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Performance Assessment of Vehicle-to-Grid Enabled Microgrids using DC Fast Charging Architecture and PI-based Control Strategy

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Abstract - The rapid growth of electric vehicles (EVs) and renewable energy resources has created significant opportunities for advanced energy management in modern power systems. Vehicle-to-Grid (V2G) technology enables electric vehicles to operate as distributed energy storage resources capable of exchanging power with the utility grid. This paper presents a DC fast charging-based Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) architecture integrated within a renewable-energy-based microgrid. The proposed system consists of four EV batteries connected to a 1500 V DC bus through bidirectional off-board chargers. A 50 kW photovoltaic array and a 100 kW wind turbine are integrated into the microgrid to support a 150 kW AC load. PI-controller-based charging and inverter control strategies are implemented to regulate bidirectional power flow and maintain DC bus voltage stability. MATLAB/Simulink simulations are performed to evaluate system performance under V2G and G2V operating modes. Results demonstrate successful active power regulation, stable DC bus voltage maintenance at 1500 V, smooth battery charge-discharge transitions, and excellent power quality. The total harmonic distortion (THD) of the grid current is limited to 0.02%, which is significantly lower than the IEEE 1547 limit of 5%. The proposed architecture effectively enhances renewable energy utilization, improves grid stability, and demonstrates the feasibility of using EV batteries as distributed energy storage resources in future smart microgrids.

Keywords – Electric Vehicle, DC fast charging, Grid-tie-inverter, Vehicle-to-grid, Off-Board Charger, Microgrid

I. INTRODUCTION

Energy storage systems are important components of a microgrid as they enable the integration of intermittent renewable energy sources. Electric vehicle (EV) batteries can be utilized as effective storage devices in microgrids when they are plugged-in for charging. Most personal transportation vehicles sit parked for about 22 hours each day, during which time they represent an idle asset. EVs could potentially help in microgrid energy management by storing energy when there is surplus (Grid-To-Vehicle, G2V) and feeding this energy back to the grid when there is demand for it (Vehicle-To-Grid). V2G applied to the general power grid faces some challenges such as; it is complicated to control, needs large amount of EVs and is hard to realize in short term [1]. In this scenario, it is easy to implement V2G system in a microgrid. The Society of Automotive Engineers classifies electric vehicle (EV) charging into three levels. Level 1 charging involves using a regular household outlet (120V) and the vehicle's onboard charger. This is the slowest charging option, suitable for people who drive less than 60 kilometers a day and have the entire night to recharge their vehicle. Level 2 charging used for public or household stations provides power 20kW at 200V or 240V and up to 80A [2]. Level 3 charging, commonly known as DC fast charging, delivers power up to 90 kW at 200-450V, allowing EVs to be charged in just 20-30 minutes. This type of charging is preferred for implementing Vehicle-to-Grid (V2G) systems in microgrids because it enables rapid power transfer, which is essential when EVs are used as energy storage units. Additionally, the DC bus in these charging systems can facilitate the integration of renewable energy sources into the grid. In most previous studies, the V2G concept has been applied to larger power grids to provide services like peak load reduction, valley filling, frequency regulation, and spinning reserves[2].

The V2G development in a microgrid facility to support power generation from intermittent renewable sources of energy is still at its infancy. Also, level 1 and level 2 ac charging is utilized for V2G technology in most of the works reported [3]. These ac charging systems are limited by the power rating of the on-board charger. An additional issue is that the distribution grid has not been designed for bi-directional energy flow. In this scenario, there is a research need for developing technically viable charging station architectures to facilitate V2G technology in microgrids.This work proposes a dc quick charging station infrastructure with V2G capability in a microgrid facility. The dc bus used to interface EVs is also used for integrating a solar photo-voltaic (PV) array into the microgrid. The proposed architecture allows high power bi-directional charging for EVs through off-board chargers. Effectiveness of the proposed model is evaluated based on MATLAB/Simulink simulations for both V2G and G2V modes of operation.

II. DC FAST CHARGING STATION CONFIGURATION FOR V2G

The configuration for a DC fast charging station to implement Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) infrastructure in a microgrid is illustrated in Figure 1 [4]. Electric vehicle (EV) batteries are linked to a DC bus via external (off-board) chargers. A grid-connected inverter links this DC bus to the utility grid, using an LCL filter and a step-up transformer to manage the connection.

