Comprehensive Study on Electric Vehicle Charging Infrastructure and Technology

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Abstract:
Electric Vehicles (EVs) are gaining popularity due to their role in reducing air pollution, utilizing renewable energy sources, and offering lower charging costs compared to internal combustion engine (ICE) vehicles. However, EVs can be truly sustainable only when charged from renewable energy sources. With advancements in power converter technology and EV charging infrastructure, bidirectional charging systems have emerged, enabling Vehicle-to-Grid (V2G) operation to support the grid. Charging an EV during the day and supplying power back to the grid when needed allows EV owners to get financial profits. However, the integration of power converters in bidirectional charging can impact grid parameters, leading to power quality issues. To mitigate these effects and enhance grid stability, this paper proposes a feed forward decoupled control method. The proposed control approach effectively reduces harmonics and improves the total behaviour of the system. The model is developed and simulated in MATLAB/Simulink to validate the effectiveness of the suggested method.
Keywords: Electric Vehicle, Vehicle-to-Grid, bidirectional, charging system

I. Introduction

The adoption of Vehicle-to-Grid concept is gaining momentum due to its ability to minimize dependence on fossil fuels, lower emissions, and contribute to the decarbonisation of transportation [1]. Additionally, it plays a key role in modern urban mobility solutions by enabling controlled power exchange between electric vehicle batteries (EVB) and the power grid [2]. In a V2G-enabled system, electric vehicles (EVs) act as distributed energy resources (DERs), temporarily storing and supplying energy to the grid based on demand [3], [4]. This enhances grid stability, reliability, and efficiency while increasing overall power generation capacity [5]. EVs with bidirectional power transfer capability support utility operators by providing reactive power compensation, load balancing, harmonic filtering, peak load shaving, and reserve power management [6]. Additionally, EV owners can benefit from financial incentives by supplying stored energy back to the grid when required [7], [8]. To facilitate seamless bidirectional power transfer, an efficient charging system is necessary to ensure proper EV battery charging and power injection into the grid while lowering power quality disturbances.

The performance of bidirectional EV chargers depends on various factors, including charging and discharging strategies, power conversion efficiency, and system topology [9]. Bidirectional DC-DC converters are particularly advantageous due to their high voltage conversion ratios, scalability, efficiency, and ability to operate in both charging and discharging modes [10], [11], [12]. These converters help improve voltage stability, frequency regulation, and overall power quality of the grid [13]. In addition, smart grid integration and IoT-based energy management systems enable dynamic pricing models, allowing EVs to optimize energy exchange based on time-of-use tariffs [14]. EVs are also envisioned as active energy resources that not only supply energy back to the grid also facilitate charging for other EVs, contributing to the progress of a smart grid ecosystem [15], [16]. Integrating multiple energy sources further enhances the V2G framework [17], [18]. Several studies have reviewed the benefits and policies associated with V2G implementation [19]. Furthermore, system-level EV coordination strategies can significantly reduce load curtailment, improving grid resilience compared to independent EV operations [20].

This paper presents a 3-phase bidirectional EV charging system connected to a 400V, 50Hz grid with support for both Grid-to-Vehicle and Vehicle-to-Grid. The model utilizes a bidirectional DC-DC converter to regulate power flow operating in buck operation for charging and boost operation for discharging. A Proportional-Integral (PI) controller is employed to supervise battery voltage and current, ensuring stable power transfer. The examination evaluates the State of Charge (SOC), electric vehicle battery voltage, and current during charging and discharging, along with the impact of V2G and G2V operations on grid voltage and inverter performance.

The formation of this article is as follows:

Section I support an overview of existing research and highlight the significance of a bidirectional charging system. Section II describes the system model, which has been developed using MATLAB/Simulink. Section III explains the control strategy implemented to regulate bidirectional power flow. Section IV presents the simulation results with detailed discussion of the findings. Finally, in section V summarizes the key findings derived from the study.

