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Research Article

Design and Implementation of Operational Mode for Electric Vehicle Charging Stations Integrated with Grid-Connected Photovoltaic Systems

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Abstract: This study investigates how electric vehicle (EV) charging can work together with photovoltaic (PV) power generation through smart charging techniques and a voltage-to-grid (V2G) system. A new model for an electric vehicle charging station (EVCS) was created and evaluated to understand how well it works, how it can be improved, and how efficient it is. By combining the EVCS with the PV system, the goal is to decrease power wastage, boost PV self-usage, and decrease customer costs. The charging station model features a centralized charging station offering both slow and fast battery charging options, along with two charging voltage choices (48 and 60 V) within a 2.5 kW-capacity PV system. The model simulation runs on the Simulink MATLAB software. To control the voltage, current, and state of charge (SoC) of EV batteries during charging and discharging, a method called constant current-constant voltage (CC-CV) is used. This method focuses on effectively maximizing charging power and preventing battery overcharging. Fuzzy logic controllers adjust the duty cycle to maintain stable current and voltage. In the V2G system, electric vehicles (EVs) can charge, discharge, and serve as energy storage for the grid. Moreover, smart charging is being implemented to improve coordination among electric vehicles, local electricity production, and other power needs. Through a specific control system, EVs can be charged when there is a surplus of solar power, but they will refrain from charging during peak energy usage times.

Keywords: CC-CV; Electric vehicle; EVCS; Photovoltaic; State of charge; Voltage-to-grid

1. Introduction

When photovoltaic (PV) systems are linked to the grid, they function as generation units within the power system. These systems can be centrally or distributedly incorporated into the power grid. Centralized PV systems resemble traditional utility-scale power plants in terms of size, location away from end-users, and connection to transmission grids or occasionally medium voltage (MV) distribution grids. Decentralized PV systems are typically smaller in scale, widely dispersed, located nearer to consumers, and frequently linked to the distribution network (Ackermann et al., 2001). The integration of PV systems into the power system can lead to overvoltage and component overloading. These shorten the lifespan of electrical system components and require costly grid upgrades (Luthander, 2018). One of the main difficulties

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associated with photovoltaic (PV) systems is their unpredictable generation patterns. Unlike conventional power plants, which can be adjusted to meet specific demands, PV systems without battery storage cannot be controlled and are considered nondispatchable sources of power. This limitation poses a significant challenge because power plants are typically designed to cater to consumers' fluctuating power needs. PV power production fluctuates throughout the year and day, influenced by the movement of the sun across the sky. Typically, the highest levels of PV power are generated around midday during sunny summer days, significantly surpassing production levels at other times of the day. Production is completely halted during the night. In addition to these predictable patterns, intermittent cloud cover can further affect power generation, leading to a decrease in energy production (Widén and Munkhammar, 2019). This variable aspect of PV power can lead to voltage and frequency fluctuations. Adding storage components, such as batteries, can overcome these problems. However, the abovementioned problems will not occur when PV is off-grid. The excess power generated by PV plays a crucial role in maintaining the voltage profile. This surplus power needs to be minimized to almost zero to guarantee the system's stable operation and the reliable supply of electricity to consumers (Das and Hasan, 2021). Consequently, if the system has no batteries, there is a possibility of electricity shortages (Ajiwiguna and Kirom, 2024). To overcome this, Hasanah et al., 2024 studied a modified perturb and observe control for improving the maximum power point tracking performance on grid-connected PV systems.

The power grid has a restricted capacity for accommodating distributed generations (DGs) such as photovoltaics (PVs) and new loads such as electric vehicles (EVs) without expensive upgrades to the utility system. Nevertheless, when PVs and EVs are connected to the grid, there is often a discrepancy between energy demand and power generation. One way to address this issue is to harness the synergy between PVs and EVs through coordination, control, and smart charging strategies for EVs (Gonzalez Venegas et al., 2021; Luthander, 2018; Bollen and Rönnberg, 2017). The inclusion of PVs as DGs and high-consuming loads such as EVs not only interrupted the grid performance but also offered opportunities for grid performance improvement (Singh and Verma, 2023; Catal, 2020). Figure 1 presents the underlying power system theory of PV-EV integration in the power grids.

Figure 1(a) shows a PV system and EVs in the distribution grid. Simplified electric circuit representations when being a power consumer, power producer, and in a power balance state are shown in Figure 1 (b)-(d), respectively. In Figure 1 (b)-(d), PDG is the DG power generation (kW), PL is the load (kW), VT is the voltage level at the transformer substation (V), VL is the voltage level at the load/customer's side (V), ITL is the current flowing from the transformer to the load (A), ILT is the current flowing from the load to the transformer (A), Ploss is the dissipated power loss (kW), R is the equivalent resistance of the feeder (Ω), X is the equivalent reactance of the feeder (Ω), j is an imaginary unit, cos Φ is the power factor, sin Φ is the reactive power factor, QL is the reactive power on the customer's side (kVA). Figure 1(b) shows the voltage drop phenomenon, assuming a much higher value of R compared to X in typical distribution grids (Akinyemi et al., 2022). When a customer is using electricity, the voltage on their side is often lower than the substation's manageable voltage level. This voltage drop is primarily due to the current flowing through the cables and the resistance they offer, leading to heat-induced power loss. During times of excessive demand, there is a possibility of undervoltage, where the voltage falls below safe levels, and the components may become overloaded with too much current or heat. This situation poses risks to both the users and the appliances being used (Rama-Mohan et al., 2020). The voltage rise phenomenon is shown in Figure 1(c). When the customer is a power producer, the customer's voltage level is typically higher than the substation's controlled voltage level. Power losses occur as heat when currents travel from the customer's end to the substation. Excessive generation poses risks such as overvoltage, exceeding safe limits, and component overloading due to high current or heat. When a power producer achieves a balance between production and consumption with zero reactive power, the voltage on the customer's end usually stays within a safe range. Furthermore, there are no power losses because no current flows between the substation and the customer, as shown in Figure 1(d).