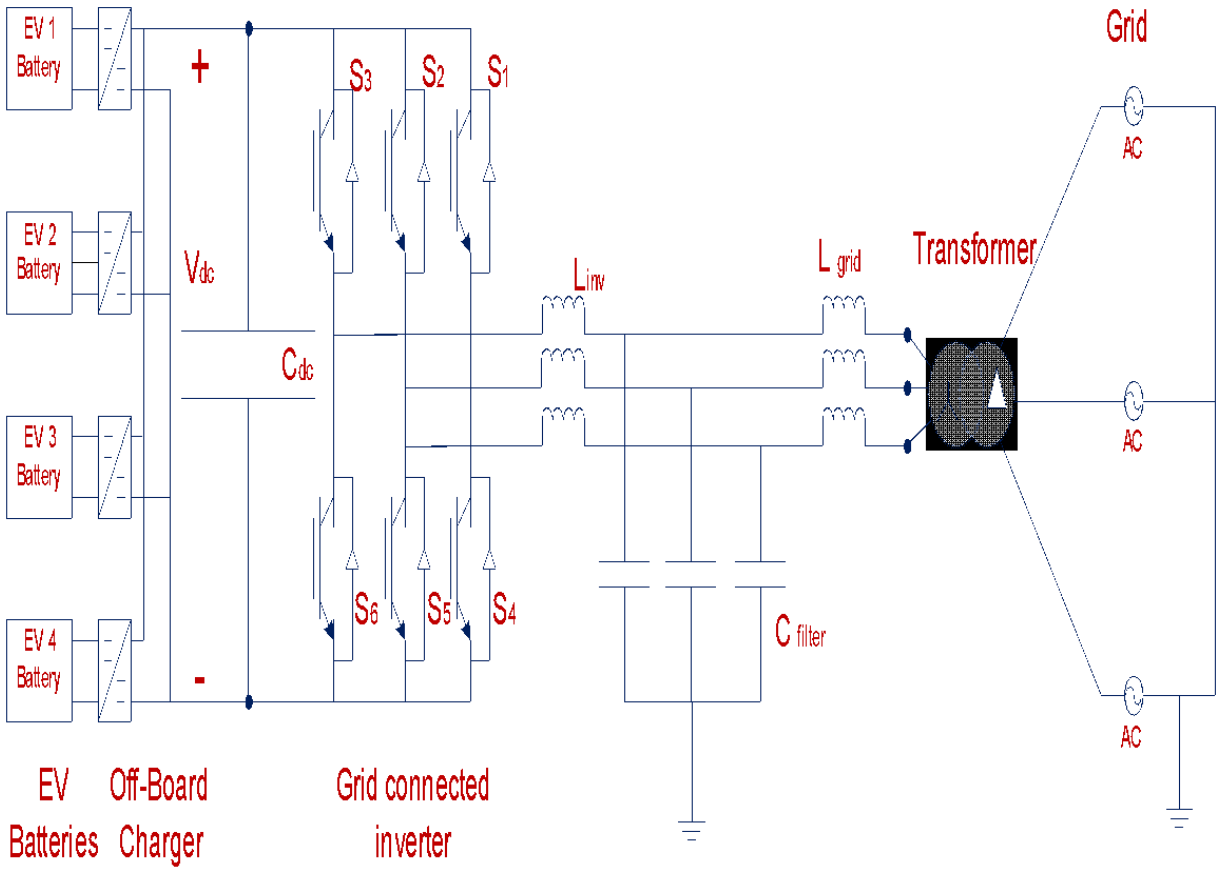


Figure. 1 EV charging station for fast dc charging

A. EV Battery Charger configuration

For DC fast charging, the chargers are located outside the vehicle and housed within an Electric Vehicle Supply Equipment (EVSE). A bidirectional DC-DC converter serves as the core component of an off-board charger with Vehicle-to-Grid (V2G) functionality. This converter acts as the link between the EV battery system and the DC distribution grid. The configuration, as shown in Fig.2 ,includes two IGBT or MOSFET switches, which are controlled by complementary signals, meaning they switch on and off in a coordinated manner.

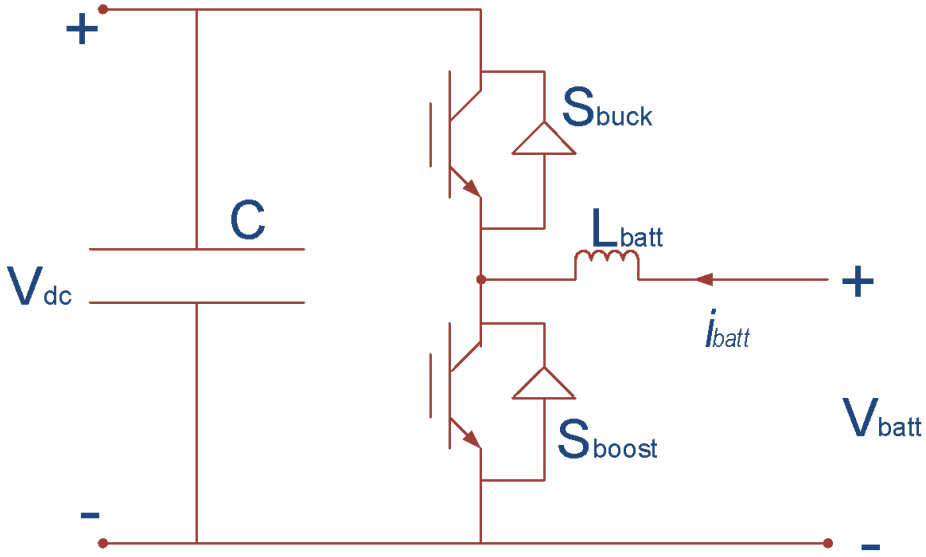


Figure. 2 Battery charger configuration

1. **Buck Mode of Operation (*Charging Mode*):**

When the upper switch (S_{buck}) is operating, the converter acts as a buck converter stepping down the input voltage (Vd) to battery charging voltage ($Vbatt$) . During the on state, current flows through the switch and inductor to the battery. This is the charging operation, where the power flow is from the Grid-to-Vehicle (G2V). When the switch is off, the current takes its return path through the inductor and diode of lower switch and completes the circuit. If D is the duty ratio of the upper switch, the battery voltage is given by

$$V_{batt} = V_{dc}\ \mathrm{D} \qquad (1)$$

2. **Boost Mode of Operation (*Discharging mode*):**

When the lower switch (S_{boost}) is operating, the converter acts as a boost converter stepping up the battery voltage (Vbatt) to the DC B bus voltage (Vdc).When the switch is in on state, current continues to flow through the inductor and completes its circuit through the anti-parallel diode of the upper switch, and the capacitor. The net power flow in this case is from the Vehicle-to-Grid (V2G) and the battery operates in discharge mode. If the capacitor is large enough to provide a constant dc voltage, the output voltage during boost mode of operation is given by

$$V_{dc} = \frac{V_{batt}}{1-D} \qquad (2)$$

B. Grid Connected Inverter and LCL Filter

The grid-connected inverter (GCI) transforms the DC bus voltage into a three-phase AC voltage, and it also enables reverse current flow through the anti-parallel diodes of the switches in each leg as shown in Fig.3. To reduce harmonics and ensure a clean sinusoidal output of both voltage and current, an LCL filter is connected to the inverter's output terminals. The process used to determine the parameters for the LCL filter in this setup follows the method outlined in [4].

III. CONTROL SYSTEM

A. Off-board charger control

A constant current control strategy [5] using PI controllers is implemented for charge/discharge control of the battery charger circuit and is shown in Fig.3. The controller first compares the reference battery current with zero, in order to determine the polarity of the current signal, to decide between charging and discharging modes of operations. Once the mode is selected, the reference current is compared with the measured current and the error is passed through a PI controller to generate the switching pulses for S_{buck}/S_{boost}. S_{boost} will be turned off throughout the charging process and S_{buck} will be turned off throughout the discharging process.