II. System design

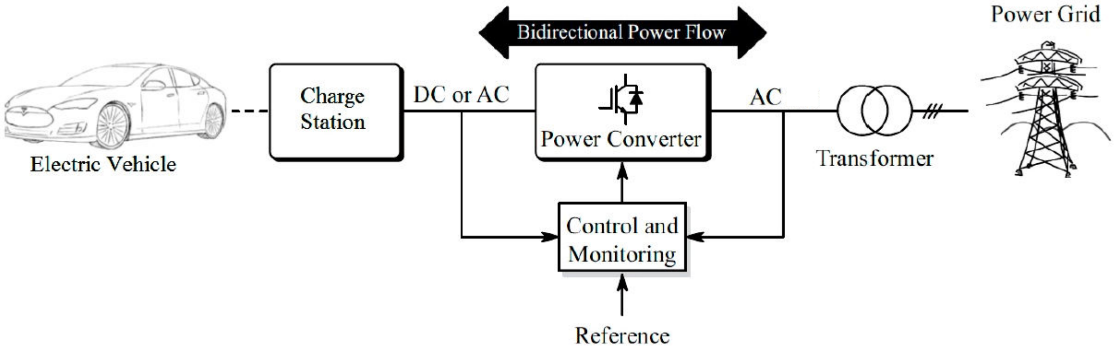

Fig.1 Architecture of the EV charging system

Figure 1 illustrates the offered three-phase bidirectional electric vehicle (EV) charging system, providing an overview of its structure. The system consists of an EV battery and a charging station, which facilitates charging based on either AC or DC configurations. In this model, a DC-based charging configuration is implemented. A 3-phase Voltage Source Converter (VSC) is incorporated to convert DC to AC during the discharging phase, enabling power transfer back to the grid. A feedforward control strategy is applied to monitor and regulate the converter output voltage, ensuring stable operation. Additionally, Phase-Locked Loop (PLL) is employed to maintain synchronization between the grid voltage and frequency. The diagram also includes a bidirectional arrow, representing the charging and discharging process, along with the power flow direction.The proposed model is developed using a battery voltage rating of 240V and a capacity of 1000Ah. A comprehensive list of system parameters is provided in Table I for reference.

III. Control Methodology

A 3-phase voltage source converter (VSC) is controlled using a feed forward decoupled control strategy with d-q axes to improve the system stability and response time is depicted in fig.2. The proposed control method effectively achieves the DC-bus voltage and bidirectional power flow in both the modes of operation.

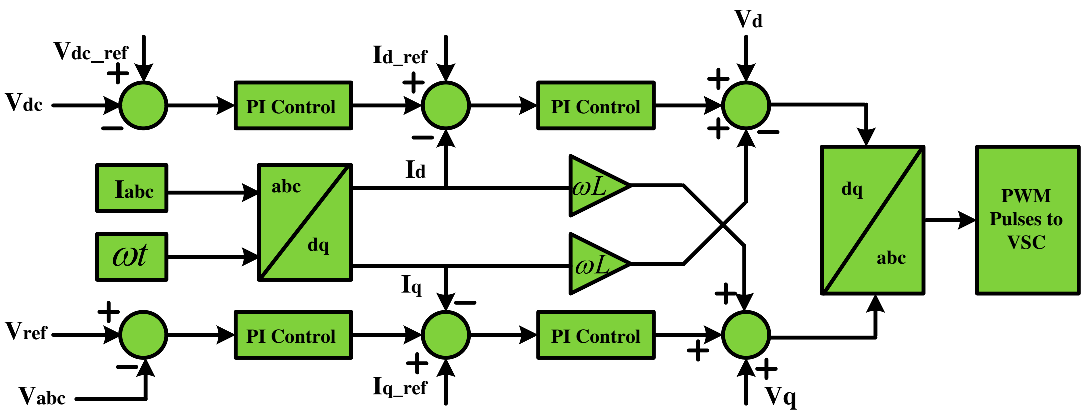

Fig.2 Feedforward decoupled control method for VSC converter

The outer voltage loop controls thevoltageby comparing reference DC-bus voltage (V_{dc_ref}) with the actual dc-link voltage (V_{dc}) and is analysed via PI controller to achieve controlled voltage which is shown in fig.2. The reference DC-bus voltage is as follows:

$$I_{dref} = K_{p1}(V_{dcref} - V_{dc}) + K_{i1}\int (V_{dcref} - V_{dc})dt \text{ ------ } (1)$$