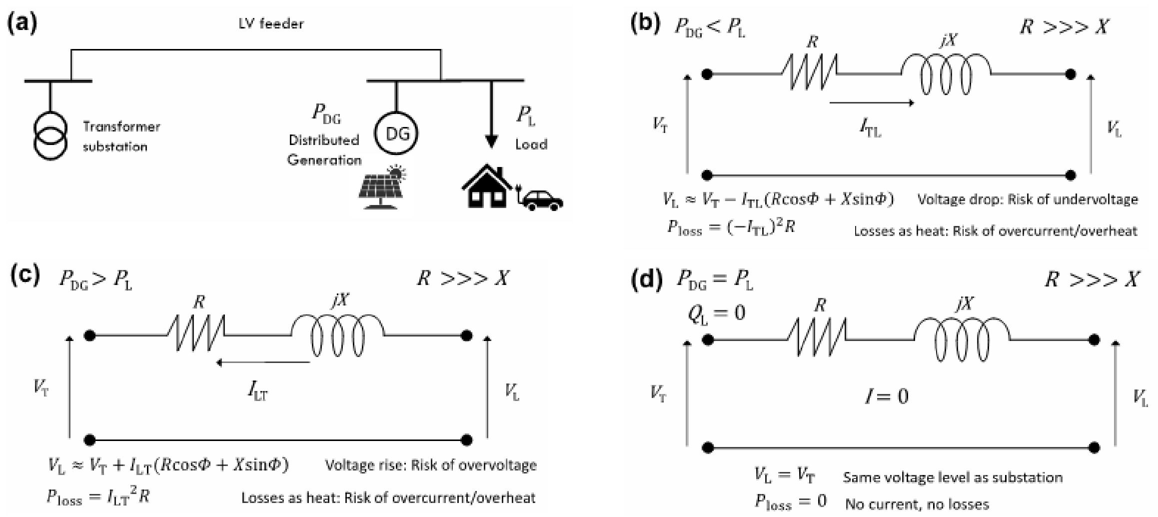


Figure 1 (a) DG into grid and its simplified electric circuit representations when being (b) a power consumer, (c) a power producer, and (d) in power balance

When an EV is connected to the power grid for charging, it functions as an electricity consumer within the power system. The current power grid infrastructure was not originally built to accommodate a high volume of EV charging demands, which may present new challenges when a significant number of EVs are added to the power system (Mahmud et al., 2023). The challenges include under-voltage problems and component overloading. These issues reduce the lifespan of power grid equipment, such as substation transformers. In such instances, there may be a need to upgrade the power grid, which can be quite expensive. The greater the charging power of an EV charger, the greater its effect on the power system. Using higher power chargers can result in increased load variability as the EV charging load fluctuates more frequently and rapidly (Ramadhani et al., 2021). This phenomenon is called a voltage-to-grid (V2G) scheme. Whulanza, 2023 reviewed another study regarding EV when it is combined with PV system.

This research outlines the development and simulation of an EVCS integrated with a grid-connected PV system using MATLAB/Simulink. A charging model accommodating both slow and fast charging options was established, employing the CC-CV technique in conjunction with fuzzy logic to effectively manage voltage, current, and SoC. The system also integrates V2G capabilities and assesses three intelligent charging strategies—uncontrolled, controlled, and delayed dispatch—across various operational scenarios. Critical performance metrics, including charging duration, grid import/export dynamics, PV utilization efficiency, battery depth of discharge, and overall lifespan, were thoroughly examined. The results show that smart charging strategies significantly improve PV energy use, reduce grid dependency, shorten charging time, and extend battery life. The findings highlight that PV–EVCS integration is technically feasible and economically promising, although its practical implementation requires supportive policies and sustainable business models.

This paper is arranged as follows: Section 1 addresses the need to design and simulate the EV battery charging station within a grid-connected PV system. Section 2 literates the enhancement of PV-EV synergy, or what we call the V2G scheme, through a brief review of EVs' smart charging scenario, as well as its mathematical models and algorithms. Section 3 describes the simulation process for designing the EV battery station within the PV system. Section 4 discusses the results and also quantitative metrics, namely, charging time, grid import/export, PV utilization, SoC, and battery life. Finally, Section 5 concludes the study.

2. Methods

2.1 Enhancing PV-EV Synergy (V2G concept)

Analytical methods and design charts were used for the simulation using the Simulink MATLAB platform. The simulation describes the PV system, charging station, smart charging of the EV battery scenario, and V2G scheme. The V2G concept was described in Nasir et al., 2023. The V2G system necessitates a centralized scheduling mechanism for managing the charging and discharging activities of EVs. The advantages and obstacles associated with the V2G concept have been explored in detail (Mastoi et al., 2023), including features such as active power regulation, reactive power support, load balancing, and current harmonic filtering. However, the challenges include reduced battery life, communication overhead between EVs and grids, and changes in the distribution network infrastructure. The integration of EVs into the grid offers energy storage and system services solutions. Figure 2 illustrates the V2G concept, which describes the integration described above.

