



RESEARCH ARTICLE

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FUZZY LOGIC CONTROLLER – BASED CONTROL FOR FAST EV CHARGING STATIONS IN DC MICROGRID SYSTEMS

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ARTICLE INFO

Article History

Received on: January 26, 2026

Reviewed on: February 27, 2026

Accepted on: April 10, 2026

Published on: June 30, 2026

Keywords:

Bidirectional Converter, DC–DC Converter, Electric Vehicles (Evs), Fast Charging, Lithium-Ion Battery, Neutral-Point-Clamped (NPC) Converter, Solar Photovoltaic (PV) Systems, Fc Controller.

ABSTRACT

This project proposes an advanced fuzzy logic controller (FLC) for fast EV charging stations integrated with DC microgrids. Unlike conventional PI controllers, which struggle with dynamic operating conditions, the FLC adapts in real time using parameters such as battery state of charge, grid conditions, and battery health. In Grid-to-Vehicle (G2V), Grid + Photovoltaic to Vehicle (G+PV2V) modes, the controller ensures efficient fast charging by optimizing current flow, reducing voltage ripples, and maintaining DC-link stability. In Vehicle-to-Grid (V2G) mode, it dynamically regulates battery discharge to enhance grid support while protecting battery life. Simulation results show that the proposed FLC significantly reduces charging time and improves system efficiency, achieving a runtime of 213.3 seconds compared to 317 seconds using a PI controller. Overall, the FLC-based strategy enhances system stability, responsiveness, and adaptability, making it a suitable solution for smart EV charging in modern DC microgrids.



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I. INTRODUCTION

In recent years, electric vehicles (EVs) gained popularity as they are able to decrease the consumption of oil fuels, enhance air purity in metropolitan cities, eliminate noise pollution, and promote eco-friendly transport networks [1]. This has opened up a new era, and thus, EVs are predicted to substitute conventional vehicles with internal combustion engines in the near future. In this regard, to create a uniform charging procedure for EVs, charging standards were developed by the Society of Automotive Engineers and International Electrotechnical Commission based on electrical requirements, charging methods, and charging duration. With respect to charging duration, charging of EVs is classified under three categories, including slow charging (Level 1), which takes more than 8 hours; medium charging (Level 2), which takes 6 hours; and fast charging (Level 3), which takes only 30 minutes to fully charge the EVs' batteries altogether [2].

Level 1 charging is appropriate for residential purpose or charging during night time; nevertheless, the longer charging time makes it unsuitable for daily driving range of traditional vehicles. Level 2 charging supports higher power levels along with faster charging times than Level 1 charging and is still not appropriate as a vehicle onboard charging system owing to time constraints. Rapid charging is thus highly desirable for EVs. Level 3 charging consists of off-board fast-charge connectors of high power levels of 80-240 kW, which facilitates fast charging of the vehicle battery. With the rising use of EVs, the need for a large number of charging stations arises [3]. The planning, placement, and operational impact of EV charging stations on modern power systems have been widely studied [4], [5]. At present, the popular method of charging the EV is by connecting it to 120 V (Level 1) or 240 V (Level 2) AC receptacles as per the SAE J1772 (2010) recommendation [6], [7].

Though this slow-charging system is able to charge the battery fully within several hours, it is inefficient owing to longer charging times [6]. Therefore, fast charging is preferred to minimize the charging time and facilitate wider diffusion of EVs [7]. Advanced converter topologies and integrated renewable-based charging stations have been proposed to improve efficiency and scalability [8], [9]. CHAdeMO standard is an off-board DC fast-charging technology, and hence, higher power level charging can be achieved using this, and fast-charging station has a wide use of this for implementation [10], [11]. A microgrid is a decentralized self-contained source of electrical supply that incorporates the use of the main grid supply and renewable sources of electricity in order to minimize dependence on the main grid supply [12], [13], [14]. Of the renewable sources of electricity, solar photovoltaic sources are very popular. Hence, the incorporation of solar PV-based BESSs in the DC-based charging stations may greatly reduce grid stress and make the entire system reliable [15].

II. LITERATURE AND RESEARCH GAP

II.1 LITERATURE

[1] **H. Tu, H. Feng, S. Srdic, and S. Lukic** highlight that there is an urgent need for efficient charging infrastructure as the adoption rate for electric vehicles is extremely fast. Extreme Fast Charging (XFC) is cited as one promising solution that can offer charging times comparable to conventional refueling times. This paper discusses rapid EV charging methods in general as well as the requirements for XFC. The importance of employing Solid-State Transformers in Extreme Fast Charging stations is also discussed along with Medium-Voltage SST configurations for such applications.

[2] **Z. Moghaddam, I. Ahmad, D. Habibi, and Q. V. Phung** discuss various robust design approaches in the context of electric machines, power electronics, and drive systems, as featured in a special issue of the IEEE Transactions on Energy Conversion journal. The authors address significant areas of tolerance analysis, robust optimization, and reliability enhancement of electrical machines, power converters, and control systems. The inclusion of modeling uncertainties, robustness/reliability analysis, and optimization of complex designs by the authors also portrays the recent trends in the area of study.

[3] **B. Bilgin et al** state that vehicle electrification has inevitable importance for fuel consumption and greenhouse gas emissions. Improved powertrain efficiency, high power and energy density components, and optimized control strategies are the key factors to extend driving range and lower energy consumption in electrified transportation systems.

[4] **S. Rivera, S. Member, B. Wu, S. Kouro, V. Yaramasu, and J. Wang**, in this paper, do a critical review on electric vehicle charging technologies: converter topologies, power levels, and charging control strategies. Their work focuses on different fast and efficient charging techniques to be used in lithium-ion batteries in order to improve charging efficiency and prolong battery life; furthermore, using the sensitivity analysis, it employs genetic algorithms to find the optimum charger sizing. In addition, various converter topologies such as neutral point clamped converters and bipolar DC bus systems have been explored for EV charging applications [16], [17]. Harmonic distortion and power quality issues during fast charging have also been reported as critical challenges in distribution systems [18]. Multilevel inverter technologies are widely used to mitigate these issues and improve power quality [19].

II.2 RESEARCH GAP

A literature study shows that the majority of existing EV fast-charging stations use traditional AC grid-based systems and PI controller-based control methods. Since DC microgrid-based charging systems provide greater energy efficiency benefits and improved renewable energy source integration, surprisingly, relatively fewer studies have specifically focused on intelligent control methods tailored to the specific needs of high-power EV fast charging applications. Fuzzy Logic Controllers (FLCs) have been extensively used with relative success in islanded DC microgrid applications as well as in renewable energy applications, although the application of FLC-based control to DC microgrid-based EV fast-charging stations with coordinated control of solar, BESS, and EV loads is unexplored. Furthermore, it will be noted that many studies do not consider the effect of EV connection and EV disconnection switching disturbances on the DC-link voltage stability.

III. MATERIALS AND METHODS

III.1 DC MICROGRID FOR CHARGING OF EVS

A DC microgrid-based fast-charging system for electric vehicles is proposed in this section. It consists of a bidirectional AC-DC converter, a bidirectional DC-DC converter for EV battery charging and discharging, and a DC-DC boost converter to integrate REN like solar PV on the DC bus. The aim is to develop a fast-charging strategy based on the multistep constant-current methodology for enabling EV batteries to be charged within 30 minutes while reducing the impact on the utility grid. Coulomb counting is employed in the battery SOC estimation in order to control the charging process. A three-level NPC AC-DC converter provides a stable DC link voltage with reduced grid harmonics. In this system, the bidirectional DC-DC converter operates in buck and boost modes and enables controlled battery charging and discharging. A solar PV system feeds to the DC bus and is operated at maximum power point to support the charging demand in order to reduce the grid dependency and improve the overall system efficiency. The integration of photovoltaic systems with battery storage significantly improves energy utilization and reduces dependency on the utility grid [20].