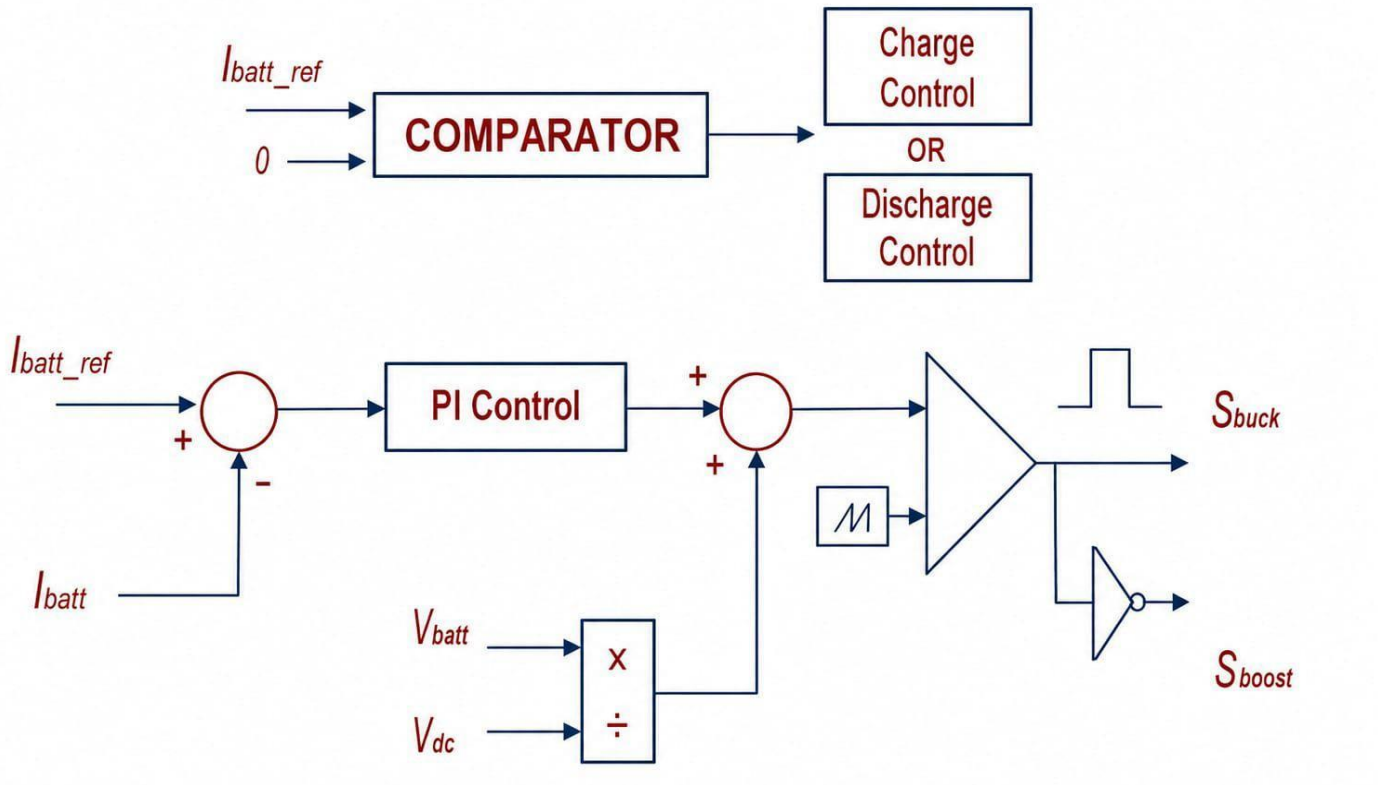


Figure. 3 Constant current control strategy

B. Inverter control

A cascade control in synchronous reference frame is proposed for the inverter controller. The conventional standard vector control using 4 PI controllers in a nested loop is shown in Fig.4 [4]. The control structure consists of two outer voltage control loops and two inner current control loops. The d-axis outer loop controls the dc bus voltage and inner loop controls the active ac current. Similarly, the q-axis outer loop regulates the ac voltage magnitude by adjusting the reactive current, which is controlled by the q-axis inner current loop. Also, dq decoupling terms L and feed-forward voltage signals are added to improve the performance during transients.