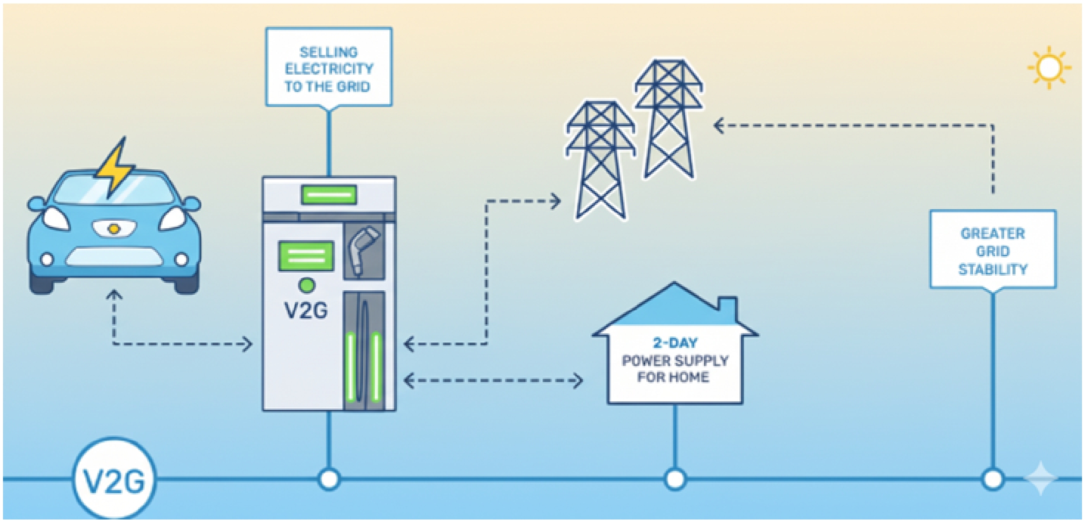


Figure 2 V2G Concept (Darshan Mehta, 2022)

V2G technology refers to the process of transferring surplus energy from EVs back to the smart grid. V2G, or vehicle-grid integration (VGI), helps in providing additional electricity to the energy grid during periods of high demand. This technology also serves as a supplementary power source when renewable energy sources, which are dependent on weather conditions, are not accessible. An example of this scenario is when a residence relying on solar power is unable to produce electricity at night. However, an EV could serve as an alternative power source in such situations (Sandström et al., 2022).

According to Nutkani et al., 2024, EVs are used as mobile energy storage units to meet peak load power requirements. This involves various power electronics components such as a motor, powertrain inverters, batteries, converters, and an on-board charger. The integration of V2G technology introduces advanced power electronics systems such as smart grids and smart charging stations. Supervising the charging and discharging of EV batteries should be conducted remotely, considering factors such as the level of battery discharge, power grid demand, battery and grid technical status, smart or traditional grid type, terms of the agreement between the vehicle owner and utility company, and the planned journey time and distance for the EV user. Additionally, according to Rajalakshmi and Wahab, 2025, an AI-based optimal design of a bi-directional capacitor-inductor-inductor-capacitor converter for EV applications could be applied to address the charging station's controller system.

2.2 Smart charging scenario

Unlike batteries in the off-grid PV system, while the technology for exchanging electricity between EVs and homes is established, the process of transferring power from EVs to the smart grid is still in the testing phase. The key factor for V2G implementation is ensuring compatibility between EVs and the smart grid (Guille and Gross, 2009). Standardizing smart grids and charging stations is crucial for the advancement of V2G technology, and IEEE is currently working on standardization efforts in this area. EVs and their chargers, referred to as power conversion equipment, are designed to be intelligent and capable of regulating the charging and discharging processes in different grid situations to facilitate the integration of V2G technology (Steward, 2017). Testing the performance of these systems necessitates the use of a genuine bi-directional power supply that can supply and absorb power in various directions and replicate a range of grid conditions. International standards impose strict and complicated test procedures that require a flexible tool to generate all grid scenarios. V2Gs must be tested according to various standards, such as IEEE 1547/UL 1741/UL 458/IEC 61000-3-15 / IEC 62116 (Basso, 2014).

2.3 V2G Algorithm

Batteries are widely recognized as efficient and environmentally friendly energy storage systems. Despite their benefits, batteries are prone to damage during use, making their condition difficult to assess. When ensuring the safe use of a battery in practical applications, three main factors must be considered: the need for self-certification or independent third-party testing, the importance of cell testing, and the requirement for battery certification (Ertugrul, 2016). Battery degradation is influenced by various factors, including charging and discharging rates, depth of discharge (DoD), temperature, voltage, cycle number, and storage state of charge (SoC). The quantification of these factors can be complex (Sovacool and Noel, 2019; Barré et al., 2013; Wang and Wang, 2013). Battery degradation can be categorized into two main types: calendar aging and cycle aging. Calendar aging (Lam et al., 2025; Krupp et al., 2022; Dubarry et al., 2018) occurs when the battery is not in use, whereas cycle aging occurs during charging and discharging. Battery temperature and SoC are the key factors influencing calendar aging, whereas cycle aging is influenced by the number of charge–discharge cycles, charging rate, and DoD. As a result, the increased number of charging cycles resulting from the V2G service expedites the battery's deterioration. Aside from those battery issues, the environmental impacts of internal combustion engines when compared to EVs from a LCA point of view are still much better (Idris et al., 2025).

The higher voltage present during charging as opposed to discharging at an equivalent power output results in a decreased charging current, consequently minimizing internal resistance losses. The proposed V2G algorithm provides the constant current-constant voltage (CC-CV) method using two fuzzy logics to mitigate the battery voltage, current, and SoC of EVs. This method maximizes the charging power in a short period and prevents overcharging the battery as the battery charging and discharging process runs. The first and second fuzzy logic controls adjust the duty cycle so that both the current and voltage are constant. The fuzzy controller is configured with input variables (e.g., voltage error, current error, and state-of-charge deviation) and output variables (e.g., duty cycle and charging power level adjustments). Each input and output variable is characterized by triangular or trapezoidal membership functions that depict low, medium, and high linguistic categories. The rule base adheres to a conventional IF–THEN format; for example, "IF voltage error is High AND SoC is Medium THEN reduce duty cycle." This framework facilitates the adaptive regulation of charging current and voltage, thereby ensuring battery safety and efficiency.

