropriate switching intervals according to predicted system operating conditions, ensuring smooth converter operation, improved voltage regulation, and efficient energy conversion over a wide operating range.

Step 6: Phase-Shift Modulation Control: The proposed converter utilizes phase-shift modulation to regulate the magnitude and direction of power transfer through the isolation transformer. Instead of varying the switching frequency, the controller adjusts the phase difference between the leading and lagging bridge switches. This modulation technique enables precise regulation of transferred power while maintaining constant switching frequency. Under the supervision of the predictive fuzzy controller, the phase-shift angle is continuously optimized according to predicted photovoltaic generation, battery charging demand, DC-link voltage, and utility grid conditions. Consequently, converter efficiency is significantly improved while switching losses and electromagnetic interference are substantially reduced.

Step 7: Predictive Fuzzy Logic Control Integration: The proposed Predictive Fuzzy Logic Controller represents the major enhancement over the conventional PSFB converter. The controller continuously receives real-time measurements from the battery, DC-link, photovoltaic system, and utility grid while simultaneously predicting future operating conditions using the predictive state forecaster. These predicted system states are processed by the fuzzy inference engine to determine the optimum converter switching sequence, phase-shift angle, and operating mode. This intelligent decision-making capability enables rapid adaptation to dynamic environmental changes, improving converter stability, battery charging accuracy, and overall energy management performance.

Step 8: Bidirectional Power Flow Operation: The proposed converter supports seamless bidirectional energy transfer between the battery and the DC-link. During charging operation, renewable energy generated by the photovoltaic array and supplementary grid power are delivered through the converter to charge the battery efficiently. During discharging operation, the stored battery energy is transferred back to the DC-link to support the electric vehicle load or export surplus power to the utility grid. The predictive fuzzy controller continuously coordinates these charging and discharging processes to maintain balanced power flow, prevent unnecessary battery cycling, and maximize renewable energy utilization.

3.3 Proposed PFLC Module

Figure 5 illustrates the proposed PFLC-based CC-PFMS developed for the solar-powered bidirectional electric vehicle (EV) charging system. The proposed energy management strategy continuously monitors the photovoltaic (PV) power generation, battery state of charge (SoC), and utility grid conditions to determine the optimal power flow direction among the PV array, battery energy storage system (BESS), and utility grid. Unlike the conventional rule-based power management strategy, the proposed PFLC integrates predictive state estimation and fuzzy inference to forecast future operating conditions before making control decisions. Based on predicted photovoltaic generation, battery charging requirements, and grid demand, the controller dynamically selects the most appropriate charging or discharging mode, thereby maximizing renewable energy utilization, maintaining battery safety, stabilizing the DC-link voltage, and improving the overall efficiency and reliability of the charging system.

Step 1: System Initialization and Data Acquisition: The proposed power management strategy begins by continuously acquiring the photovoltaic voltage, photovoltaic current, battery current, battery power, and battery state of charge from the sensing units installed throughout the charging station.

Simultaneously, the controller estimates the available photovoltaic generation based on the measured solar irradiance and predicts future operating conditions using the predictive state forecaster. These real-time and predicted measurements provide the necessary information for intelligent decision-making while enabling proactive energy management instead of conventional reactive control.