The inner current loop ensures the tracking of reference currents from the d-q axes components in the d-q frame. To control the reactive power generation the the q-axes reference current is given by

$$I_{qref} = K_{p2}(V_{ref} - V_{abc}) + K_{i2}\int (V_{ref} - V_{abc})dt \text{ ------ } (2)$$

Where $V_{ref}$is the grid voltage reference, $V_{abc}$is the actual grid voltage,K_{p2} and $Ki2$ are the gain values. The voltage components in the d-q frame are regulated by the feed forward terms are given by the below equations.

$$V_d = K_{p3}(I_{dref} - I_d) + K_{i3}\int (I_{dref} - I_d)dt + \omega L I_q \text{ ------ } (3)$$

$$V_q = K_{p4}(I_{qref} - I_q) + K_{i4}\int (I_{qref} - I_q)dt - \omega L I_d \text{ ------ } (4)$$

Where I_d, I_q are the d, q axes currents and ωLIq and ωLId are the feed forward decoupling terms. To generate the signals to the VSC, again the d-q frame is converted to abc form using the inverse park transformation. The equation for the d-q voltage components are given as follows:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta - 120^\circ) & -\sin(\theta - 120^\circ) \\ \cos(\theta + 120^\circ) & -\sin(\theta + 120^\circ) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \text{ ------ } (5)$$

Where θ is the phase angle from the Phase-Locked Loop(PLL).

IV. RESULTS AND DISCUSSIONS

The proposed model is designed to operate at a total power of 5 kW and has been developed and simulated using MATLAB/Simulink. The system's performance is analysed under both static and dynamic operating conditions across different modes of operation. Figure 3illustrates the grid voltage (V_g) and current (I_g) waveforms, where the V_g is 400V, and the corresponding grid current is 5A in Per Unit (p.u.) values. The observed results indicate that the $V_g$is 1 p.u., and the $I_g$is 0.5 p.u., with both waveforms being in phase alignment. When the $V_g$and I_g are in the same phase, it signifies that power is flowing from the grid to the electric vehicle, indicating the Grid-to-Vehicle. In this state, the EV battery is charged from the grid while maintaining a unity power factor, ensuring efficient power transfer.Figure 4 presents the $V_g$and I_g waveforms in the

Per Unit (p.u.) system, where both signals are out of phase by 180°. This phase shift indicates that the electric vehicle battery is supplying back energyto grid, which typically occurs over the peak demand hours to support grid stability. In the waveform representation, the $V_g$is depicted in green, while the $I_g$is shown in brown, clearly illustrating the power flow direction from the EV to grid. This mode of operation, known as Vehicle-to-Grid mode, enables efficient energy exchange and enhances grid reliability.