2.4 Simulation Process

To ensure the validity and accuracy of the simulation, its steps and configuration are shown in Figure 3. The comprehensive simulation procedure is represented in the flowchart, which outlines the primary steps and testing parameters associated with each charging station model. Table 1 lists the test conditions.

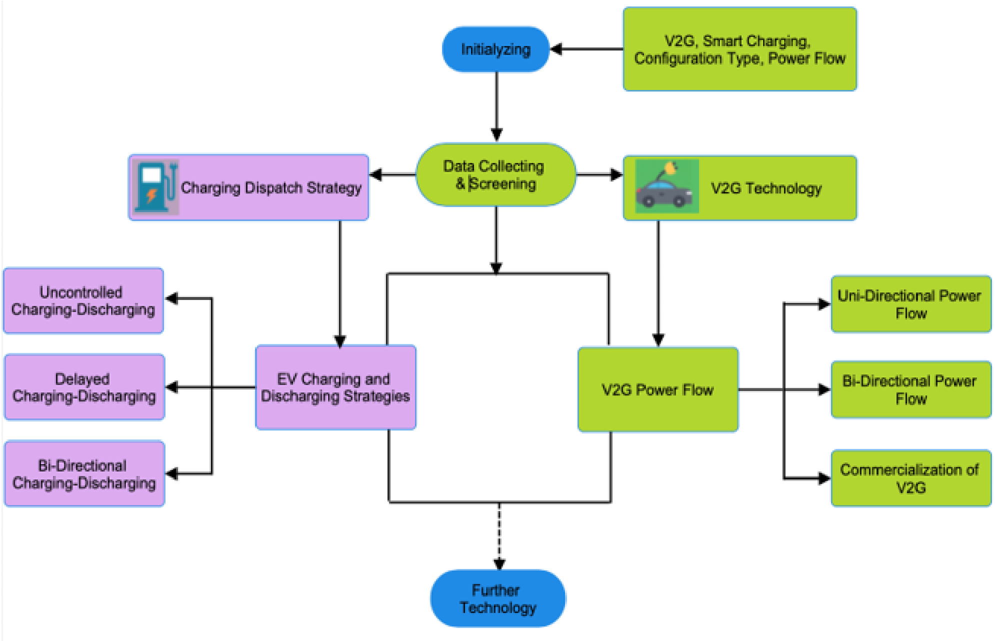


Figure 3 Flowchart of the simulation

Table 1 Simulation of charging station models' specifications and conditions

	Model No. 1	Model No. 2
Configuration Type	Plug-in Vehicle	Battery Exchanging
Power Flow	Uni & Bi-directional	Uni-directional
Charging Dispatch	Uncontrolled & Bi-directional	Controlled & delayed

The process of generating power through V2G technology is essential while EVs are in operation. Different types of EVs, including fuel-cell cars, battery-electric cars, and plug-in hybrids, are available in the market. The batteries of electric vehicles can be recharged during times of lower demand to reduce peak energy consumption. Shahid et al., 2023 stated that every EV requires three components: (a) a network connection for power flow, (b) a logical interface for control with the grid operator, and (c) an onboard instrumentation system that monitors the vehicle (Un-Noor et al., 2017). Each charging dispatch of the battery comes with advantages and disadvantages. The uncontrolled charging-discharging approach allows EVs to charge or discharge at rated power as soon as they are plugged in until the battery's storage level is equal to the maximum SoC or unplugged (Sovacool and Noel, 2019; Barré et al., 2013). The controlled charging system provides electric vehicle owners with the flexibility to make independent charging choices. However, unregulated charging practices could potentially damage local distribution grids due to issues such as power loss, imbalance in supply and demand, reduced lifespan of transformers, and harmonic distortion (Shahid et al., 2023). System operators can authorize unidirectional over-controlled charging-discharging dispatch whenever EVs are charged and discharged (Scott and Ahsan, 2021; Kern et al., 2020; Sovacool and Noel, 2019). However, EV owners must hand over the control to the system operators or aggregators as soon as the EV is plugged in. A delayed controlled charging strategy provides ancillary services to power grids by incentivizing EV owners by using more straightforward price signals. Table 2 summarizes the differences between the three EV charging and discharging dispatches.

Table 2 Summary of different EV charging and discharging dispatches

Dispatch	Advantages	Disadvantages
Uncontrolled	- Easy implementation - EV owners freely to make charging decisions - Convenience for EV owners	- Add burden to power grids - Charging costs might be higher - Unmatched with the demand-side management system
Controlled	System operators freely to make decisions	EV owners control to the system operators
Delayed	Use monetary terms	Electricity pricing signals need to be accurate effectively

The three categories of charging dispatches are referred to as smart charging scenarios. These scenarios enable EV owners to control their EVs' charging or discharging according to specific time frames and rates to meet predetermined objectives, such as reducing charging expenses or maintaining a balance between energy demand and supply. Despite this, many EV owners lack a clear understanding of the financial advantages associated with smart charging. Figure 4 depicts the charging and discharging operations of the three strategies that were previously mentioned.