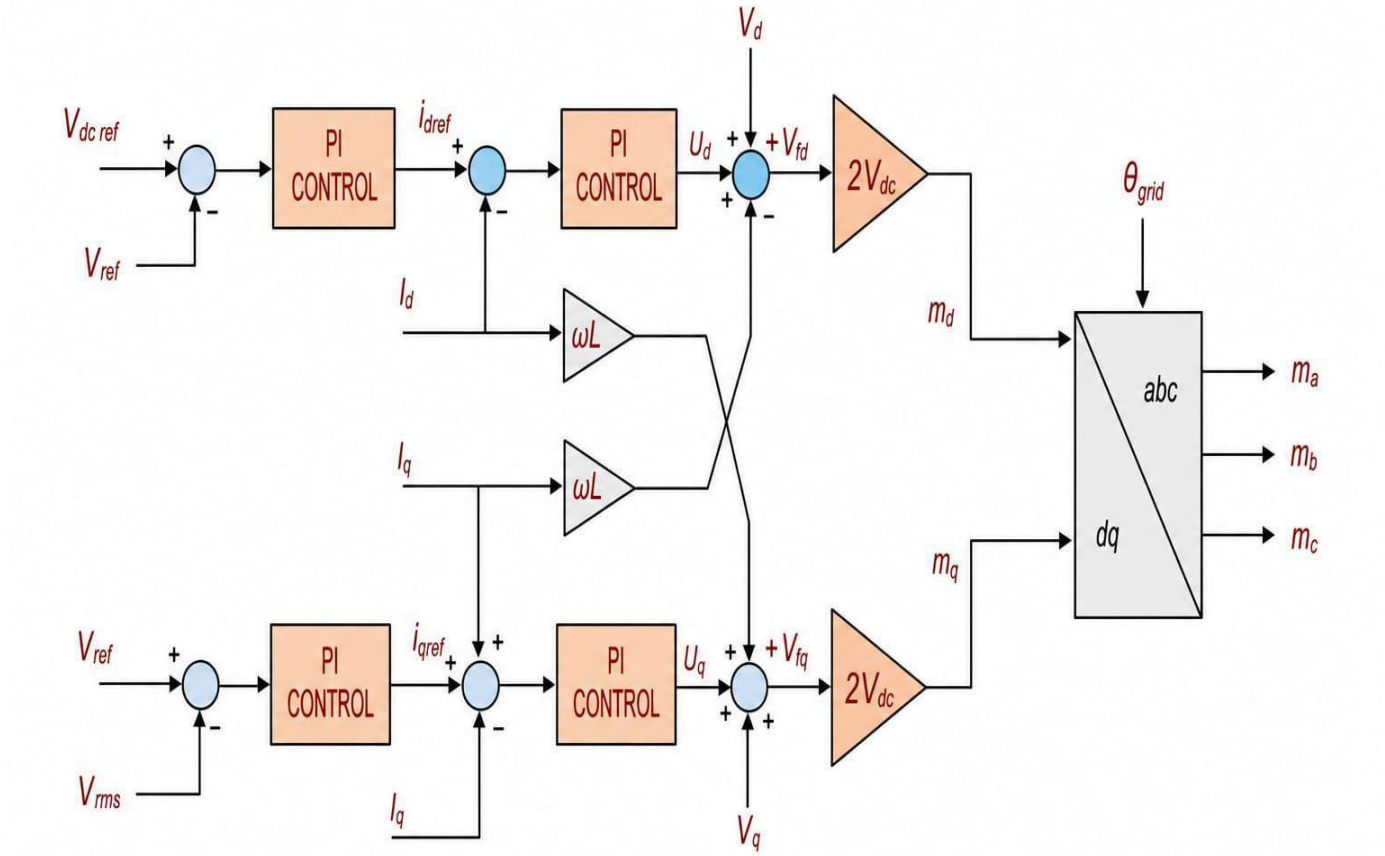


Figure. 4 Block diagram of charging station inverter control system

IV. MICROGRID TEST SYSTEM CONFIGURATION

The configuration of the proposed microgrid test system incorporates multiple distributed generation sources, electric vehicle (EV) battery storage systems, and local loads interconnected through a DC fast-charging infrastructure. The primary renewable energy sources considered in this study are a 50 kW solar photovoltaic (PV) array and a 100 kW wind turbine (WT), which collectively contribute to the power generation requirements of the microgrid. The generated power is utilized to supply a 150 kW AC load connected to the system. Under standard test conditions of 25°C ambient temperature and 1000 W/m² solar irradiance, the PV array is capable of delivering its rated output power of 50 kW.

The proposed microgrid also incorporates four electric vehicle batteries that function as distributed energy storage units. These batteries are connected to a common 1500 V DC bus through bidirectional off-board chargers, thereby forming an EV battery storage system with Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) capabilities. The EV batteries can absorb excess energy during periods of surplus generation and supply stored energy back to the microgrid whenever additional power support is required. This bidirectional power transfer capability enhances the flexibility and reliability of the overall energy management system.