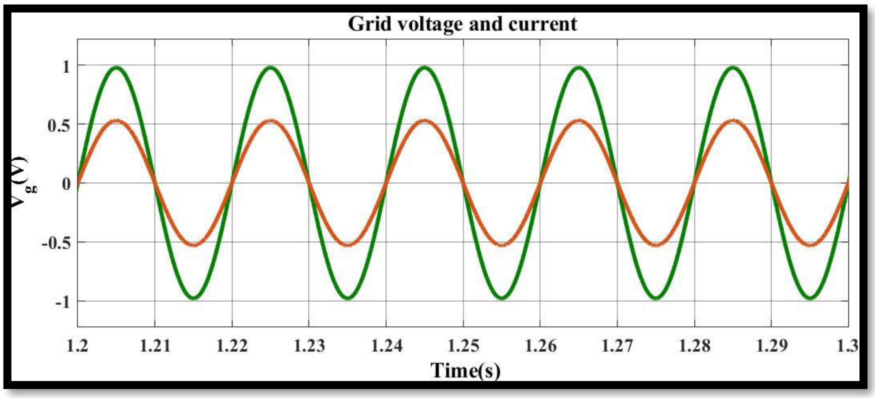

Fig. 3 Grid parameters during G2V

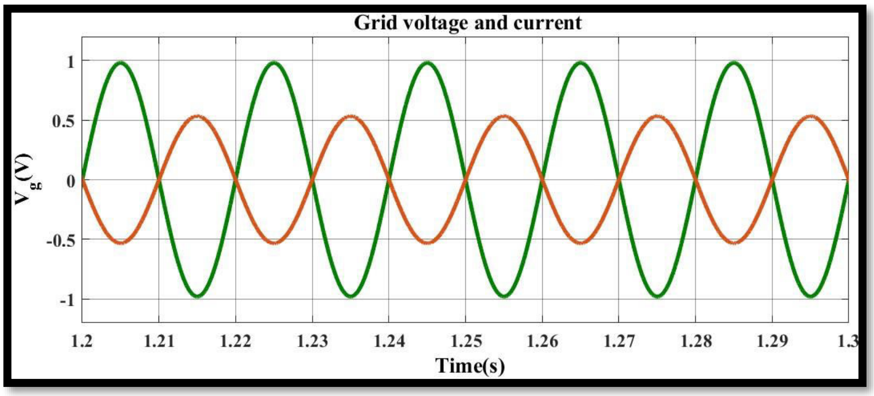

Fig. 4 Grid parameters during V2G

Figure 5 illustrates the real and reactive power characteristics of the proposed charging station. The results indicate that the system consumes 5 kW of real power, ensuring efficient power utilization with minimal losses. In the graphical representation, the active power (P_p) is depicted in green, while the reactive power (Q_p) is shown in yellow, providing a clear distinction between the power components. This analysis highlights the system's ability to effectively manage power flow, contributing to stableand efficient operation