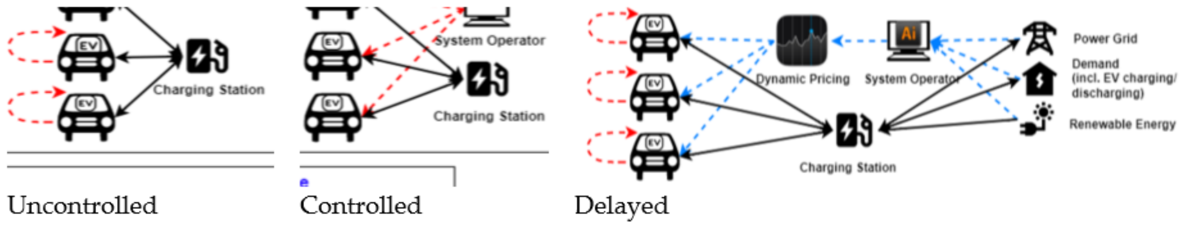


Figure 4 Schemes of EV charging strategies

The EV charging system is designed to incorporate renewable energy sources, notably solar panels, along with a battery power storage system. Two models are involved in this system: the battery model (BAT) and the inverter model (INV), as shown in Figue 5 and Figure 6, respectively. Each model serves specific purposes and offers distinct advantages in maintaining the effectiveness and longevity of the EV charging system. Figure 5 emphasizes flexible storage capacity and backup functionality. Figure 6 showcases effective power conversion from PV sources to AC for EV charging and integration with the electrical grid.

The BAT model focuses on adaptable and reliable power storage, whereas the inverter-based model prioritizes efficient power distribution and protection from solar panels (Stecca et al., 2022). Combining these models in the EV charging system can reduce reliance on traditional networks, promote the shift toward clean energy, and ensure the sustainability of charging station operations in diverse circumstances. This aligns with worldwide initiatives aiming to encourage the use of EVs as a greener and more energy-efficient option for future transportation needs.

The second model emphasizes power transmission control from the solar panels to the inverter and then to the AC output for charging the electric vehicle. It uses the Growatt Inverter SPF 5000 to convert the DC power from the solar panels into reliable AC power. An essential component of this model is the inclusion of multiple 2P DC MCBs with a 16A capacity, serving as safeguards against overcurrent. Furthermore, this system is equipped with a surge protection device (SPD) rated at 150 V, serving a crucial function in safeguarding system elements against voltage surges that can harm the device. This model prioritizes the use of batteries as the primary element for storing power in the EV charging setup. The energy generated by solar panels, with PV 1 and PV 2 serving as energy inputs, is processed by the Growatt SPF 5000 inverter. This inverter transforms the solar panel energy from DC to AC, enabling it to effectively charge the battery. This setup consists of multiple batteries placed in a series, with each battery protected by a 125A 2P DC MCB for overcurrent protection. This configuration enables the stored energy in the batteries to be used for charging EVs without grid power or as a backup energy source during emergencies. The primary benefit of this model is its capability to store surplus energy generated by solar panels in batteries for later use, such as charging EVs or feeding energy back into the grid with a V2G system. Moreover, the battery system offers flexibility in energy management, enabling the charging station to function uninterrupted even during main network outages. This feature enhances the reliability and efficiency of EV charging, particularly in regions prone to power interruptions.

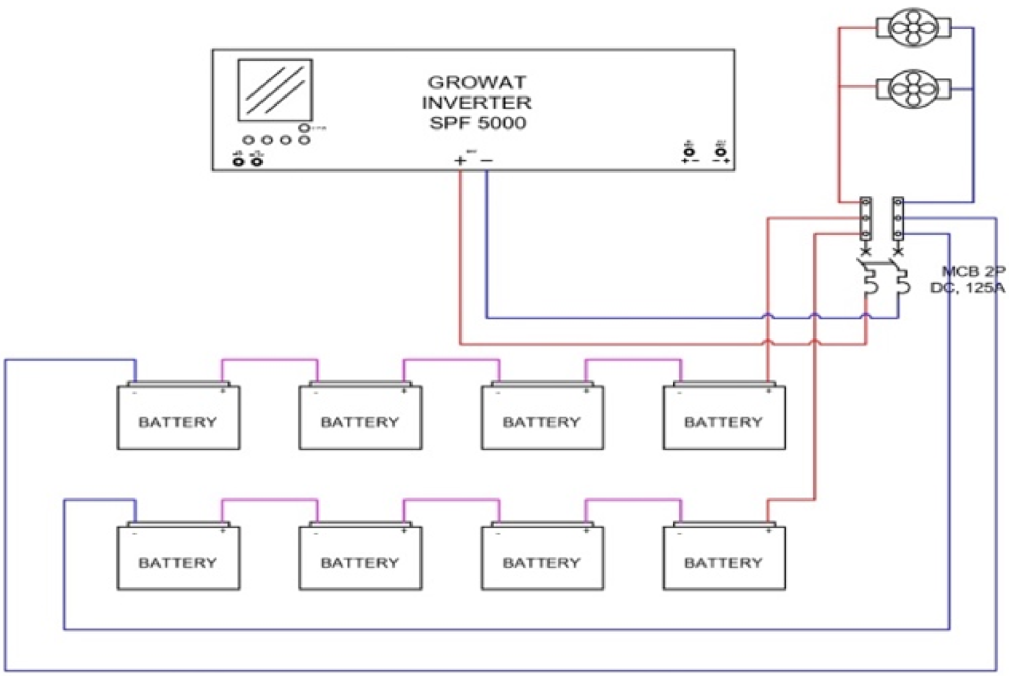


Figure 5 Model of battery charging station - Battery (BAT)

The charging station INV model is designed to efficiently control power distribution from solar panels to the grid or EVs, offering a versatile solution for using renewable energy in vehicle charging. The inverter plays a crucial role in maintaining a stable and secure energy flow to the EV or grid, especially if there is a V2G function. Additionally, the SPD and reliable grounding safeguard the system against voltage spikes, reducing the risk of damage from unforeseen power fluctuations. Both models aim to enhance the efficiency and safety of public EV charging stations.