III.2 PROPOSED SOC-BASED MULTISTEP CONSTANT CURRENT ALGORITHM

This section describes the multistep constant-current fast-charging algorithm. The charging strategy is realized by controlling several constant current levels according to the feedback of the battery current. Battery SOC estimation is done by a coulomb counting method (CCM). Although several SOC estimation techniques exist, open-circuit voltage-based methods suffer from accuracy issues due to temperature variation and battery aging.

Kalman filter-based SOC estimation requires detailed battery modeling using internal parameters such as resistance and capacitance, which are complex to measure and vary with SOC. Therefore, the CCM is adopted in this work because of its simplicity and ease of implementation. This method requires the initial SOC value and uses the measured battery current in order to update SOC during the charging process. Also, the battery current used in the algorithm as shown in

$$SOC = SOC_{(t_0)} + \frac{1}{C_{rated}} \int_{t_0}^{t_0+t} (I_{batt} - I_{loss}) dt$$

In SOC estimation based on the CCM, $SOC(t_0)$ is the initial battery SOC, C_{rated} is rated capacity, I_{batt} represents battery current, and I_{loss} accounts for internal loss currents. The effective charge exchanged with the battery is obtained by integration: Figure 1. presents a flowchart of the proposed multistep constant-current fast-charging algorithm combined with SOC estimation. SOC will be computed continuously from the measured charging/discharging currents; its accuracy mostly depends on proper initial SOC and exact current measurement. Battery charge level is defined as a ratio of available capacity to a total rated capacity

$$SOC_{(t_0)} = \frac{C_{reusable}}{C_{total}} \times 100$$

This can result in overheating when a large current is applied. As a consequence, at a low SOC, the charging current remains low. At a SOC level above 20%, a large charging current is applied for fast charging. High current charging at a low SOC also results in lithium metal deposition due to the negative anode compared to the level of Li/Li^+ at a low temperature. The solid electrolyte interface layer reduces the movement of ions but inhibits electron flow. This ensures stable electrochemical reactions with minimal decomposition.

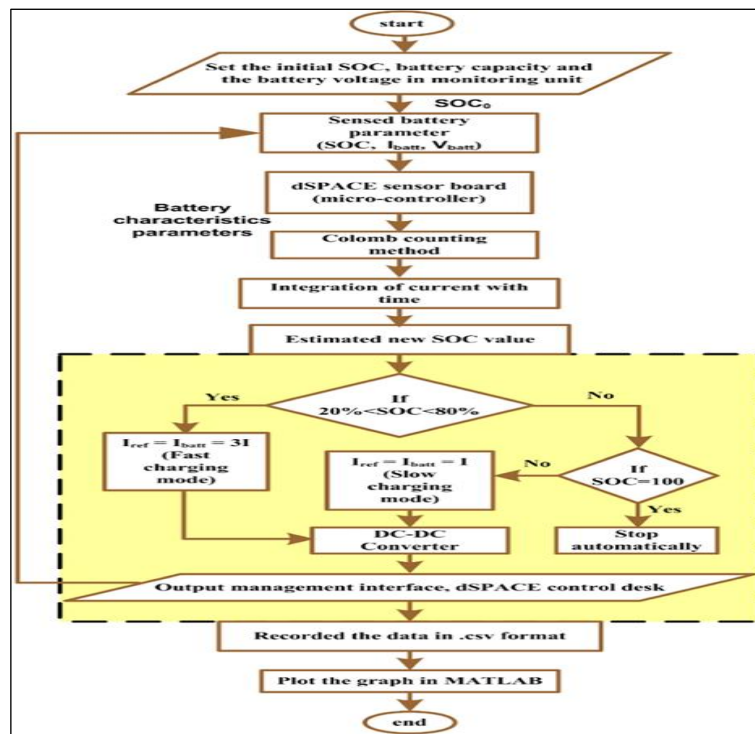


Fig. 1. Flowchart of fast charging algorithm with SOC estimation.
Source: Authors, (2026).

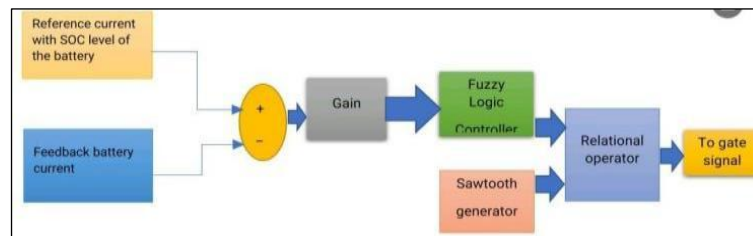


Fig. 2. Control structure of fast charging of EV.
Source: Authors, (2026).

The battery charging is controlled by using a current-controlled strategy that regulates the battery current I_{batt} against a reference current I_{ref} . The reference current is obtained from the battery SOC that is estimated using the coulomb counting method. The current error is passed through a fuzzy logic controller. Since the current ripple is small, its steady-state output is almost constant.

It is compared with a sawteeth carrier of peak value I_M to generate the gate pulse to switch S_{13} as shown in Fig. 2. The buck converter charges with varying duty cycles in the slow and fast charging phases depending on the SOC level. The slow charging process takes place between 0%-20% and 80%-100% SOC to restrict the rise in the switching voltage, and the fast charging takes place between 20%-80% SOC with an incremented current charge of almost three times the slow charge current. The sudden surge in the charge current with a 20% SOC may cause a serious load on the power utility grid, resulting in a considerable drop in the voltage level and transformer saturation. To address this issue, a fast charging DC microgrid station with solar PV and renewable resources to meet fast charging power demands and with the remaining power provided by the utility grid has been proposed.

III.3 OPERATING STAGES AND CONTROL METHOD

In this part, the functioning modes of the proposed system are discussed. There are three cases under which the functioning modes are classified. These cases are fast charging with reliance on utility grid power only, fast charging with assistance from a DC Microgrid, and power transfer from battery.

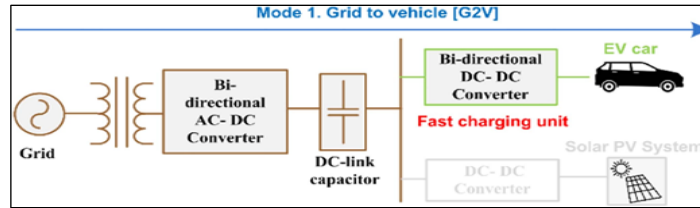


Figure 3: Power flow direction in G2V.

Source: Authors, (2026).

1) Mode 1: Grid to Vehicle (G2V), Charging: In Mode-1 charging is done using only grid power without assistance from solar PV panels. This mode of charging makes use of bidirectional NPC converters to rectify grids to charge battery using buck conversion done by DC-DC converters. Fast and slow charging currents are provided by grids alone to EV battery. The power flow for this mode is illustrated by Fig. 3.

$$P_{\text{grid}} = P_{\text{batt}}$$

a) Slow Charging (0%-20% & 80%-100% SOC)

At the beginning and end of the SOC range, the EV battery will be charged by the minimum value of grid current, $I_{\min}$. The DC-DC buck converter works at a slow charge duty cycle of D_{sc} , which will be computed by the fuzzy logic controller (FLC) as follows.

$$D_{\text{sc}}(k) = F(e(k), \Delta e(k))$$

Where:

$$e(k) = I_{\min}(k) - I_{\text{batt}}(k), \Delta e(k) = e(k) - e(k-1)$$

b) Fast Charging (20%–80% SOC): The fast-charging cycle charges the EV battery from 20% to 80% SOC with the highest current $I_{\max}$, which is three times the lowest current $I_{\max} = 3I_{\min}$. Fast-charging operations demand a large amount of power within the 80 kW to 240 kW range. Fast-charging duty cycle D_{fc} is represented as.

$$D_{\text{fc}}(k) = F(e(k), \Delta e(k))$$

Where:

$$e(k) = I_{\max}(k) - I_{\text{batt}}(k), \Delta e(k) = e(k) - e(k-1)$$

Here, $I_{\min}$ and $I_{\max}$ are the reference currents for multistep constant-current charging, and I_{batt} is the instantaneous battery current. The sudden increase in charging power during fast charging can introduce power quality issues on the grid.