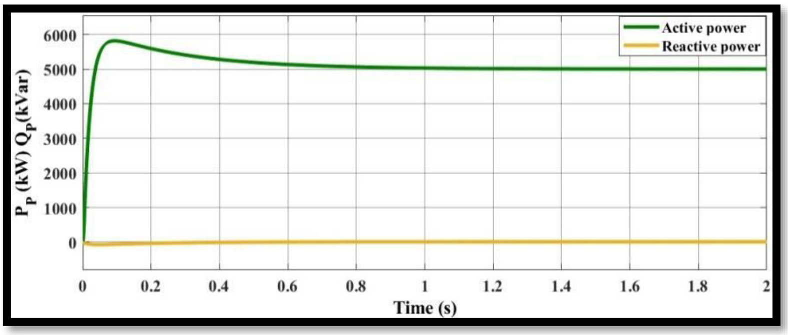

Fig.5 Active and reactive power

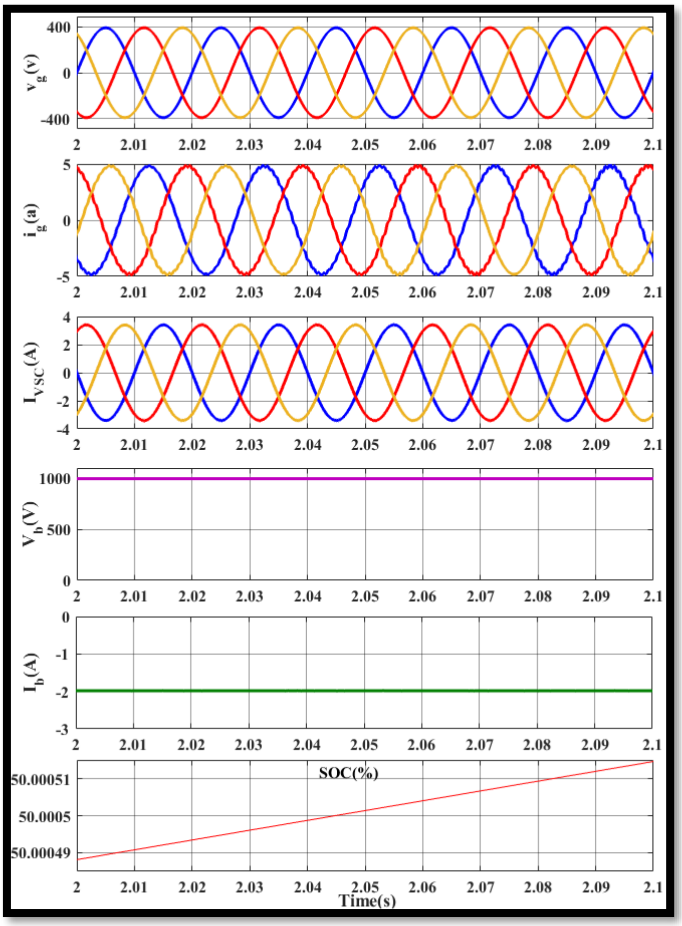

Fig.6System performance in G2V mode

The steady-state performance of the model under Grid-to-Vehicle is analysed and presented in Figure 6. The results indicate that the V_g and Ig are in phase, confirming that the grid is supplying power to charge the battery. Additionally, the converter current and battery parameters are monitored during this mode. The observations show that the battery current (I_b) is -2A, and the battery voltage (V_b) is 1000V, signifying that the EV battery is being charged. Furthermore, the State of Charge of the battery exhibits an increasing trend, indicating continuous energy transfer from the grid-to-vehicle.Figure 7 illustrates the Vehicle-to-Grid (V2G) mode, where the grid voltage (Vg) and grid current (Ig) are out of phase, indicating that the electric vehicle

(EV) is supplying power back to the grid. The power transfer occurs based on the battery's State of Charge (SOC) and grid demand, ensuring efficient energy exchange. The system dynamically adjusts power flow to support the grid, enhancing overall stability and reliability.