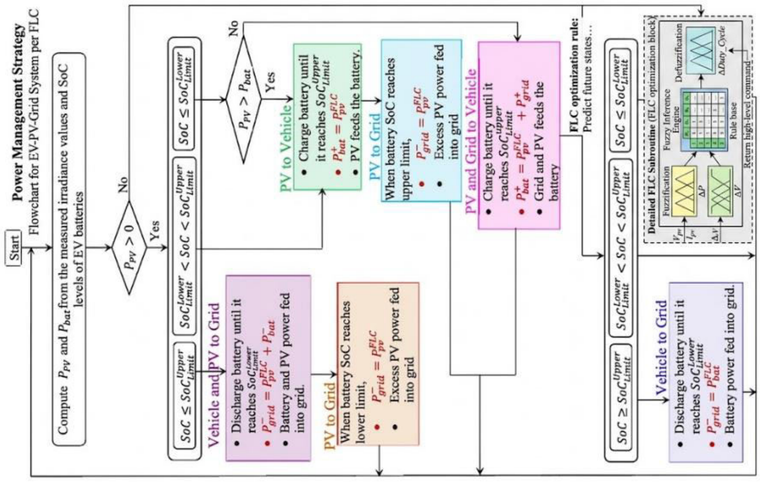

Figure 5: Proposed PFLC System

Step 2: Photovoltaic Power Availability Assessment: After estimating the available photovoltaic generation, the controller determines whether renewable energy is available for charging operations. When sufficient photovoltaic power is available, renewable energy is prioritized for battery charging and load supply to maximize solar energy utilization. Conversely, when photovoltaic generation becomes unavailable or insufficient due to low irradiance or nighttime operation, the controller automatically transfers the charging responsibility to the battery storage system and utility grid without interrupting the charging process. This adaptive switching improves charging reliability while minimizing dependence on conventional energy sources whenever renewable energy is available.

Step 3: Battery State-of-Charge Evaluation: The battery state of charge is continuously evaluated with respect to predefined lower and upper operating limits to ensure safe battery operation. When the battery charge approaches the upper limit, the controller prevents further charging and redirects excess renewable energy toward the utility grid. When the battery charge decreases below the lower operating threshold, charging priority is immediately assigned to restore battery energy. For intermediate state-of-charge levels, the controller dynamically balances charging and discharging operations according to predicted photovoltaic availability and load demand. This intelligent battery supervision prevents overcharging, excessive discharge, and unnecessary battery cycling, thereby extending battery lifetime.

Step 4: Vehicle and PV to Grid Operation: When the battery reaches its upper charging limit while photovoltaic generation remains available, the proposed controller initiates the Vehicle-and-PV-to-Grid operating mode. Under this condition, the battery begins discharging together with the photovoltaic array to support the utility grid. The predictive fuzzy controller continuously estimates future grid demand and photovoltaic generation before determining the appropriate amount of battery discharge. This coordinated operation maximizes renewable energy utilization, supports grid stability during peak demand periods, and prevents unnecessary curtailment of photovoltaic energy.

Step 5: PV to Grid Operation: Once the battery reaches its minimum permissible discharge level, battery power delivery is suspended to protect battery health. However, whenever excess photovoltaic power continues to be available beyond the charging requirement, the controller exports the surplus renewable energy directly to the utility grid. The predictive fuzzy controller continuously forecasts upcoming solar generation and grid loading conditions to determine whether energy should be exported immediately or temporarily retained for anticipated charging requirements. This predictive energy scheduling significantly improves renewable energy utilization and overall system efficiency.

Step 6: PV to Vehicle Charging Mode: When the available photovoltaic generation is sufficient to satisfy the battery charging demand, the controller activates the PV-to-Vehicle charging mode. Under this operating condition, the battery is charged exclusively using renewable energy without drawing power from the utility grid. The predictive state forecaster continuously estimates future photovoltaic availability and battery charging requirements, while the fuzzy inference engine optimizes converter switching actions to maintain efficient charging. Consequently, renewable energy utilization is maximized while reducing electricity consumption from the utility grid.

Step 7: PV and Grid to Vehicle Charging Mode: If photovoltaic generation alone becomes insufficient to achieve the desired battery charging rate, the controller simultaneously utilizes both photovoltaic power and utility grid energy for charging the battery. The predictive fuzzy controller intelligently determines the contribution of each energy source based on predicted solar generation, battery state of charge, and anticipated charging demand. This coordinated charging strategy ensures uninterrupted battery charging while minimizing grid energy consumption whenever renewable energy becomes available.

Step 8: Vehicle to Grid Operation: During periods when photovoltaic generation is unavailable and the battery maintains sufficient stored energy, the controller enables Vehicle-to-Grid (V2G) operation. In this mode, the battery supplies electrical energy back to the utility grid according to predicted grid demand and battery operating conditions. The predictive fuzzy controller continuously evaluates future battery energy availability before authorizing battery discharge, thereby preventing excessive battery depletion while simultaneously supporting utility grid stability during peak load conditions.

Step 9: Grid to Vehicle Charging Mode: When both photovoltaic generation and battery energy become insufficient to support charging operations, the controller activates the Grid-to-Vehicle charging mode. The utility grid supplies the required charging energy while the predictive controller monitors expected photovoltaic generation and battery recovery conditions. Once renewable energy becomes available again, the controller automatically reduces grid dependency and resumes photovoltaic-assisted charging. This seamless operating mode transition ensures continuous EV charging under all environmental conditions.