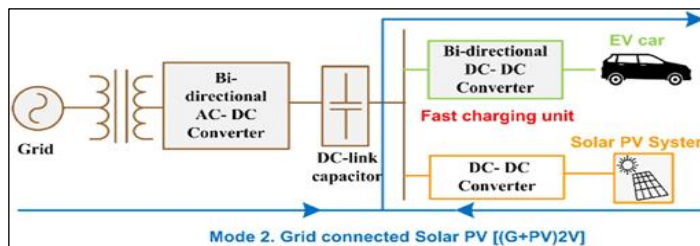


Figure 4: Power flow direction in (G+PV)2V.

Source: Authors, (2026).

2) Mode 2: Grid & Solar PV Integration ((G+PV)2V): In this case, the grid and Solar PV are connected to the DC bus as depicted in Figure 4. The DC-to-DC Boost Converter with the MPPT algorithm maximizes the power obtained from the Solar PV to charge the batteries.

a) Slow charging (SOC 0%-20%, 80%-100%): At a battery SOC of 0%-20%, 80%-100%, the solar PV source will be the sole source of power & the charging current will be based on the amount of solar power drawn.

$$I_{batt} = I_{pv}$$

b) Fast charging (SOC 20%-80%): At this stage, the EV's battery works in the SOC interval of 20%-80% and charges at the maximum permissible current I_{max} . To satisfy the higher charging power, the solar PV and the grid supply the EV at the same time. This assists in reducing the burden of the grid. The equivalent current value when more than one source is supplying current to the EV is expressed below.

$$I_{batt} = I_{grid} + I_{pv}$$

3) Mode 3: Vehicle-to-Grid (V2G) mode: In V2G operation, the NPC converter functions in inverter mode and transfers power from the EV battery to the grid. Scheme 1 is configured as an automotive converter, and in both operating modes, the control capability of the NPC converter is governed by its VPN gate driver. Under this condition, the battery discharging power is equal to the grid power, as expressed in below. The power flow for this mode is illustrated in Fig. 5.

$$P_{batt} = -P_{grid}$$

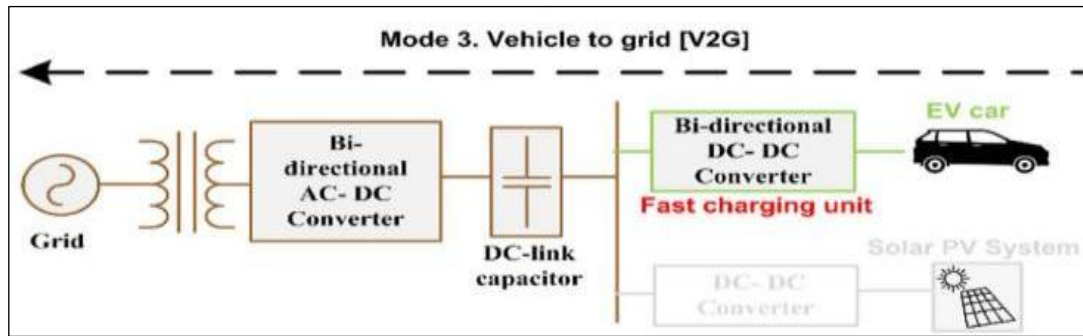


Figure. 5: Power flow direction from Vehicle to grid.
Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

Mode 1: Grid to Vehicle/ (G2V) operation

In this mode, grid to vehicle (G2V) operation takes place without relying on solar PV panels. The bidirectional NPC converter acts as a rectifier here, and for battery charging in this case, a DC-DC converter charges the EV battery in buck mode using grid power for both slow and fast charging. For SOC, DC-link voltage, and voltage ripple, a fuzzy-logic controller provides better stability and efficiency during charging, and an FLC controller helps to adjust real-time performance as shown in fig (6).

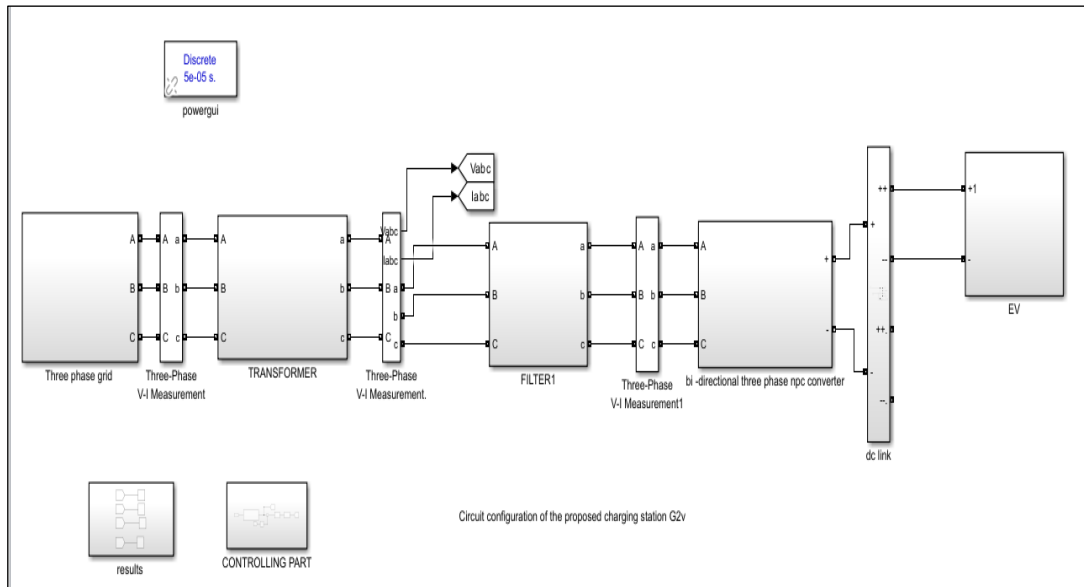


Figure. 6: Simulation configuration of the proposed charging station WITH G2V.
Source: Authors, (2026).

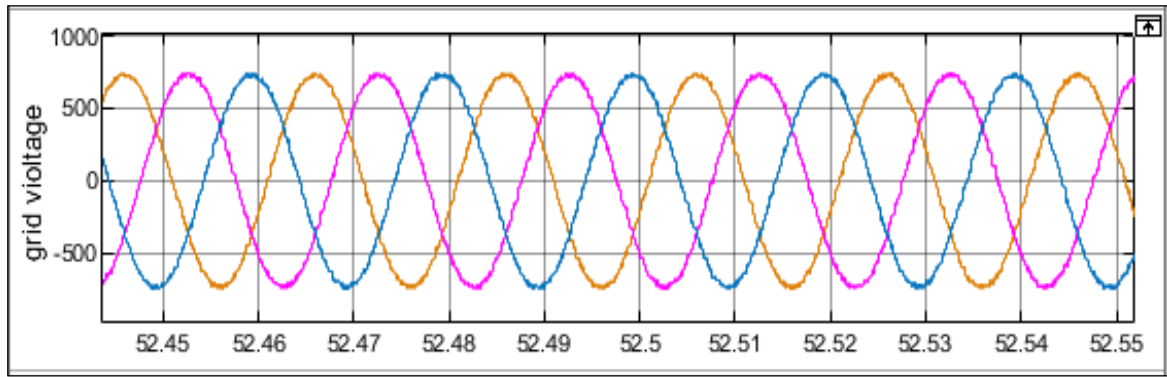


Figure.6: (a). In this figure, we can see that the grid voltage from after the step-down transformer voltage at the grid to vehicles conditions.
Source: Authors, (2026).