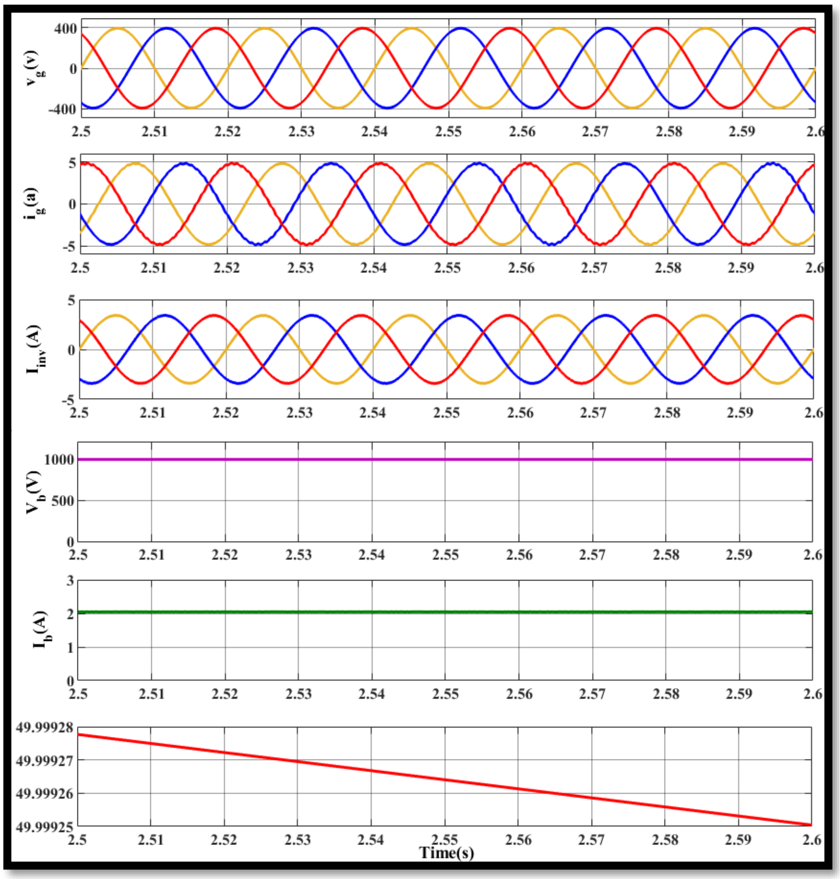

Fig.7Performance of system under V2G

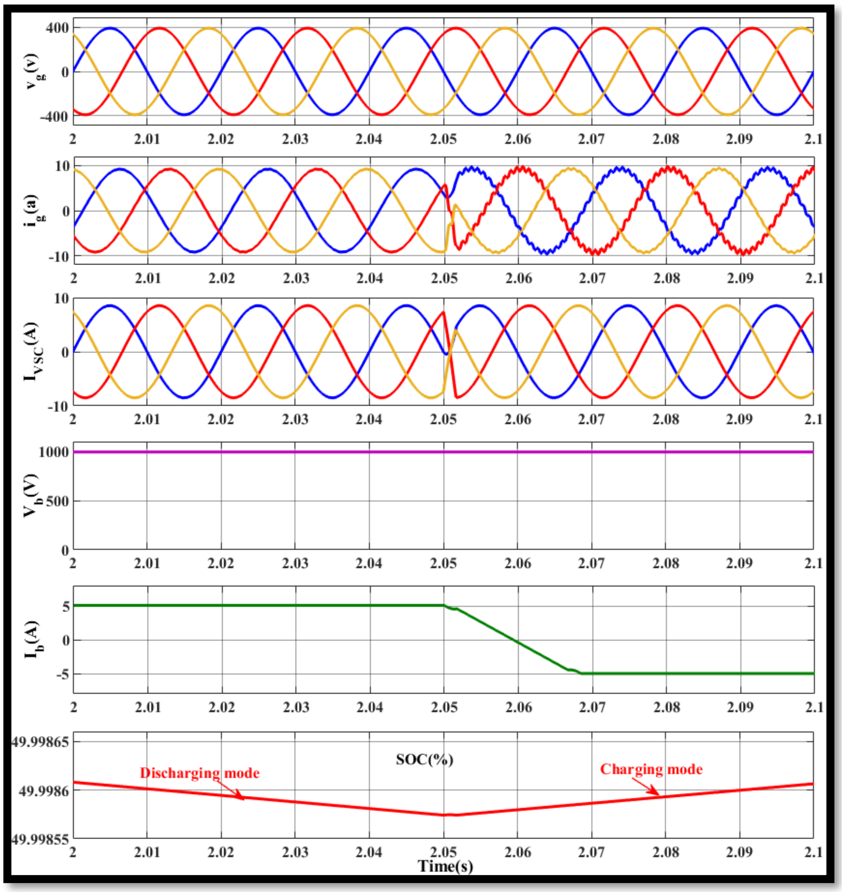

Fig.8 Performance of system under sudden change in V2G to G2V transition

The system is also evaluated under a sudden transition from V2G to G2V mode to analyse its dynamic response which is depicted in figure 8. The observations indicate that between 2 to 2.05 seconds, the system operates over V2G mode, with Vg and Ig in phase, confirming power transfer from the EV battery to the grid.After 2.05 seconds, the system undergoes a rapid shift to G2V mode, where the battery transitions from discharging 5A to charging with 5A. Despite this sudden change, the system maintains stable operation, with only minor distortions in the grid current waveform, which remain within IEEE standards, ensuring power quality and reliable performance.