Step 10: Predictive Fuzzy Logic Optimization Block: The most significant enhancement introduced in the proposed power management strategy is the Predictive Fuzzy Logic Controller optimization block. Unlike conventional threshold-based decision-making, the controller first predicts future operating states using real-time measurements of photovoltaic voltage, photovoltaic current, battery current, battery state of charge, DC-link voltage, and environmental conditions. These predicted variables are then processed through the fuzzy inference engine consisting of fuzzification, fuzzy rule evaluation, inference processing, and defuzzification stages. The optimized controller output determines the appropriate converter duty cycle, phase-shift angle, converter operating mode, and power flow direction before significant operating disturbances occur. This predictive decision-making capability substantially improves transient response, converter stability, and charging efficiency.

Step 11: Fuzzy Inference Engine Operation: The fuzzy inference engine serves as the intelligent decision-making unit within the proposed controller. It simultaneously evaluates multiple system variables, including photovoltaic generation, battery charging status, voltage deviation, current variation, and predicted future operating conditions. Using predefined linguistic membership functions and optimized fuzzy rule sets, the controller determines the most appropriate converter switching commands required for efficient power balancing. The fuzzy reasoning process effectively handles uncertainties associated with fluctuating solar irradiance, varying charging demand, and dynamic grid conditions, thereby providing robust system performance under highly nonlinear operating environments.

4. Results and Discussion

Figure 6 illustrates the complete MATLAB/Simulink implementation of the proposed solar-powered bidirectional EV charging system incorporating the photovoltaic (PV) array, MPPT-controlled DC–DC converter, bidirectional battery converter, grid-side inverter, controller, and utility grid. The PV array generates renewable power that is processed through the MPPT controller to maximize energy extraction before being transferred to the DC-link. The bidirectional converter regulates battery charging and discharging, whereas the grid-side inverter manages power exchange with the utility grid. The entire system operates at a DC-link reference voltage of approximately 400 V, supports a 50 Hz utility grid, and enables multiple operating modes including G2V, V2G, PV2V, PV2G, G2V+PV2V, and V2G+PV2G, thereby ensuring efficient power management under varying operating conditions.

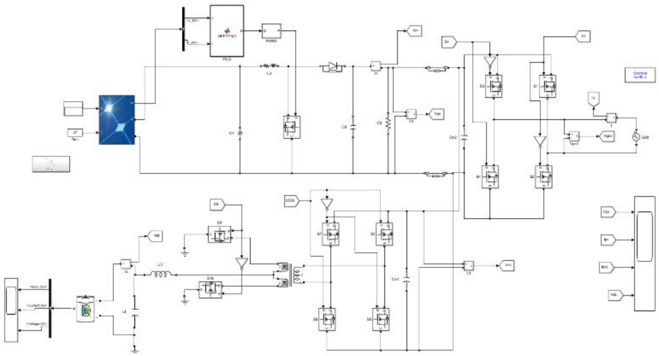

Figure 6: Overall MATLAB/Simulink Model of the Proposed Solar-Powered Bidirectional EV Charging System

Figure 7presents the Perturb and Observe (P&O)- MPPT controller used to maximize photovoltaic energy extraction. The controller continuously receives the PV voltage (VPV) and PV current (IPV) as input signals, computes the operating point, and generates the optimum duty cycle for the PWM generator controlling the boost converter. During simulation, the controller successfully tracks the maximum power point despite variations in solar irradiance, maintaining the PV operating voltage close to 200 V while increasing the PV current up to approximately 30 A, thereby ensuring maximum utilization of the available solar energy.

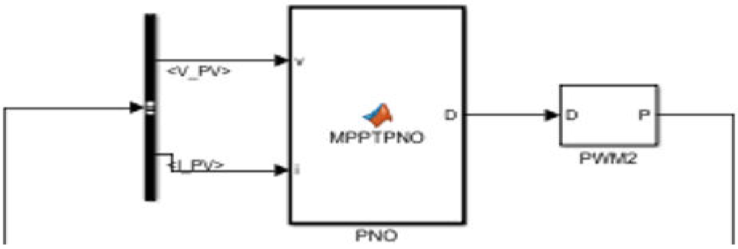

Figure 7: PPT Controller Based on Perturb and Observe (P&O) Algorithm

Figure 8 shows the output monitoring subsystem used for real-time observation of important electrical parameters. The subsystem simultaneously acquires the grid voltage (Vgrid), grid current (Ig), DC-link voltage (Vdc), and battery current (Ibat) throughout the simulation period. These measured signals enable continuous evaluation of converter performance, power flow direction, voltage regulation, charging current, and grid interaction, thereby simplifying performance analysis under different operating conditions.