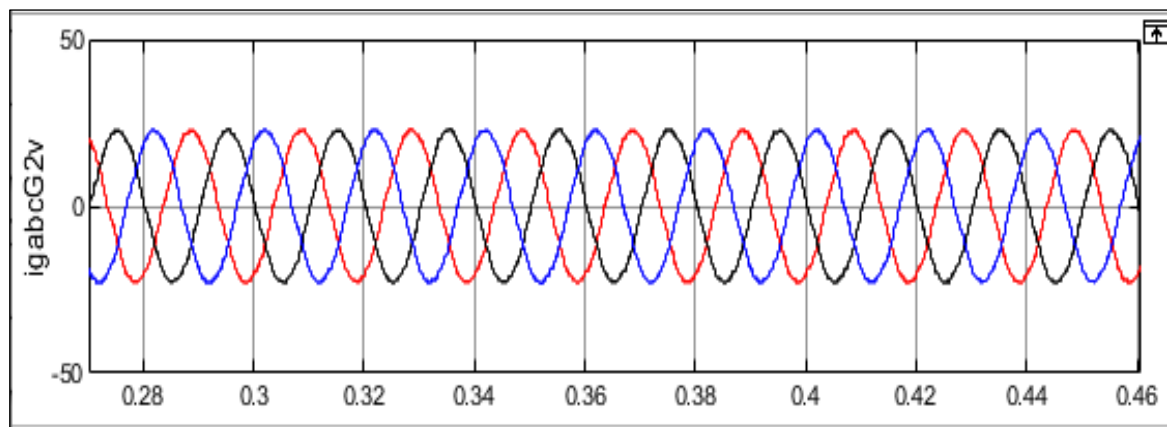


Figure. 6: (b). This figure we seen about the grid current from after the transformer to grid to vehicle conditions.
Source: Authors, (2026).

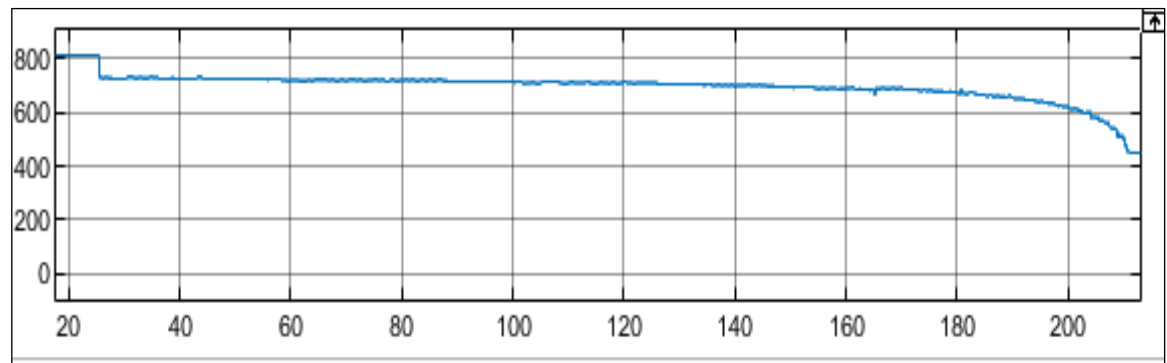


Figure.6: (c). Vdc link voltage.
Source: Authors, (2026).

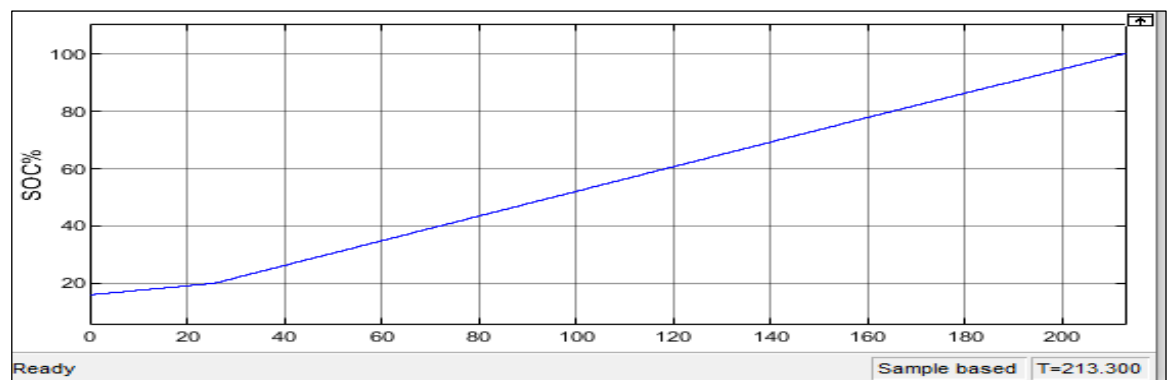


Figure 6: (d). Battery SOC.
Source: Authors, (2026).

Fig. 6(a).The grid voltage of three-phase system is in balance and of equal magnitude, and its waveform is sinusoidal with a phase difference of 120° between phases. The sinusoidal waveform of the grid voltage indicates healthy grid operation and further verifies healthy grid voltage and free from negative effects of charging system on the utility grid regarding grid voltage balance and grid power quality. Fig. 6(b) The grid current in the three-phase system for the proposed topology takes a balanced and near sinusoidal form without harmonic distortion and maintains alignment with the grid voltage. The grid and grid voltage are in near-unity power factor operation due to alignment between grid and grid voltage. Fig. 6(c). DC-link voltage is very well controlled around its reference value during the whole charging time. The fluctuation is only minor, which indicates that the power flow is well maintained in stable operation and the designed control scheme successfully provided voltage stability in a wide operating range. Fig. 6(d). Smooth rise of state-of-charge follows with almost linear transient in time domain; this reflects that the charging process is well-regulated and very efficient. No sudden changes or oscillations are observed which further confirms that the proposed charging strategy avoids sudden transients and yields safe operation of batteries.

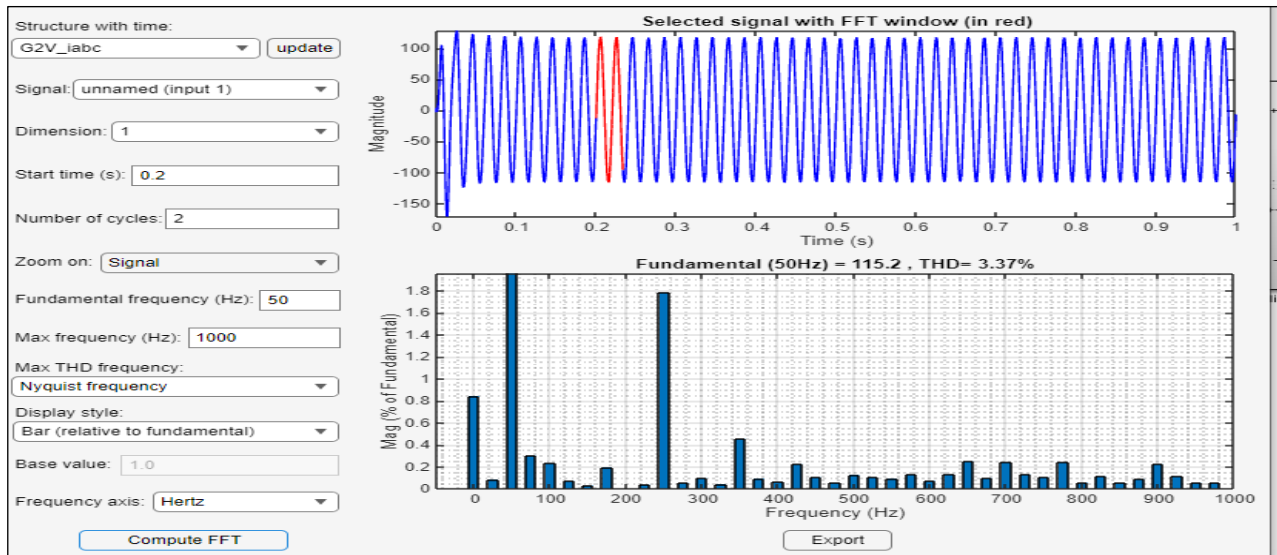


Figure. 6: (e). THD values of after transformer current.