3. Results and Discussion

The performance metrics employed in this study, specifically charging time, grid import/export power, PV utilization rate, and SoC evolution, were selected to facilitate a thorough evaluation of both system-level efficiency and user-centric impacts. Charging time serves as a direct measure of user convenience and is a crucial factor in EV adoption. The grid import and export power metrics reflect the utility grid's demand, which is vital for assessing grid stability under various charging strategies. The inclusion of PV utilization rate allows for an assessment of the effectiveness of incorporating renewable energy sources while quantifying the balance between self-consumption and dependence on grid electricity. Furthermore, the analysis of SoC evolution aids in tracking the charging behavior of the EV battery, ensuring that smart charging and V2G approaches do not jeopardize battery safety. Finally, indicators related to battery longevity, such as cycle count and depth of discharge, were considered to evaluate the long-term sustainability of the proposed system. Collectively, these metrics provide a well-rounded appraisal of technical performance, integration of renewable energy, and user-relevant outcomes.

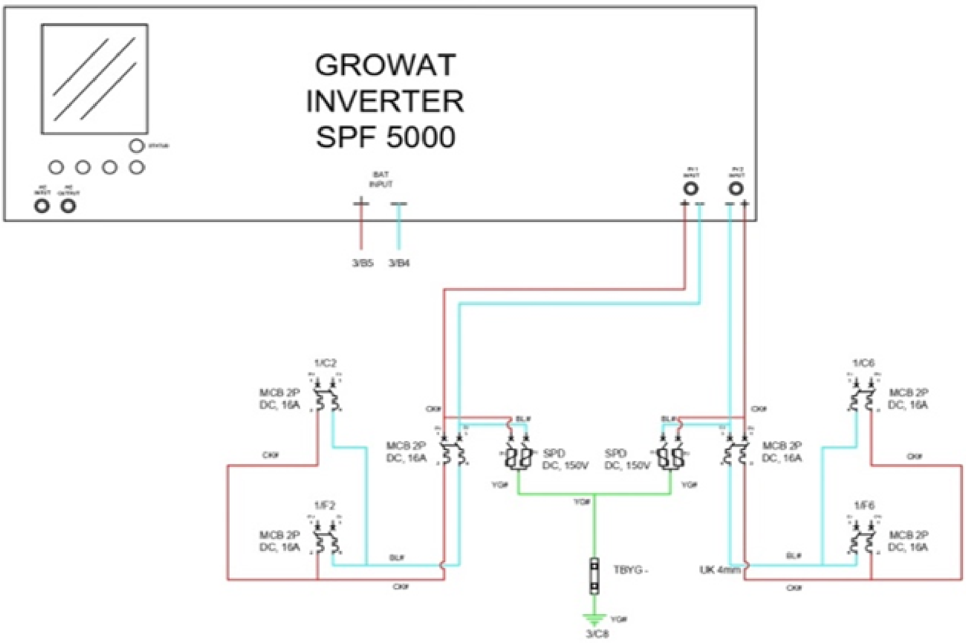


Figure 6 Model of battery charging station - Inverter (INV)

3.1 Simulation Results of the CC-CV Method

Power electronics play an important role as the CC-CV method is implemented during the charging process. A CC-CV algorithm is used to charge and discharge a battery. The battery CC-CV block is charged and discharged for 10 h. The initial SoC value is 0. When the battery is being charged, the current is constant until the battery reaches the maximum voltage, and the current decreases to 0. The model uses a constant current when the battery is discharging. The voltage switches from a constant current to a constant voltage when it reaches its highest state of charge. Two separate control systems are used once both criteria are satisfied. When the voltage reaches the battery's peak level, the charging method shifts from constant current to constant voltage. The transition occurs when the voltage and current are at one-third of their maximum values. The SoC then increases as the transition progresses in both scenarios. The CC-CV method aims to maximize power and minimize the battery charging time.

3.2 Simulation Result of Charging Dispatch Strategy and Power Flow

The microgrid consists of PV generation, a battery, an emergency generator, loads, and a V2G-enabled EV charging station. The battery is used for solar smoothing, peak shaving, and energy arbitrage when the microgrid is connected to the main grid. The batteries and PV inverters were then used in the grid-following mode. When the microgrid is disconnected from the main grid, the battery inverter acts as the primary power source, while the PV inverter adjusts its power output accordingly. The emergency generator kicks in only when the battery is depleted and sufficient solar energy is not being produced. The EV batteries can provide backup power for both the microgrid and the main electrical grid. Frequent uncontrolled charging practices result in a greater DoD and irregular cycling, which can accelerate the battery degradation process. By minimizing high-current peaks, the implementation of controlled charging methods helps alleviate cycle stress, whereas delayed charging tends to prolong idle periods at mid-SoC, thereby reducing calendar aging effects. The simulation results indicate that uncontrolled charging led to deeper discharge cycles, with an average DoD of approximately 85%. In contrast, both the controlled and delayed charging strategies decreased the DoD to approximately 70% and 75%, respectively. These findings imply that smart charging solutions not only enhance grid stability but also prolong battery lifespan by alleviating cell stress. Table 3 summarizes the impact of battery life on the developed dispatch strategies.