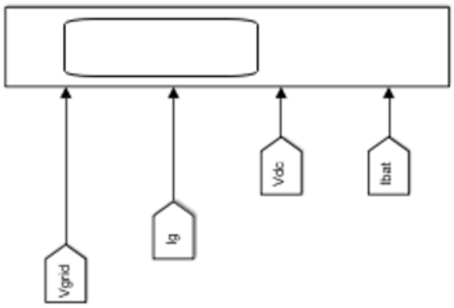

Figure 8: Output Monitoring Block of the Proposed System

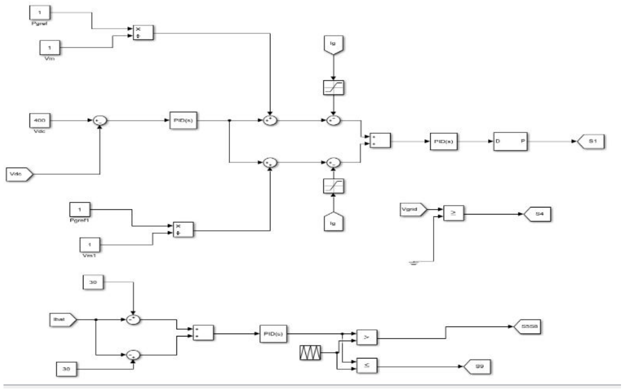

Figure 9: Proposed Coordinated Control Strategy

Figure 9 illustrates the complete control architecture employed in the proposed charging system. The upper control loop regulates the DC-link voltage by comparing the measured Vdc with the reference value of 400 V, after which a PID controller generates the required control signal for PWM pulse generation. Simultaneously, current regulation is achieved using the measured grid current (Ig) to maintain unity power factor operation. The lower control loop regulates the battery charging current around the reference value of approximately 30 A using another PID controller. Together, these coordinated control loops generate switching pulses (S1–S10) for stable converter operation during all bidirectional charging and discharging modes.

Figure 10 presents the simulation results obtained during simultaneous Grid-to-Vehicle (G2V) and Photovoltaic-to-Vehicle (PV2V) charging operation using MPPT control. The grid voltage remains sinusoidal with a peak magnitude of approximately ±220 V at 50 Hz, while the grid current varies according to charging demand between approximately ±3 A and ±10 A. The DC-link voltage is successfully maintained around 400–480 V, exhibiting only small ripple. The PV voltage settles near 170–180 V, whereas the PV current increases from approximately 2 A to 10 A as irradiance increases. The battery charging current rapidly reaches approximately 30 A and remains nearly constant with very low ripple, confirming effective coordinated power sharing between the grid and photovoltaic source.