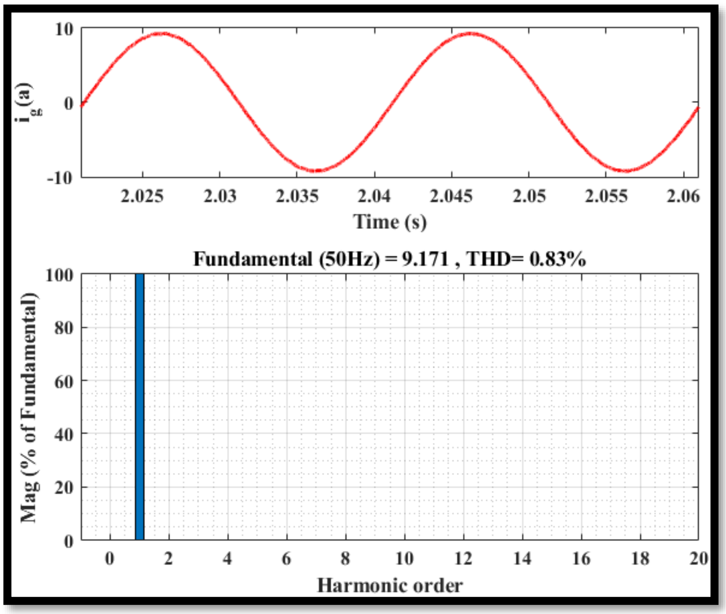

Fig.9 THD analysis of grid current in G2V mode

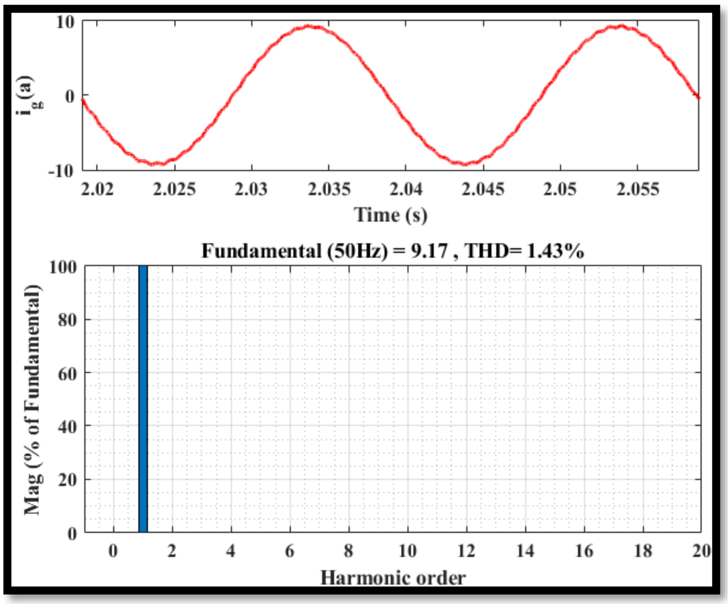

Fig.10 THD of grid current during V2G mode

The power quality improvement of the proposed model is evaluated through harmonic analysis. The Total Harmonic Distortion (THD) of the grid current is analysed in both G2V and V2G modes to assess power quality. The results indicate that in G2V mode, the THD is 0.80%, which is significantly low depicted in fig.9, while in V2G mode the THD is 1.53% due to power being fed back to the grid shown in fig.10. In both operating modes, the system ensures that harmonic levels remain within the IEEE standards applicable in India, maintaining overall grid stability and power quality.

V. Conclusion

This paper presented a bidirectional electric vehicle (EV) charging system designed to efficiently manage power flow and ensure smooth energy transfer. The proposed model was developed and simulated in MATLAB/Simulink to evaluate its performance. A feedforward decoupled control method was implemented to regulate active power independently, contributing to improved system stability. MATLAB results confirm that the recommended controller effectively enhances power quality, achieving THD values of 0.8% in G2V mode and 1.53% in V2Goperation. Additionally, the system demonstrated reliable charging and discharging of the battery during sudden mode transitions, ensuring seamless operation between G2V and V2G modes. These findings show the efficacy of the control strategy in maintaining system performance and improving power quality in bidirectional EV charging applications.

Table 1
System Parameters

Parameters	Value
DC link voltage	V_{dc} = 700V DC
Each Nominal voltage of battery	V_b= 1000 V
Battery rated capacity	C_b= 200 Ah
Bidirectional converter inductance	L = 13.4 mH
Filter values	L_i=0.1H, L_g=0.608mH, Cf=27.6µf
Switching frequency	f_s = 5 kHz

References:

1. A. Abuelrub, *et al.*,"Feasibility Study for Electric Vehicle Usage in a Microgrid Integrated With Renewable Energy," in *IEEE Transactions on Transportation Electrification*, vol. 9, no. 3, pp. 4306-4315, Sept. 2023.
2. S. Kumar, T. Upadhyay and O. H. Gupta, "Power Quality Improvement and Signal Conditioning of PV Array and Grid Interfaced Off-Board Charger for Electric Vehicles with V2G and G2V Capabilities," in *Chinese Journal of Electrical Engineering*, vol. 9, no. 4, pp. 132-143, December 2023.
3. M. Mazumder and S. Debbarma, "EV Charging Stations With a Provision of V2G and Voltage Support in a Distribution Network," in IEEE Systems Journal, vol. 15, no. 1, pp. 662-671, March 2021.