Source: Authors, (2026).

The above Fig. 6(e) shows the FFT and THD analysis results of the transformer current in the G2V conversion process with a FLC. The current waveform is almost sinusoidal, which is an effective result of current regulation. The fundamental current at a frequency of 50 Hz is approximately 115.2 A with a THD ratio of 3.37%, which also satisfies grid specifications.

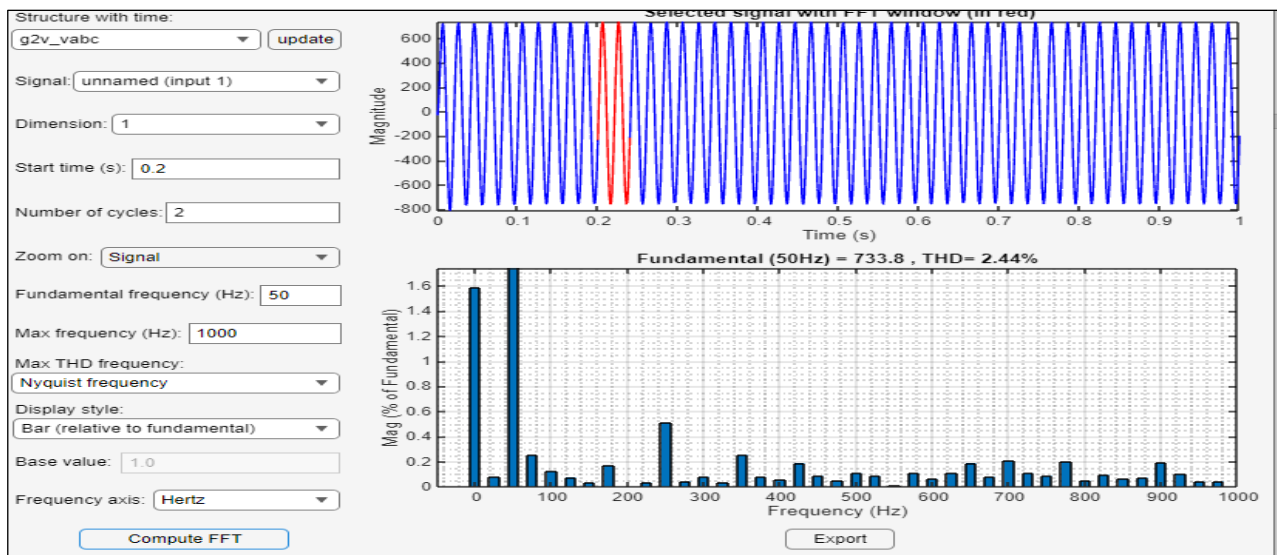


Figure. 6: (f). THD values of after transformer voltage.

Source: Authors, (2026).

Fig. 6(f). Shows FFT and THD analysis of transformer voltage in G2V mode. The transformer voltage waveform is nearly sinusoidal and stable. The fundamental voltage at 50 Hz is about 733.8 V with a low THD of 2.44%. This indicates good voltage quality, reduced harmonics, and compliance with grid standards.

Mode 2: Grid + Photovoltaic to Vehicle/ (G+PV2V) operation

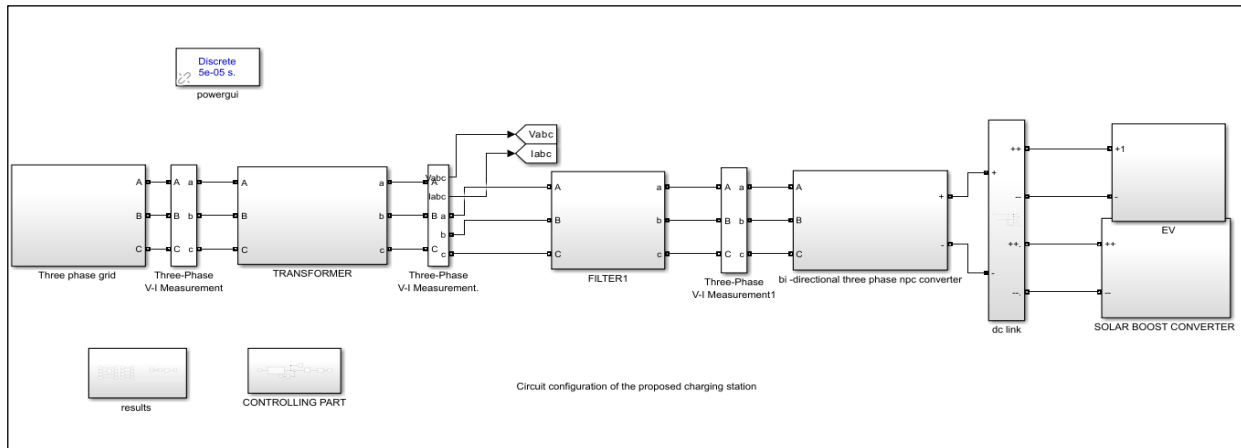


Figure.7: Simulation configuration of the proposed charging station WITH G+PV2V.

Source: Authors, (2026).

The above figure shows the DC charging station configuration which consists of a three-phase grid with an isolation transformer, a three-level AC-DC NPC converter, a bidirectional DC-DC converter for charging and discharging an EV battery, an EV battery, and a boost DC-DC converter for incorporating a PV system. The transformer increases the electrical distance between the grid and the charging station.

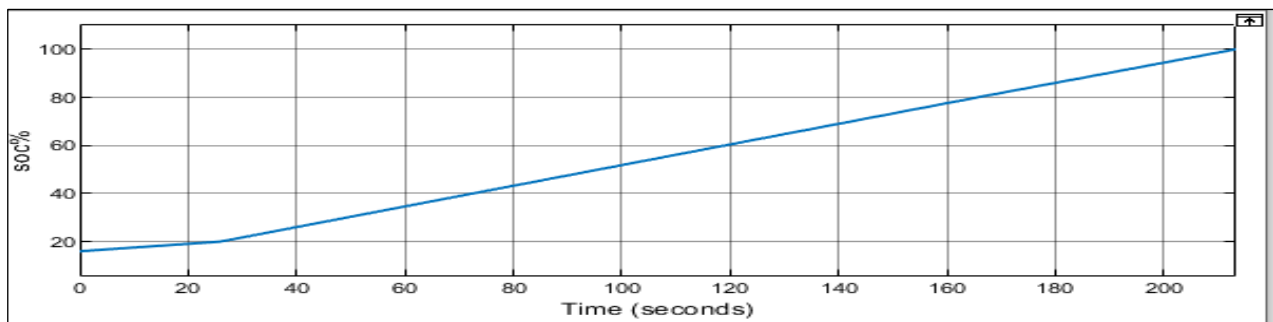


Figure.7: (a). Battery SOC.