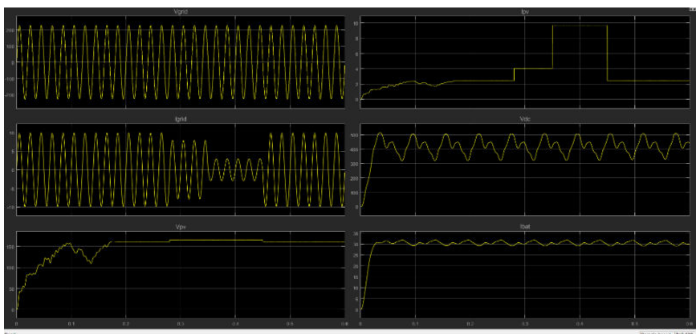

Figure 10: Simulation Results for G2V+PV2V Operating Mode with MPPT

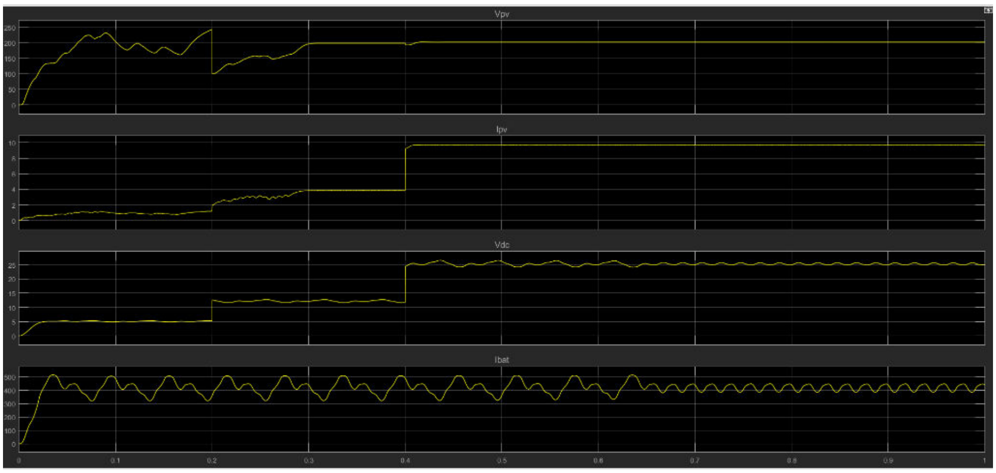

Figure 11: Simulation Results for PV2V Operating Mode with MPPT

Figure 11 illustrates the system performance when the electric vehicle battery is charged solely from the photovoltaic source. The PV voltage gradually stabilizes close to 200 V, while the PV current increases in steps from approximately 1 A to 10 A according to changing solar irradiance. The converter maintains the DC output voltage around 25 V with minimal fluctuations throughout the simulation. The battery charging current initially rises rapidly to nearly 420 A, subsequently settling between 300 A and 400 A with acceptable ripple, demonstrating stable PV-only charging under MPPT operation.

Figure 12 presents the operating characteristics when photovoltaic power simultaneously supplies both the electric vehicle and the utility grid. The grid voltage remains sinusoidal at approximately ±220 V, whereas the grid current increases from nearly ±2 A to ±5 A as additional photovoltaic power becomes available. The PV voltage initially stabilizes near 200 V before settling around 160 V following changes in operating conditions. The PV current increases progressively up to approximately 8 A, while the DC-link voltage remains regulated between 400 V and 480 V. The battery charging current also increases from nearly 8 A to approximately 23 A, confirming efficient sharing of photovoltaic power between vehicle charging and grid export.

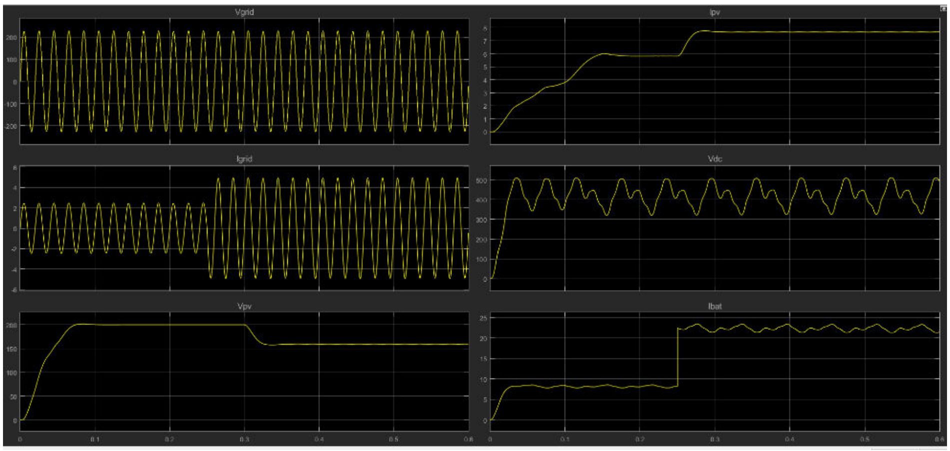

Figure 12: Simulation Results for PV2V+PV2G Operating Mode with MPPT

Figure 13 shows the system response when photovoltaic energy is delivered exclusively to the utility grid. The grid voltage remains constant at approximately ±220 V, while the exported grid current increases up to nearly ±20 A during maximum solar generation. The PV voltage remains close to 200 V for most of the simulation before briefly decreasing to approximately 100 V and recovering rapidly under MPPT control. The PV current varies between approximately 3 A and 6 A, whereas the DC-link voltage remains regulated around 400–480 V, demonstrating stable photovoltaic grid injection.