4. A. Aktas, *et al.*,"Medium-Duty Delivery Truck Integrated Bidirectional Wireless Power Transfer System With Grid and Stationary Energy Storage System Connectivity," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 12, no. 5, pp. 5364-5382, Oct. 2024.
5. S. Arandhakar, *et al.*,"Emerging Intelligent Bidirectional Charging Strategy Based on Recurrent Neural Network Accosting EMI and Temperature Effects for Electric Vehicle," in *IEEE Access*, vol. 10, pp. 121741-121761, 2022.
6. M. Lingamaiah, A. Mittal and S. Kumar, "Reliable Power Flow Management and Control in Solar PV Based Electric Vehicle Charging System with G2V and V2G Integration," *2024 IEEE Silchar Subsection Conference (SILCON 2024)*, Agartala, India, 2024, pp. 1-6.
7. M. Yilmaz and P. T. Krein, "Review of the Impact of Vehicle-to-Grid Technologies on Distribution Systems and Utility Interfaces," in *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5673-5689, Dec. 2013.
8. Q. Sun, *et al.*, "Multiport PV-Assisted Electric-Drive-Reconstructed Bidirectional Charger With G2V and V2G/V2L Functions for SRM Drive-Based EV Application," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 3, pp. 3398-3408, June 2023.
9. L. Malle, A. Mittal and S. Kumar, "A Single Phase Grid-Integrated PV System Using Cascaded PI and PR Controller for Power Quality Improvement," *2022 IEEE 10th Power India International Conference (PIICON)*, New Delhi, India, 2022, pp. 1-6.
10. Q. Dang, D. Wu and B. Boulet, "EV Fleet as Virtual Battery Resource for Community Microgrid Energy Storage Planning," in *IEEE Canadian Journal of Electrical and Computer Engineering*, vol. 44, no. 4, pp. 431-442, Fall 2021.
11. I. A. Zenhom, M. F. Shaaban and W. A. Omran, "Grid Interactive Charging of EVs in PV-Powered Parking Lots Considering Uncertainties," in *IEEE Access*, vol. 11, pp. 111292-111301, 2023.
12. Lingamaiah, M., Sirsa, A., Mittal, A., Kumar, S. (2024). Optimal Battery Control and Performance Enhancement with Fuzzy Logic Maximum Power Point Tracking in Solar PV System. ICAER 2023. Green Energy and Technology. Springer, Singapore.
13. S. Taghizadeh, *et al.*,"A Multifunctional Single-Phase EV On-Board Charger With a New V2V Charging Assistance Capability," in *IEEE Access*, vol. 8, pp. 116812-116823, 2020.
14. M. Venkatesan, *et al.*,"Efficient Bidirectional Wireless Power Transfer System Control Using Dual Phase Shift PWM Technique for Electric Vehicle Applications," in *IEEE Access*, vol. 12, pp. 27739-27755, 2024.
15. R. H. AlNahhal, *et al.*, "Optimal Planning of Parking Lots of PEVs Incorporating V2G for Reliability Improvement of Distribution Systems," in *IEEE Access*, vol. 10, pp. 123521-123533.

16. Malle, L., Mittal, A. & Kumar, S. OSG-PLL-based method of a solar PV grid-interfaced transformer-less cascaded H-bridge multilevel inverter for power quality enhancement. ElectrEng (2024).
17. V. Shah and S. Payami, "Integrated Converter With G2V, V2G, and DC/V2V Charging Capabilities for Switched Reluctance Motor Drive-Train Based EV Application," in *IEEE Transactions on Industry Applications*, vol. 59, no. 3, pp. 3837-3850, May-June 2023.
18. E. Gümrükcü, *et al.*,"Decentralized Energy Management Concept for Urban Charging Hubs With Multiple V2G Aggregators," in *IEEE Transactions on Transportation Electrification*, vol. 9, no. 2, pp. 2367-2381, June 2023.
19. A. Bala Naga Lingaiah and N. Reddy Tummuru, "A PV-Utility Integrated Cascaded Interleaved Configuration-Based IPT Charging System for Residential V2G and G2V Applications of EV," in *IEEE Transactions on Transportation Electrification*, vol. 10, no. 3, pp. 6583-6595, Sept. 2024.
20. A. Kazemtarghi, S. Dey and A. Mallik, "Optimal Utilization of Bidirectional EVs for Grid Frequency Support in Power Systems," in *IEEE Transactions on Power Delivery*, vol. 38, no. 2, pp. 998-1010, April 2023.