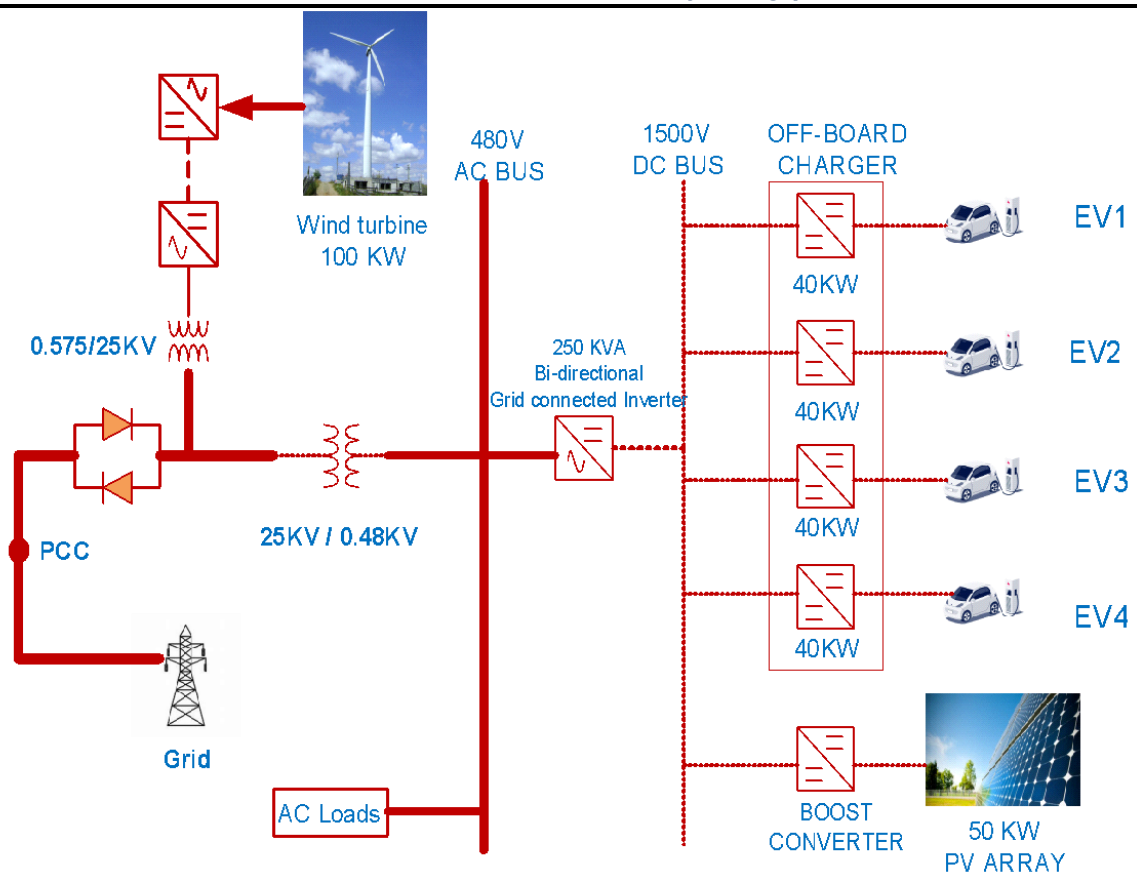


Figure. 5 Proposed microgrid test system configuration

V. SIMULATION RESULTS

The design procedure for the charging station is adapted from [4], and the parameters obtained are listed in the Appendix. The wind turbine operates at its rated speed, delivering a maximum power output of 100 kW. The solar PV array operates under standard test conditions (1000 W/m² irradiance and 25°C temperature), producing a maximum output of 50 kW. A 150 kW resistive load is connected to the 480 V AC bus. The reactive current reference for the grid-connected inverter (GCI) is set to zero, enabling operation at unity power factor. The initial state of charge (SOC) of the EV batteries is set at 50%. After reaching steady-state conditions, the batteries of EV1 and EV2 (as shown in Fig. 1) are used to perform Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) power transfers. The current set-points for the battery charging circuits of EV1 and EV2 are detailed in Table I, with the corresponding results shown in subsequent figures.The battery parameters for EV1 during Vehicle-to-Grid (V2G) operation and for EV2 during Grid-to-Vehicle (G2V) operation are depicted in Figures 8 and 9, respectively.

TABLE 1. Current set-point to EV Batteries

Time range (s)	**0 to 1**	**1 to 4**	**4 to 6**
Current set-point to EV1 Battery(A)	0	+80	0
Current set-point to EV2 Battery(A)	0	0	-40