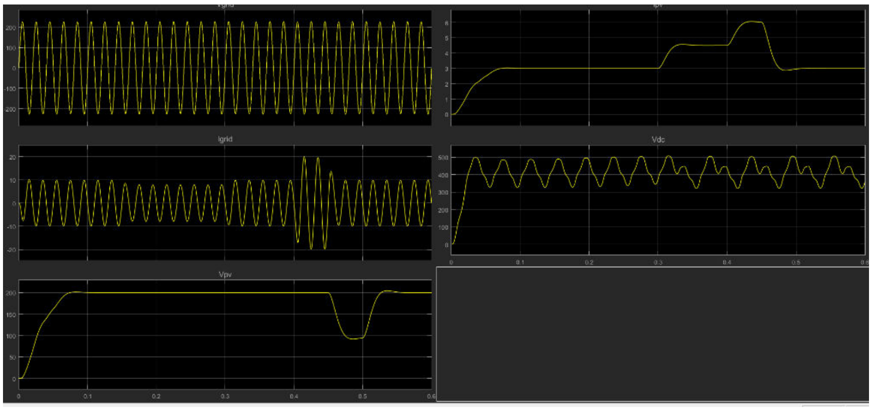

Figure 13: Simulation Results for PV2G Operating Mode with MPPT

Figure 14 illustrates the simultaneous export of energy from both the electric vehicle battery and photovoltaic array to the utility grid. The grid voltage maintains a sinusoidal waveform with an amplitude of approximately ±220 V, while the grid current remains around ±10 A throughout the simulation. The PV voltage is maintained near 180 V, except for a temporary reduction to nearly 70 V, after which the MPPT controller restores the operating point. The PV current reaches approximately 8 A, whereas the battery current changes from −20 A during discharge to approximately +10 A before returning to −20 A, clearly indicating bidirectional battery power transfer.

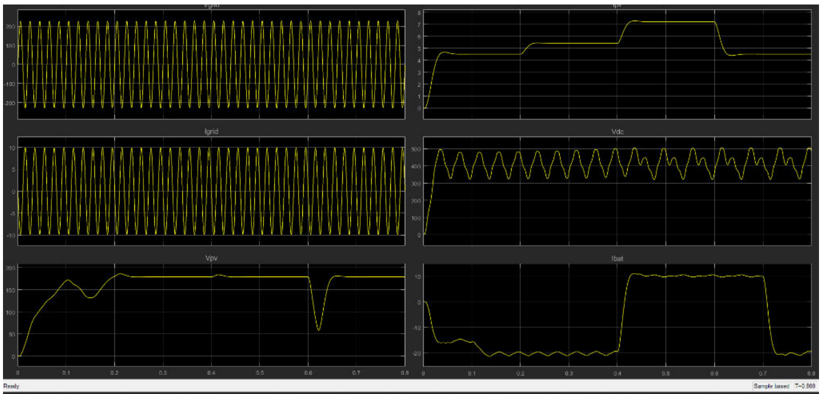

Figure 14 Simulation Results for V2G+PV2G Operating Mode with MPPT

Figure 15 presents the Vehicle-to-Grid (V2G) operating mode, in which the electric vehicle battery supplies energy back to the utility grid. The grid voltage remains balanced with a peak value of approximately ±220 V, and the injected grid current reaches nearly ±10 A. The DC-link voltage is maintained around 400–480 V, ensuring stable inverter operation. The battery current remains negative at approximately −25 A, confirming continuous battery discharge to the grid with only minor ripple, thereby demonstrating stable bidirectional converter operation.

Figure 15: Simulation Results for V2G Operating Mode with MPPT

Figure 16 illustrates Grid-to-Vehicle charging under MPPT operation. The grid voltage remains sinusoidal at approximately ±220 V, while the grid current reaches nearly ±10 A to satisfy charging requirements. The photovoltaic voltage varies between 350 V and 480 V, and the photovoltaic current stabilizes close to 30 A, indicating effective solar energy harvesting. Throughout the charging process, stable voltage regulation and coordinated power transfer are achieved, ensuring reliable charging performance.