Source: Authors, (2026).

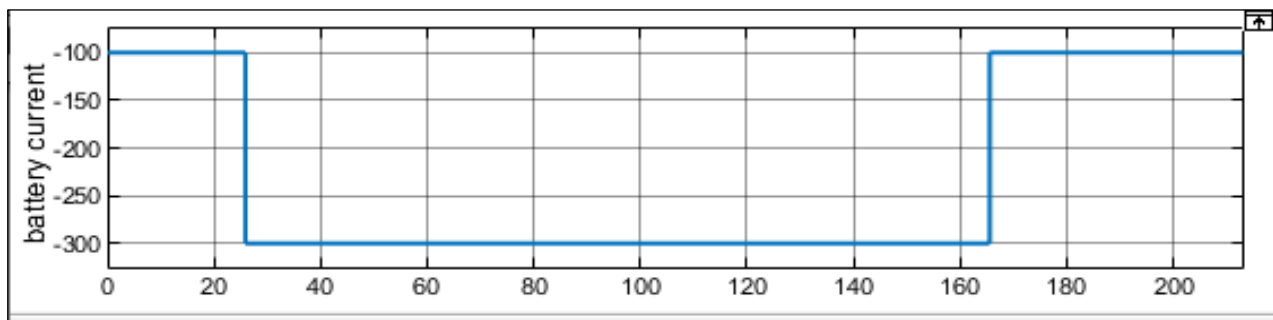


Figure. 7: (b). Battery current.

Source: Authors, (2026).

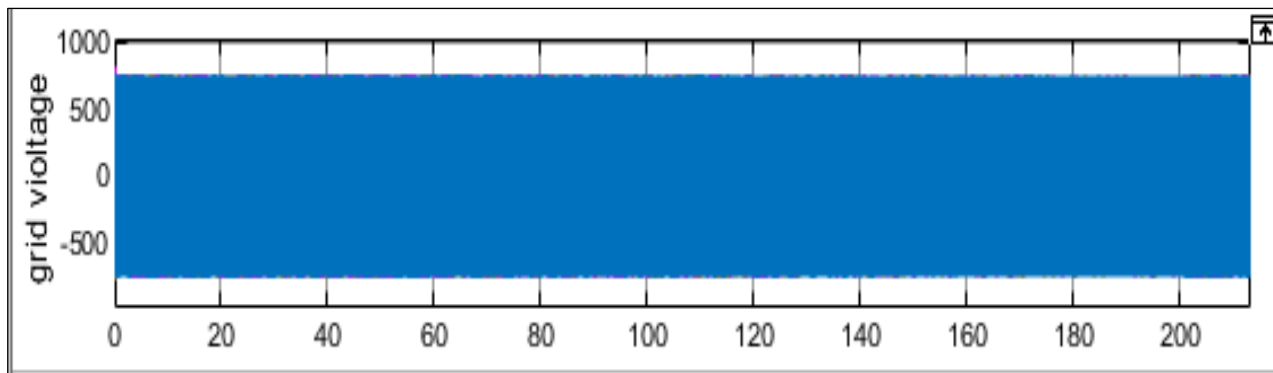


Figure. 7: (c). Grid voltage.

Source: Authors, (2026).

Fig. 7(a). The SOC increases gently from a low initial SOC to a high one of the battery efficiently and controllably. Together, the plots illustrate that solar energy is effectively harvested and employed for battery charging operations with steady system vibrations. Fig. 7(b): Battery current is represented with marked steps according to the stages of the charging process. When the battery is charged, the current is first kept small and is increased according to the fast-charging cycle towards the end of the cycle as the battery is trickle-charged to prolong battery life. Fig. 7(c): Grid voltage is regular with even amplitude without any drops or peaks even as the EV is being charged through the conversion system as the system does not affect the grid's voltage level during EV charging processes.

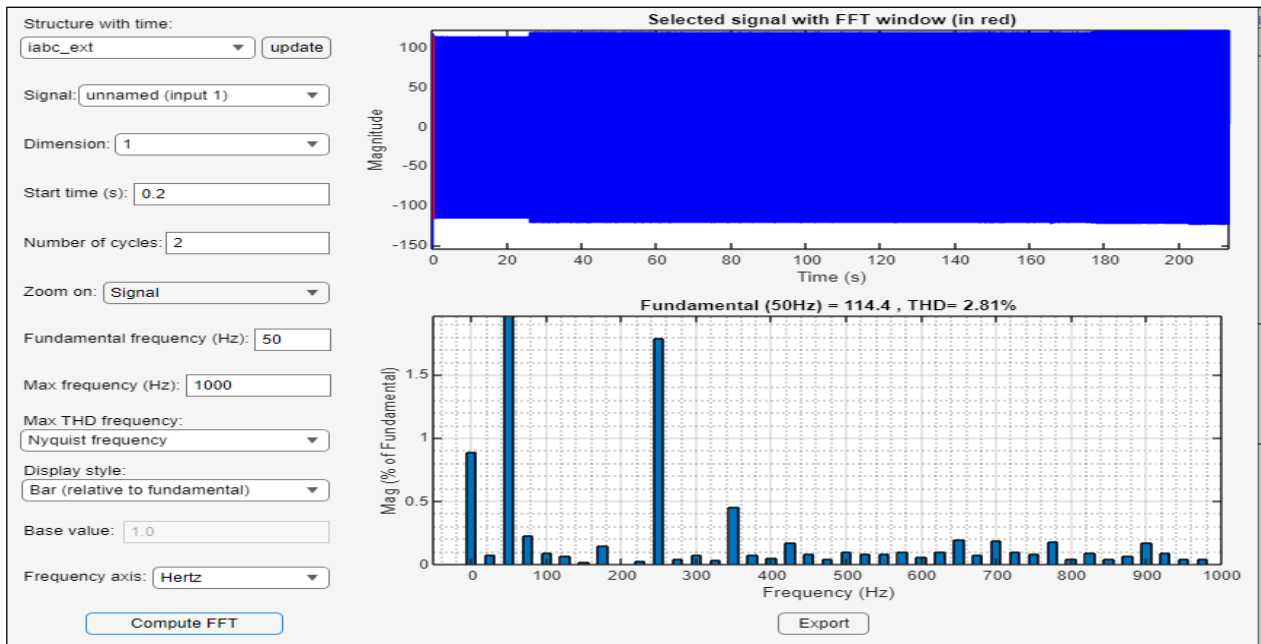


Figure. 7: (d). THD values of Grid current.
 Source: Authors, (2026).