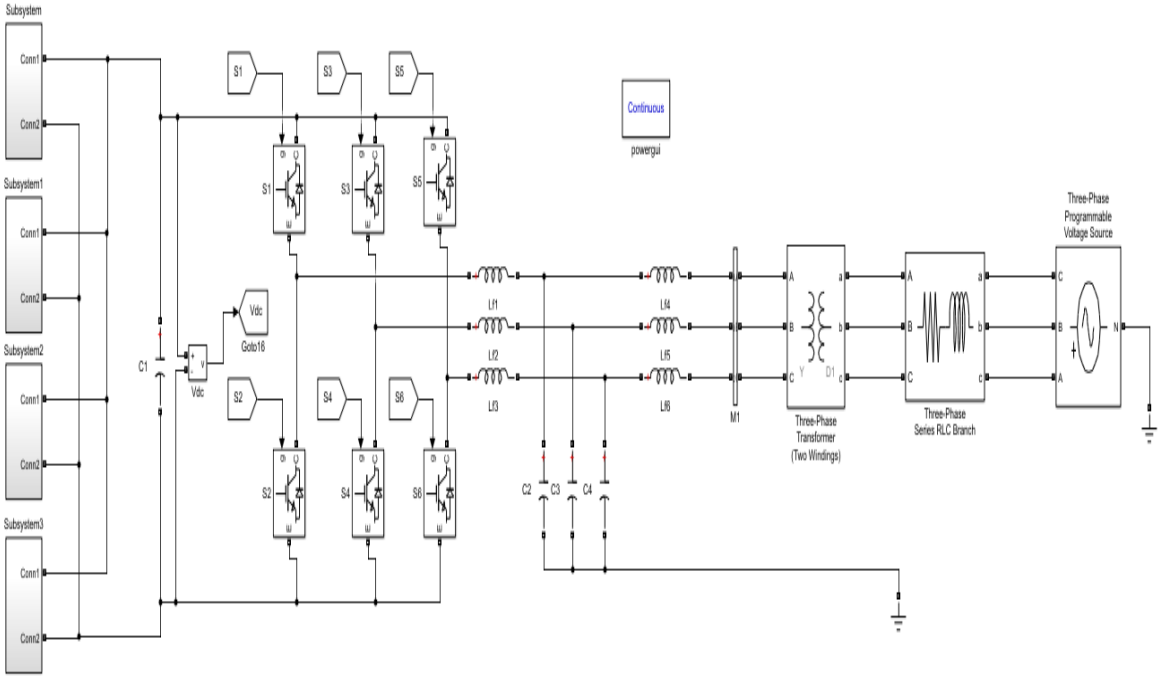


Figure 6. Simulation circuit of EV charging station for dc fast charging

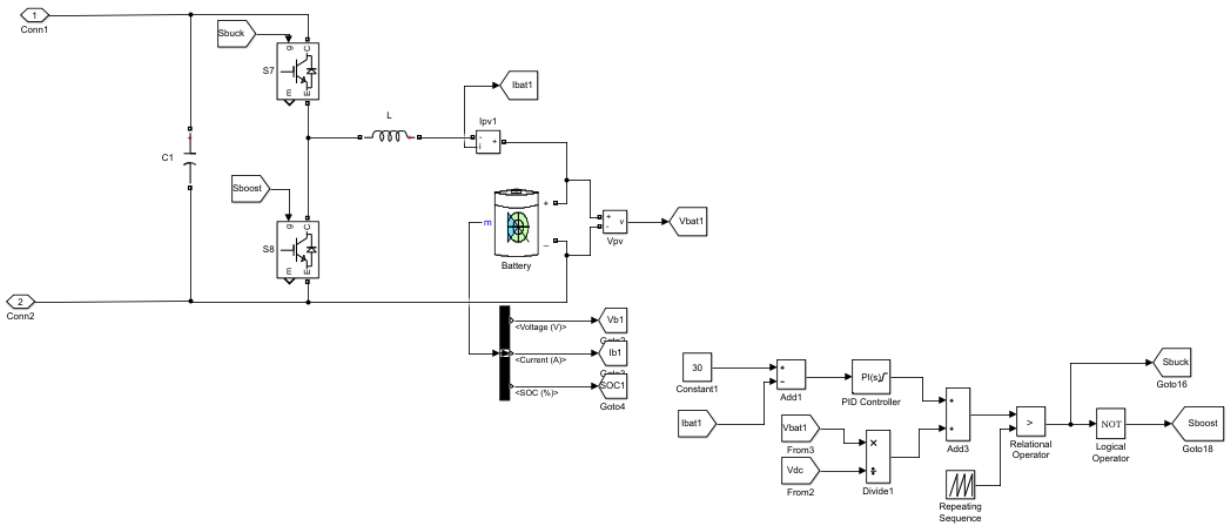


Figure 7. Simulation circuit of EV batteries

Figure 8 shows the performance of EV1 battery during Vehicle-to-Grid (V2G) operation. The battery discharges at approximately 80 A from 1 s to 4 s, causing the battery voltage and SOC to decrease gradually. This confirms successful energy transfer from the EV battery to the microgrid under controlled operating conditions and Figure 9 illustrates the charging behavior of EV2 battery during Grid-to-Vehicle (G2V) operation. After 4 s, the battery receives a charging current of approximately 40 A, resulting in an increase in battery voltage and SOC. The results demonstrate effective battery charging and stable operation of the proposed charging system.