Figure 17 presents the performance of the proposed Fuzzy Logic Controller during Grid-to-Vehicle charging. The grid voltage remains highly sinusoidal with a peak magnitude of approximately ±220 V, while the grid current remains stable around ±10 A. The photovoltaic voltage is regulated almost perfectly at 400 V, and the photovoltaic current settles near 30 A with significantly reduced oscillations compared with the MPPT-based controller. These results demonstrate that the FLC provides faster dynamic response, superior voltage regulation, reduced steady-state ripple, and improved charging stabilit

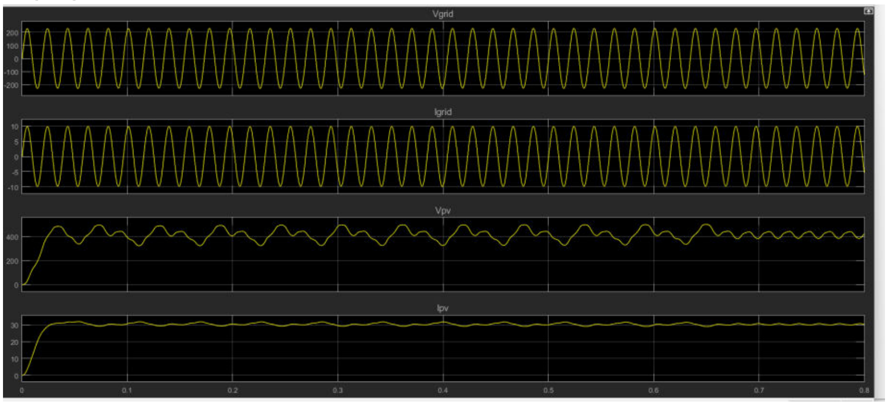

Figure 16: Simulation Results for G2V Operating Mode with MPPT

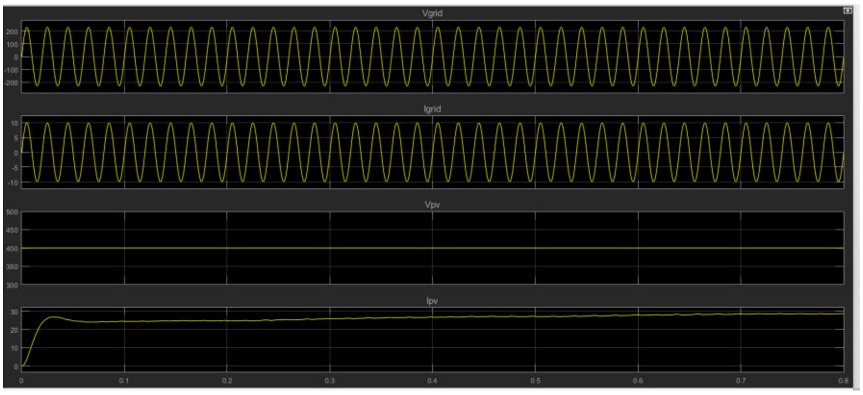

Figure 17: Simulation Results for G2V Operating Mode Using FLC.