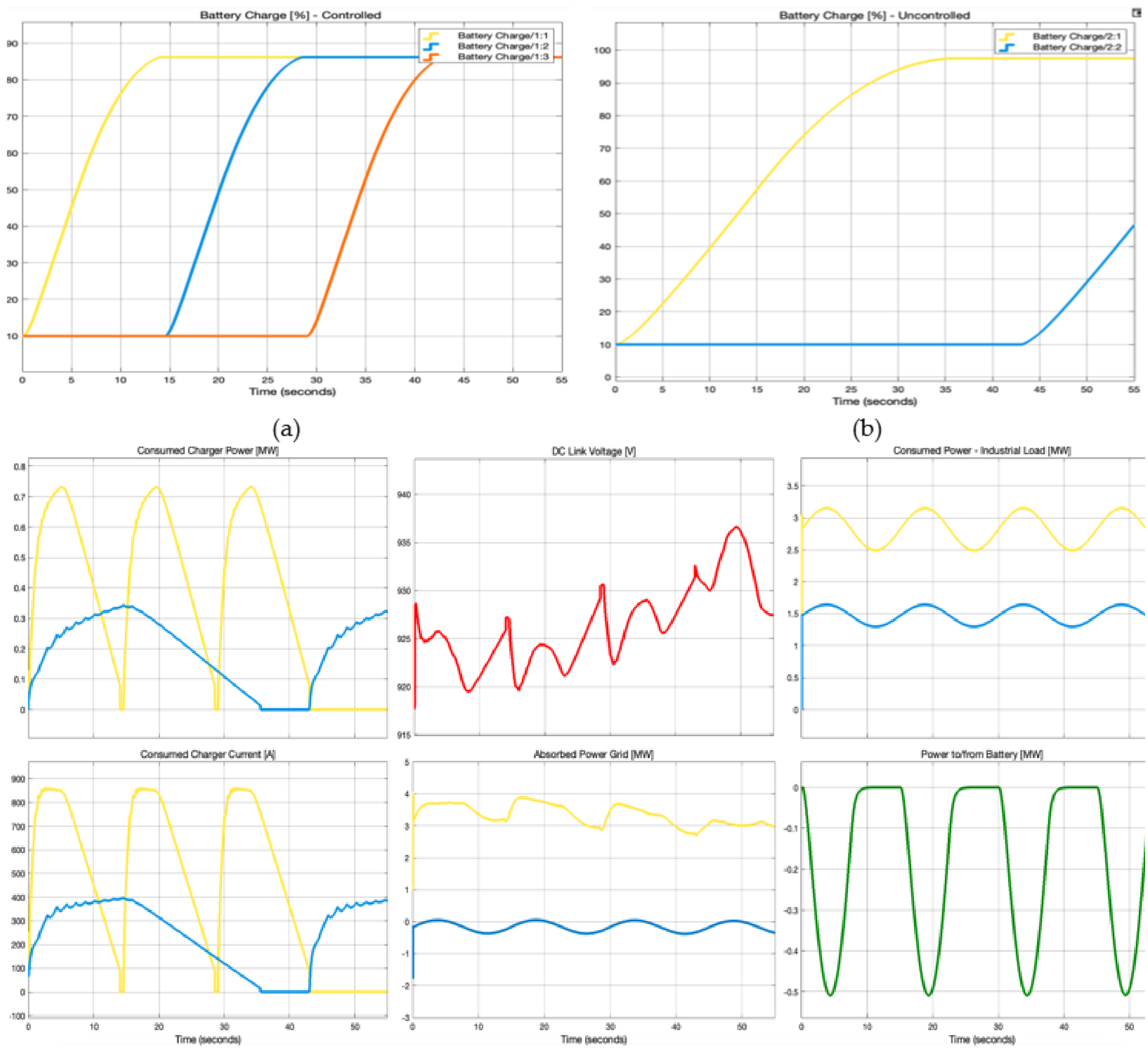
Table 3 Summary of battery life impact on different EV charging and discharging dispatches

Dispatch	Charging Time (min)	Grid Import (kW)	PV Utilization (%)	Avg. DoD (%)	Battery Life Impact
Uncontrolled	72	3.2	68	85	Faster degradation
Controlled	55	2.5	84	70	Longer life
Delayed	60	2.8	79	75	Moderate impact

Figure 7 shows how batteries react during controlled and uncontrolled charging. The controlled charging results (Figure 7(a) and 7(b)) indicate that three EVs were charged within 55 s of the simulation. During the same time frame, only two electric vehicles were charged. The graph in Figure 7(c) shows the response to controlled and uncontrolled dispatches with a yellow and blue lines, respectively. The graph displays the following: i) the amount of power consumed during both controlled and uncontrolled dispatch; ii) the current flowing through the system; iii) the DC link voltage; iv) the power absorbed from the grid into the vehicle; v) the power consumed by the industrial load; and vi) the power flowing through or from the battery.

In V2G operation, electricity moves from the battery to the grid. The charger should be able to handle AC power with a sinusoidal current, as in the G2V mode. The DC-DC converter must consistently take power from the battery. Therefore, the battery current gradually increases to compensate for the voltage decrease that occurs naturally during the discharge process. Figure 8(a) shows the power grid voltage (v_s) and AC output current (i_s) over two grid cycles. Figure 8(b) displays the battery current (i_{TB}) and voltage (v_{TB}) over a two-hour operation period. The G2V operation mode of the bidirectional charger produced simulation results. In Figure 8(c), the power grid voltage (v_s) and AC input current (i_S) are displayed over two grid cycles in Figure 8(c). The input current is nearly sinusoidal and synchronized with the power grid voltage, confirming the effectiveness of the hardware topology and control algorithm used in the full-bridge AC-DC bidirectional converter. Figure 8(d) shows the battery charging current (i_{TB}) and voltage (v_{TB}) in the initial two hours of operation. This simulation employs a battery model that is set up to mirror an actual battery pack for a more accurate outcome. During this period, the battery current remains steady, while the battery voltage rises in a nearly straight line. This setup ensures the proper functioning of the DC-DC reversible converter.