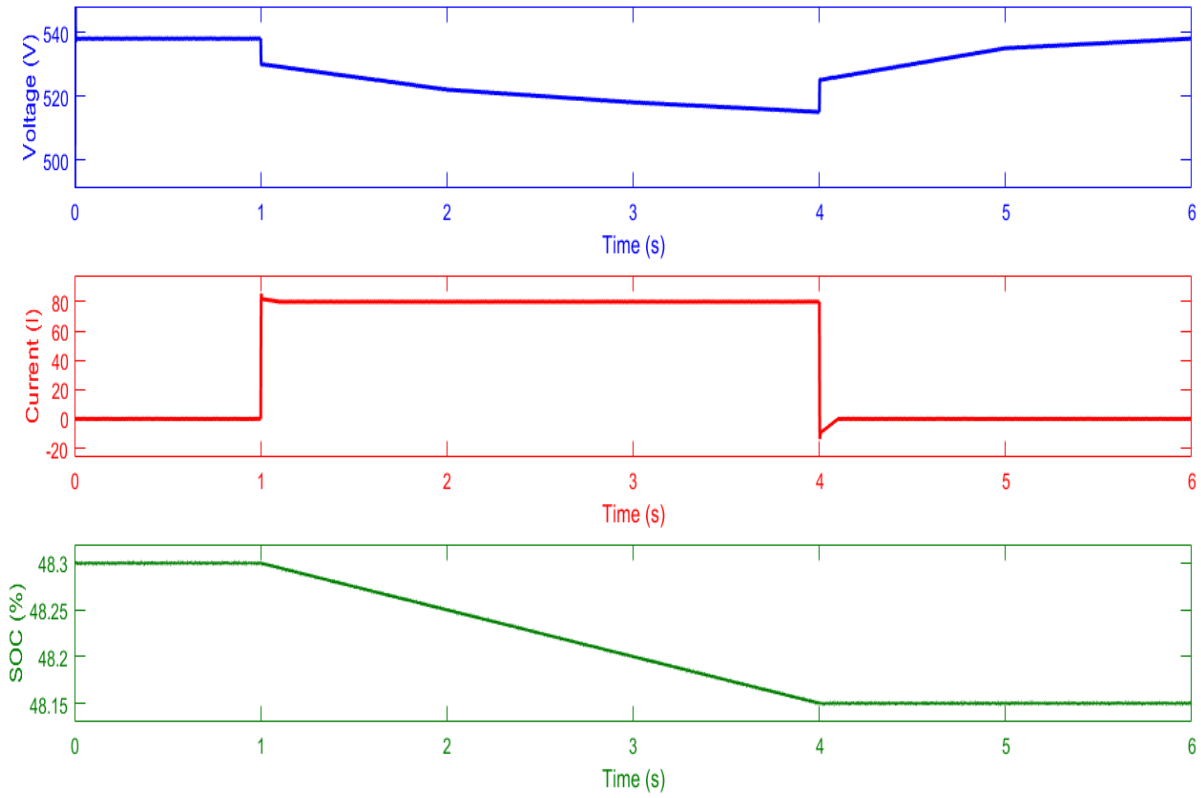


Figure. 8 Voltage current and SOC of EV1 battery during V2G operation

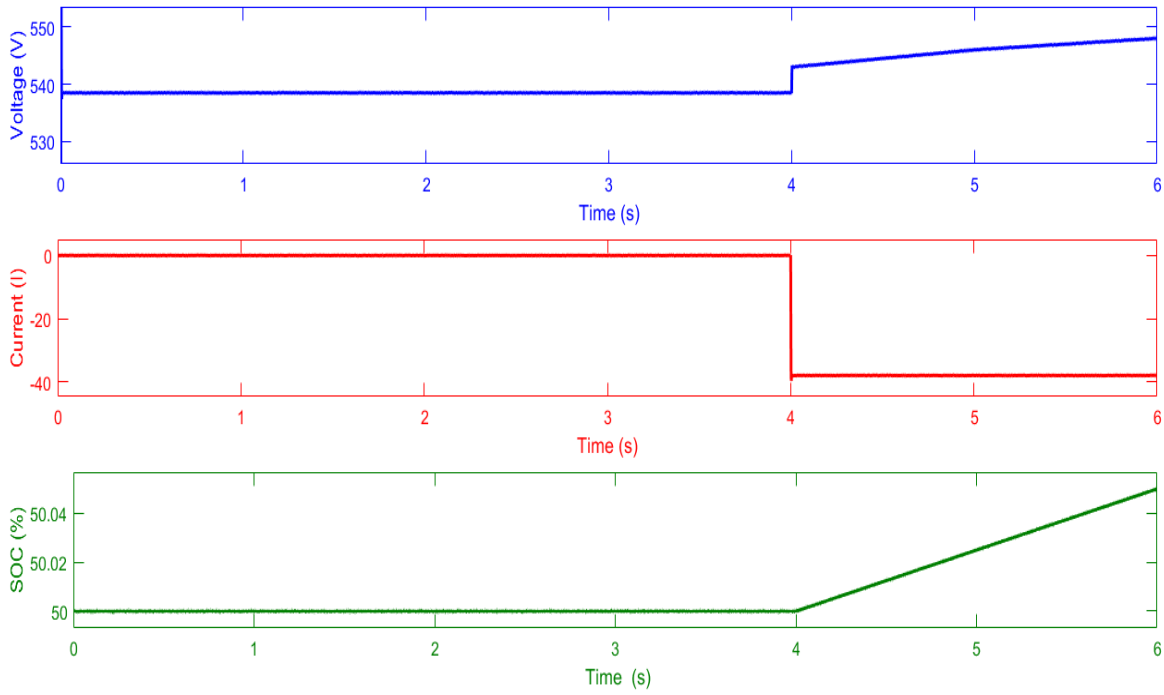


Figure. 9 Voltage current and SOC of EV2 batteries during G2V operation

Fig. 10 illustrates the active power contributions from different components of the system. The grid power adjusts to account for the power transferred by the EVs. From 1 second to 4 seconds, the negative polarity of the grid power indicates that power is being supplied to the grid from the vehicle, demonstrating Vehicle-to-Grid (V2G) operation. At 4 seconds, the polarity switches, indicating that the grid is now supplying power to charge the vehicle battery, showing Grid-to-Vehicle (G2V) operation. Additionally, the net power at the point of common coupling (PCC) remains zero, reflecting optimal power balance within the system.

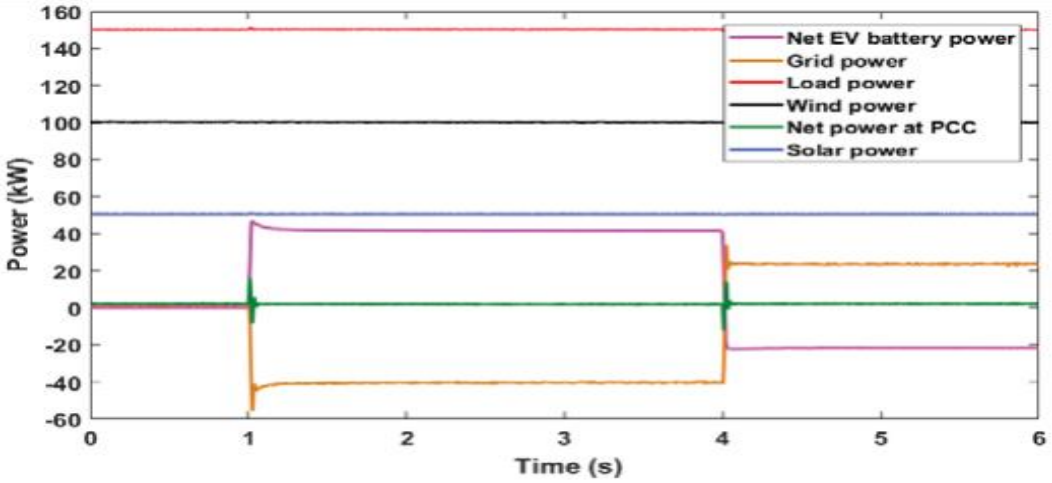


Figure. 10 Active power profile of the various components in the system

The DC bus voltage is maintained at 1500 V through the outer voltage control loop of the inverter controller, as displayed in Figure 11. This regulation is accomplished by the inner current control loop, which adjusts by tracking the variations in the d-axis reference current, as illustrated in Figure 12.

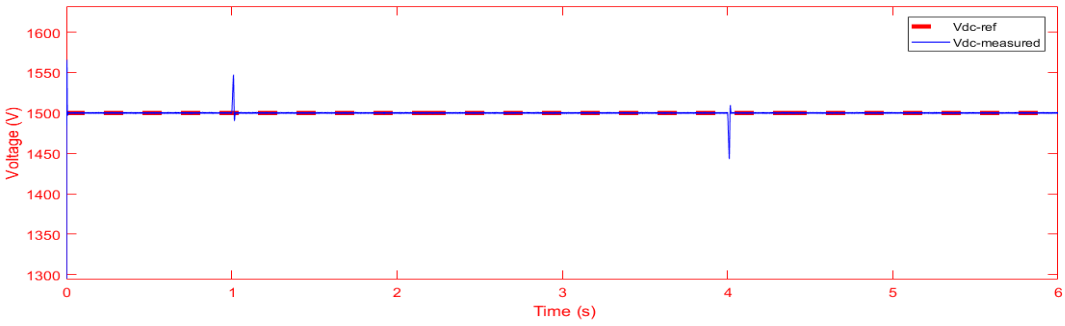


Figure. 11 Variation in DC bus voltage

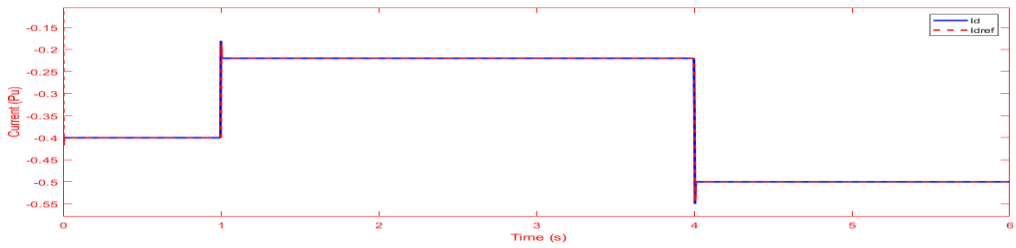


Figure. 12 Reference current tracking by inverter control

Fig.13 displays the grid voltage and current at the point of common coupling (PCC). During Grid-to-Vehicle (G2V) operation, the voltage and current are in phase, while during Vehicle-to-Grid (V2G) operation, they are 180 degrees out of phase, indicating reverse power flow.