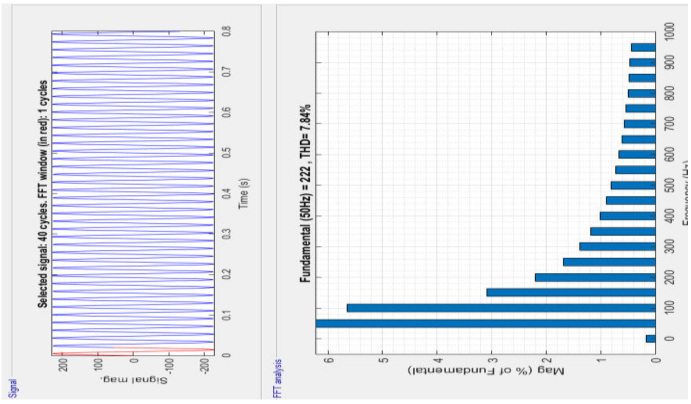

Figure 18: THD Analysis for G2V Operating Mode Using MPPT

Figure 18 presents the Fast Fourier Transform (FFT) analysis of the grid voltage during Grid-to-Vehicle operation using the MPPT controller. The waveform exhibits a 50 Hz fundamental component with a magnitude of approximately 222 V. The calculated Total Harmonic Distortion (THD) is 7.84%, indicating the presence of significant harmonic components generated by converter switching. Although the system operates satisfactorily, the harmonic content exceeds the recommended IEEE 519 limit of 5%, suggesting the need for an improved control strategy.
Figure 19 presents the FFT analysis of the proposed FLC during Grid-to-Vehicle operation. The grid voltage maintains a 50 Hz fundamental component with an amplitude of approximately 226.9 V, while the measured THD is reduced to only 0.50%. Compared with the conventional MPPT control (7.84% THD), the proposed FLC achieves a 93.62% reduction in harmonic distortion, fully satisfying the IEEE 519 power quality standard and demonstrating superior waveform quality, stable converter operation, and significantly improved grid power quality.

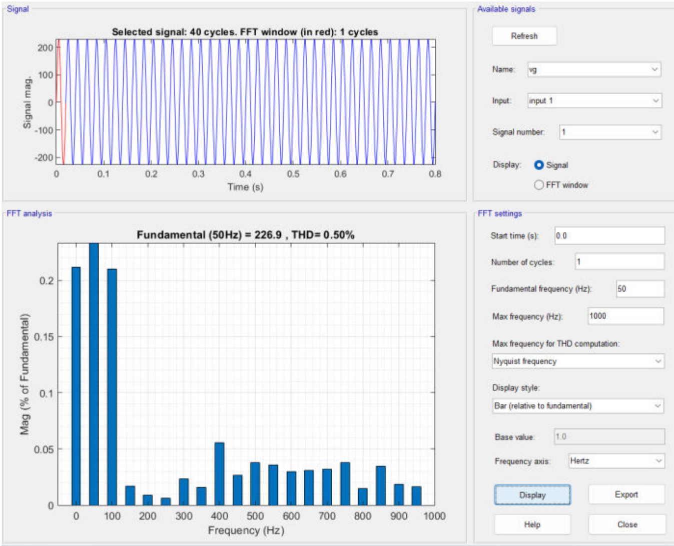

Figure 19: THD Analysis for G2V Operating Mode Using FLC.

Table 1. THD Comparison Between Conventional MPPT and Proposed FLC for G2V Operating Mode

Parameter	Conventional MPPT	Proposed FLC	Improvement
Operating Mode	G2V	G2V	–
Fundamental Frequency (Hz)	50	50	Same
Fundamental Voltage (V)	222.0	226.9	+2.21%
Total Harmonic Distortion (THD) (%)	7.84	0.50	93.62% Reduction
IEEE 519 Compliance	No (>5%)	Yes (<5%)	Achieved
Grid Voltage Quality	Moderate	Excellent	Improved
Converter Performance	Higher Harmonic Content	Very Low Harmonic Content	Significantly Improved
Overall, Power Quality	Acceptable	Superior	Enhanced

5. Conclusion

The simulation and performance evaluation demonstrate that the proposed FLC based Solar-Powered Bidirectional Electric Vehicle Charging System provides significant improvements over the conventional P&O- MPPT-based control strategy in terms of dynamic response, power quality, voltage regulation, and energy management. The proposed controller successfully supports all operating modes, including G2V, V2G, PV2V, PV2G, G2V+PV2V, and V2G+PV2G, while maintaining a stable DC-link voltage of approximately 400 V and ensuring reliable bidirectional power transfer between the photovoltaic system, electric vehicle battery, and utility grid. Compared with the conventional MPPT controller, the proposed FLC exhibits faster transient response, lower steady-state oscillations, improved battery charging stability, enhanced utilization of photovoltaic energy, and superior coordination of power flow under varying operating conditions. Furthermore, harmonic analysis confirms the effectiveness of the proposed approach, where the THD is reduced from 7.84% with the conventional MPPT controller to only 0.50% using the proposed FLC, corresponding to a 93.62% reduction and full compliance with the IEEE 519 power quality standard. These improvements result in higher converter efficiency, improved grid voltage quality, reduced switching stress, enhanced system reliability, and more efficient renewable energy utilization, demonstrating that the proposed FLC-based charging system is a highly effective and intelligent solution for next-generation grid-connected electric vehicle charging applications.

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