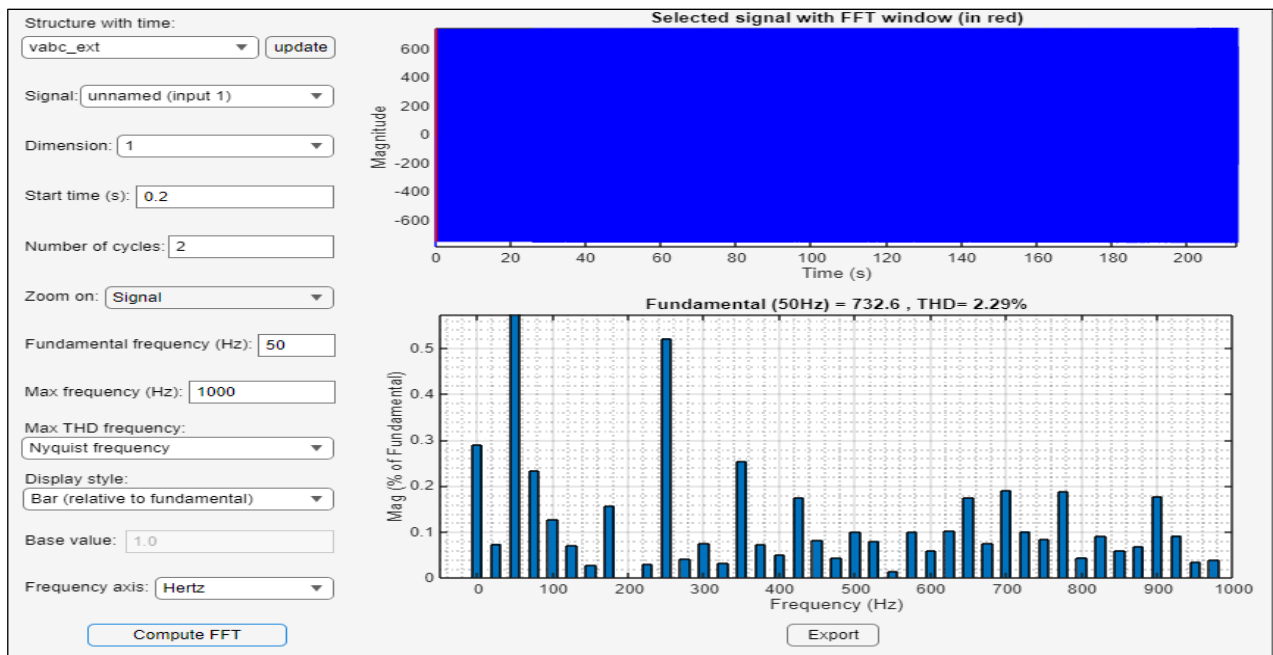


Fig. 7: (e). THD values of Grid voltage.
 Source: Authors, (2026).

Fig. 7(d): The dominant 50 Hz fundamental component is observed in FFT analysis of grid current, thus indicating good synchronization with the grid. The THD 2.81% is within the limits according to IEEE; therefore, the power quality is good. Fig. 7(e): The system is working at 50 Hz fundamental frequency and nominal voltage magnitude. The THD at 2.29% is in the low distortion levels and shows other specifications a Hi-Fi equipment should have. Harmonics are included but with small amplitudes relative to the fundamental. The voltage quality is good and it satisfies the standard power quality conditions.

Mode 3: Vehicle to Grid/ (V2G) operation

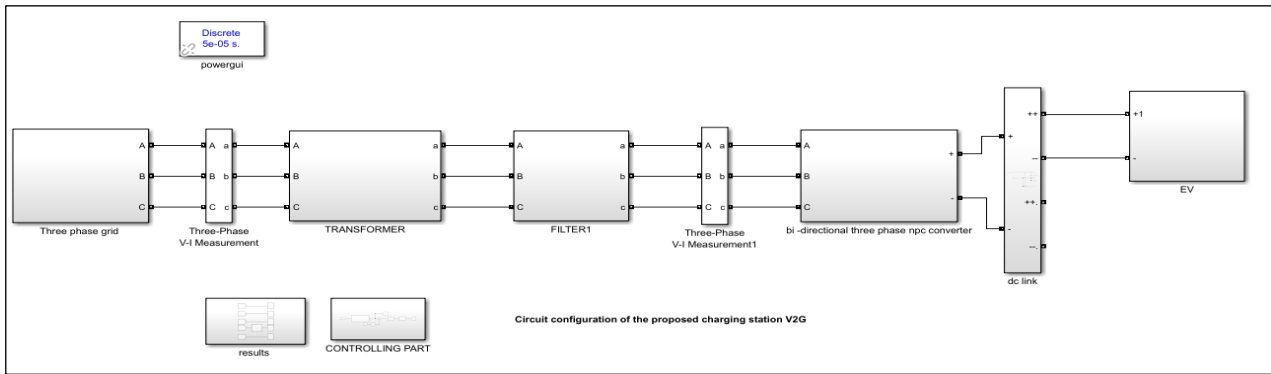


Figure. 8: Simulation configuration of the proposed charging station WITH V2G.
Source: Authors, (2026).

The circuit arrangement of the proposed Vehicle-to-Grid (V2G) charging station is shown in the figure below. A transformer is used for both voltage transformation and electrical isolation purposes. Additionally, a filter for both harmonic reduction and improvement of the waveform quality has been used. The three-phase bidirectional AC-DC converter allows both G2V and V2G operations between the grid and the EV. The converter is connected to the battery of the EV using a DC-link. Sensors for the voltage, current, and control unit are also used.

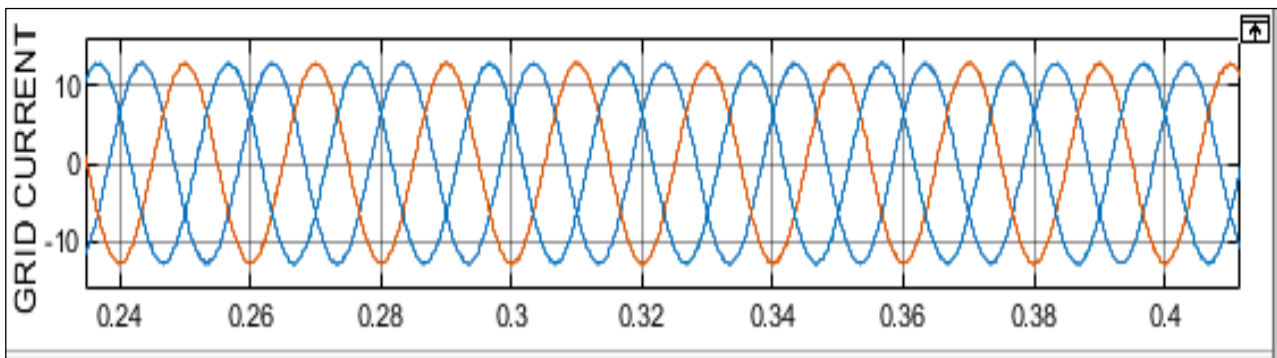


Figure 8: (a). After the EV has been discharged, the grid-side current values are observed to assess the effect of the discharge.
Source: Authors, (2026).

Fig. 8(a): The grid currents are also sinusoidal and well regulated, remaining almost in phase with the grid voltages, hence confirming near-unity power factor operation, low distortion, and effective power exchange between the system and the grid.

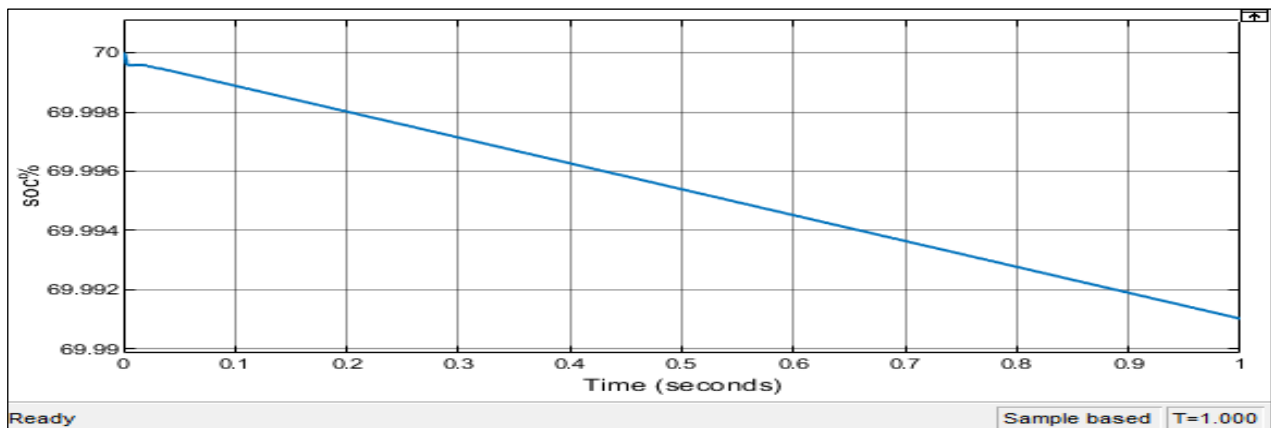


Figure: 8(b). Battery SOC.
Source: Authors, (2026).