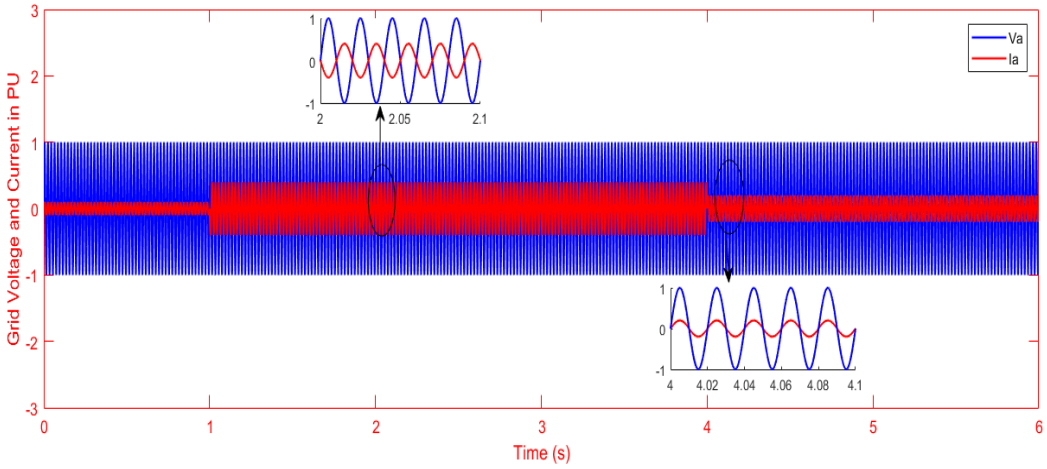


Figure. 13 Grid injected current and voltage during V2G & G2V mode

An analysis of Total Harmonic Distortion (THD) was performed on the current injected into the grid, with the results presented in Figure 14. As per IEEE Standard 1547, power systems operating at 69 kV or below must maintain harmonic current distortion below 5% THD. The THD of the grid-injected current in this system was measured at 0.02%, which was achieved through the careful design of the LCL filter.

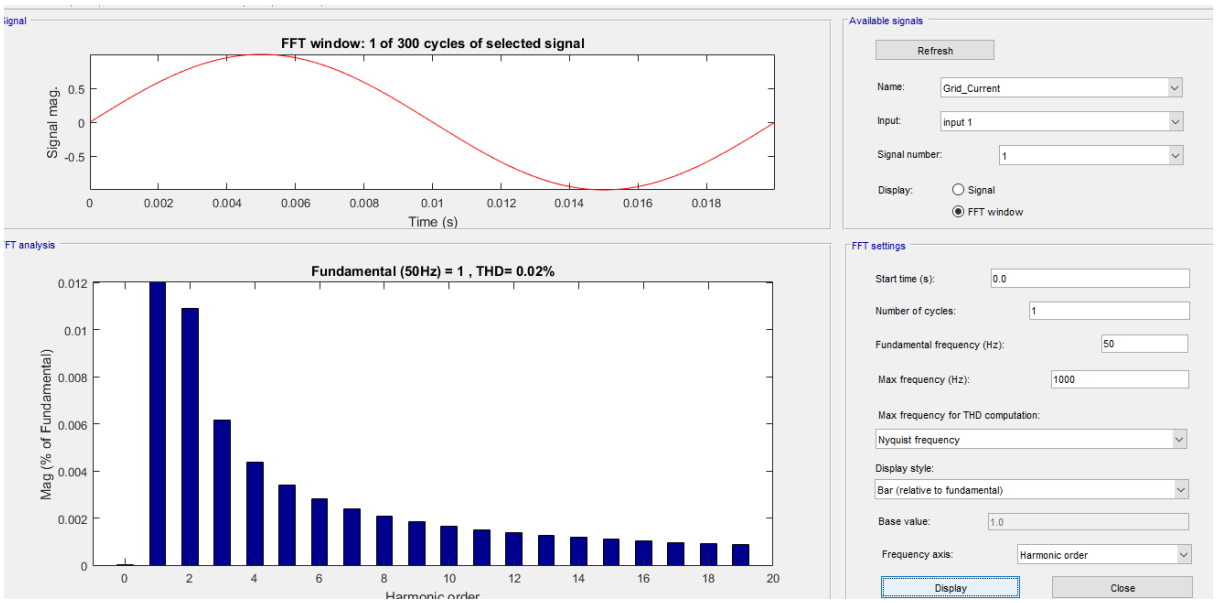


Figure. 14 Grid injected current THD

Table 2. Comparison of Proposed System with Existing Studies

Feature	Existing Studies	Proposed Work
Vehicle-to-Grid Capability	Yes	Yes
Grid-to-Vehicle Capability	Yes	Yes
DC Fast Charging	Limited	Yes
PV Integration	Partial	Yes
Wind Integration	Partial	Yes
PI Controller	Limited	Yes
Microgrid Application	Partial	Yes
THD Analysis	Limited	0.02%
Renewable Energy Integration	Partial	Yes

VI. CONCLUSIONS

This paper presented a Vehicle-to-Grid enabled microgrid employing a DC fast charging architecture and PI-based control strategy. The proposed system integrates electric vehicle batteries, photovoltaic generation, wind energy sources and utility grid infrastructure through a common DC bus. A bidirectional off-board charger was developed to facilitate both Grid-to-Vehicle and Vehicle-to-Grid operations. The proposed control strategy successfully regulates battery charging and discharging currents while maintaining stable DC bus voltage. Simulation studies carried out in MATLAB/Simulink demonstrated effective active power regulation, reliable energy transfer and successful operation under both charging and discharging conditions. The EV batteries effectively functioned as distributed energy storage resources capable of supporting renewable energy integration and microgrid stability. The grid-connected inverter maintained stable DC bus voltage at 1500 V and provided accurate current tracking performance. Harmonic analysis confirmed excellent power quality with a current THD of only 0.02%, which is significantly below IEEE 1547 limits. The results indicate that the proposed architecture can improve renewable energy utilization, reduce peak load demand, enhance grid stability and support the development of future smart-grid infrastructures. Future work may focus on battery degradation analysis, economic feasibility assessment, artificial intelligence-based energy management systems and real-time hardware implementation.

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