In addition to the waveform analysis, quantitative data were collected. The average charging duration for three EVs under an uncontrolled charging approach was 72 min. In contrast, implementing controlled and delayed charging strategies reduced the charging duration to 55 and 60 min, respectively. During the uncontrolled charging phase, the grid import power peaked at 3.2 kW, while it was measured at 2.5 kW under controlled conditions. The utilization rates of the PV systems improved significantly, increasing from 68% in the uncontrolled scenario to 84% with controlled charging and 79% with delayed charging. The evolution of the SoC demonstrated a more rapid and stable increase when employing controlled dispatch, achieving a full charge of 100% in less than 1 h, compared to nearly 1.3 h required in the uncontrolled scenario. Consumers can diminish their dependency on grid electricity by emphasizing the utilization of PV energy, particularly during periods of peak tariffs, which results in reduced monthly electricity expenses. For example, by synchronizing EV charging with peak solar generation times, the self-consumption of PV energy can be increased from approximately 68% to over 80%, consequently decreasing grid reliance by as much as 20%–25%.



(c) Response control

Figure 7 Battery charge responses in controlled and uncontrolled strategy

The findings indicate that the integration of PV systems with EV charging stations, facilitated through smart charging and V2G strategies, significantly enhances PV utilization, reaching up to 84%. Additionally, the dependence on the grid is reduced by 20%–25%, along with shorter charging durations and prolonged battery lifespan due to managed and delayed charging practices. These findings underscore the considerable influence of such integration on grid stability and battery efficiency while simultaneously decreasing electricity expenses for consumers, postponing expensive grid infrastructure upgrades, and minimizing carbon emissions through the maximization of renewable energy usage. Furthermore, the V2G functionality contributes to increased resilience by allowing EVs to function as distributed energy storage systems and backup power sources. Taken together, these effects position the integration of PV systems with EV charging stations as a viable, sustainable, and economically advantageous approach to advancing the shift toward clean energy and electric mobility. The novelty of this research is the integration of a fuzzy-controlled CC–CV charging algorithm with a comprehensive Simulink model of a bidirectional EV charging station linked to a grid-connected PV microgrid. Concurrently, it offers quantitative insights into both user- and grid-level metrics, including charging duration, grid import/export dynamics, PV utilization, SoC, and DoD. The documented enhancements, such as the reduction of charging time from 72 to 55 minutes, an increase in PV utilization from 68% to 84%, and a decrease in DoD from 85% to 70%, illustrate that coordinated smart charging can significantly enhance PV self-consumption and alleviate battery strain in practical implementations of small-scale PV systems combined with EV charging stations.

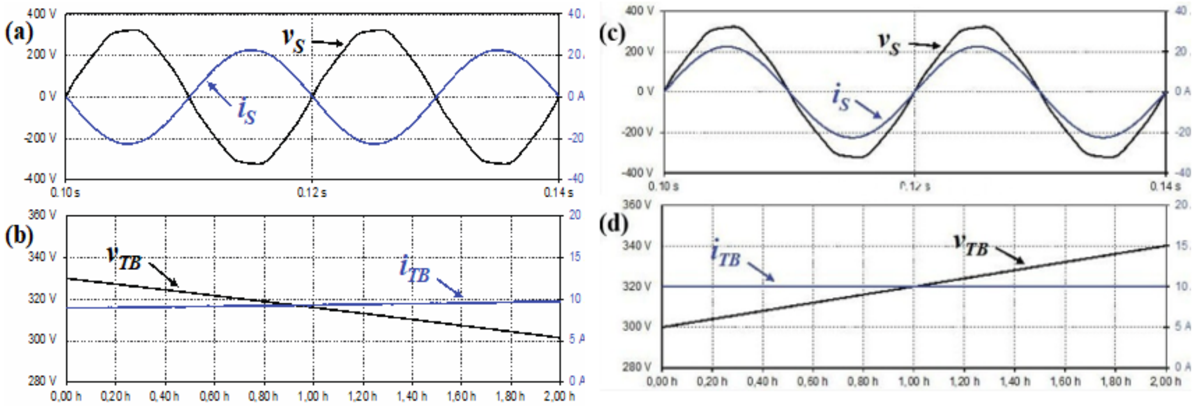


Figure 8 V2G and G2V Grid Voltage and Current

4. Conclusions

This study outlined the design and simulation of a fuzzy-controlled bidirectional electric vehicle (EV) charging station integrated with a 2.5 kW PV microgrid. The study employed a constant current–constant voltage (CC–CV) charging algorithm regulated by fuzzy logic controllers to enhance charging efficiency and facilitate safe bidirectional power exchange, encompassing both G2V and V2G operations. The simulation outcomes indicated notable enhancements compared to the uncontrolled charging scenarios. The charging duration was shortened from 72 to 55 minutes through controlled management, thereby increasing user convenience. Additionally, the use of PV energy increased from 68% to 84%, while the energy imported from the grid decreased from 3.2 kW to 2.5 kW. These findings underscore the efficacy of intelligent charging strategies in optimizing renewable energy consumption and decreasing grid electricity reliance. Furthermore, battery stress was alleviated, and the average depth of discharge (DoD) decreased from 85% to 70%, suggesting a potential extension in battery lifespan. These findings validate that the proposed fuzzy-controlled CC–CV algorithm can significantly enhance charging efficiency, promote PV energy self-consumption, reduce grid dependency, and contribute positively to battery health alongside the centralized EV charging station model. Future research will aim at experimental validation, broader integration efforts, and real-time implementation featuring adaptive scheduling that accounts for varying PV generation and load demands.

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Author's Contribution

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Author's Contribution

Declared that the preparation of the graphical abstract used ChatGPT.

Conflict of Interest

The authors have no conflicts of interest to declare.

Declaration of AI

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