The EV battery discharges in order to send energy into the grid, and this can be seen from the decline of its SOC see Fig. 8(b). Discharge operation is smartly managed by adapting the discharge current on-the-fly using real-time SOC level, grid load conditions and battery health parameters through a fuzzy logic controller. This allows an efficient transfer of the energy while preserving battery life and grid stability.

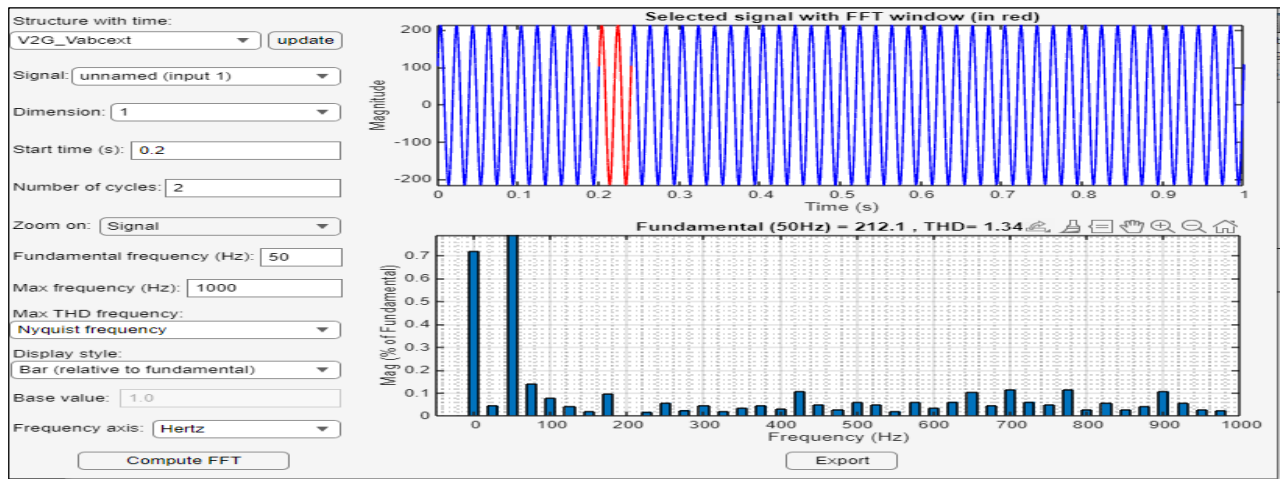


Figure. 8: (c). Vehicle to grid of the voltage THD values.

Source: Authors, (2026).

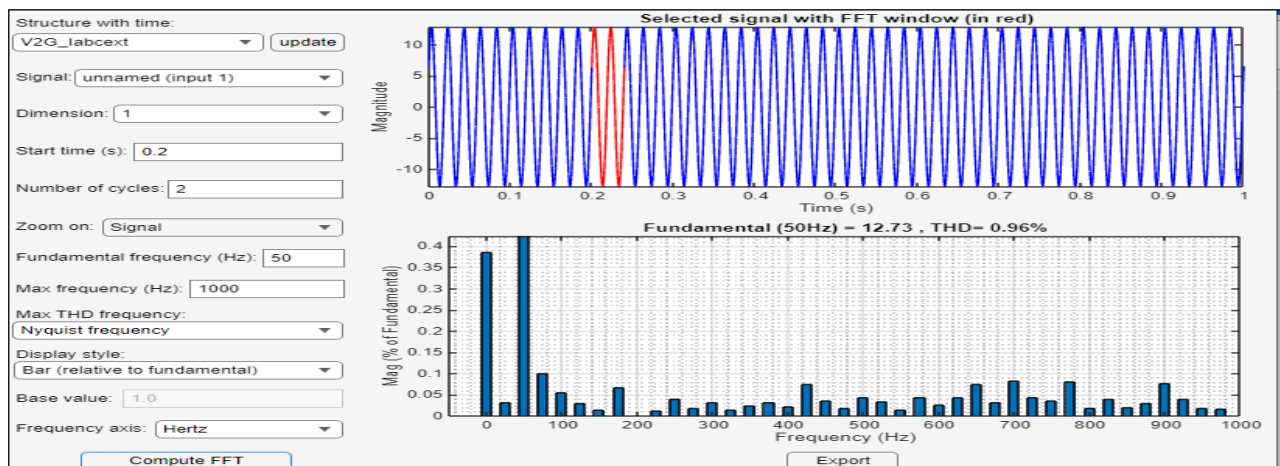


Figure.8: (d). Vehicle to grid of the current THD values.

Source: Authors, (2026).

The FFT results for system voltage and current are presented through harmonic bar graphs. Fig.8(c): Although it has a lower THD of approximately 1.34%, it is dominantly composed of a 50 Hz fundamental signal, which indicates an undistorted voltage waveform. Fig.8(d): Similar to the voltage waveform, it dominantly contains a 50 Hz fundamental signal with an extremely lower THD of about 0.96%, which ensures a nearly sinusoidal current waveform.

Table 1: Existing model.

PI controller	Vabc	Iabc
G2V	5.88	7.34
G+PV2V	5.28	5.67
V2G	6.12	11.16

The PI controller provides the highest THD values for both Vabc and Iabc in all modes of operation. Voltage THD is about 5.3–5.9% which is close to the permissible limit, while current THD fluctuates considerably up to 7.34% during G2V mode operation. This means weaker harmonic attenuation, and worse current quality especially in charging.

Table 2: Proposed Model.

Fuzzy Logic Controller	Vabc	Iabc
G2V	2.44	3.37
G+PV2V	1.69	3.88
V2G	1.34	0.96

Source: Authors, (2026).

On the other hand, for all modes of operation the FLC gives significantly lower THD percentages. Voltage THD is suppressed to the level of 1.34–2.44%, and current THD decreases towards 0.96–3.88% implying better harmonic reduction sequence. The enhancement is particularly significant in PV+G2V operating mode, where current THD reduce are below 2%. Overall, the key difference is that the FLC provides much better power quality, smoother current waveforms, and stronger harmonic reduction than the PI controller. This clearly shows the advantage of the FLC over the PI controller for EV charging.

V. CONCLUSION

In this work, a DC microgrid-integrated fast charge station for an EV based on an FLC is proposed. The FLC was used to control the DC link voltage, grid current, and battery charging operation according to various operating conditions. It was demonstrated that due to its control action depending on system reaction, the FLC provided soft and stable DR operation even during dynamic charging. Simulation results show that the introduced FLC-based model enjoys a high quality of voltage and current harmonic components compared with the conventional PI-controlled counterparts. Enhancement of power quality was observed in G2V, PV+G2V, V2G modes, with THDs within acceptable norms. The controller even allowed slow, safe charging from a very low SOC to full charge. In addition, the proposed charging station enables an electric vehicle to be safely charged in such a way that is slow enough to charge from a low state of charge without disturbing system stability. The programmability of the FLC implemented the adaptation capability to different operating conditions in absence of a need for an exact mathematical model. In summary, the study reveals that FLC-based control is a sturdy and efficient answer to DC microgrid fast charging stations, and is promising for future EV fast chargers with renewable power penetration and two-way energy flow. In conclusion, the reliability, efficiency and power quality of DC microgrid based EV fast charging stations can be proved enhanced by using Fuzzy Logic Controller.

VI. AUTHOR'S CONTRIBUTION

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