EMPOWERING HYBRID EVS WITH BIDIRECTIONAL DC -DC CONVERTER FOR SEAMLESS V2G AND G2V INTEGRATION

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ABSTRACT

This paper unveils a groundbreaking wide-range DC-DC converter with significant voltage gain and bidirectional capability, engineered explicitly for Hybrid Electric Vehicle (HEV) chargers. This converter facilitates both Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations. It aims to revolutionize efficiency, voltage range, and bidirectional power flow capabilities, marking a significant leap forward from existing solutions. A meticulous comparative analysis between established systems and the proposed converter highlights its distinct advantages and evolutionary strides within the HEV charging infrastructure landscape. By enhancing the versatility and performance of HEV chargers, this converter promises to address critical challenges in energy management and integration. Its innovative design not only optimizes energy transfer but also supports future advancements in smart grid technology and sustainable transportation. The results of this study underscore the converter's potential to drive forward the next generation of electric vehicle infrastructure, paving the way for more efficient and resilient energy systems.

Keywords: Vehicle-to-Grid (V2G), Hybrid Electric Vehicle (HEV), Grid-to-Vehicle (G2V).

INTRODUCTION

The global push towards energy decarbonisation has led to an increased focus on utilizing variable renewable energy sources and electrifying transport systems. A significant concept gaining momentum in this context is Vehicle-to-Grid (V2G) technology, which leverages the energy storage capacity of electric vehicle (EV) batteries to support renewable energy integration. V2G allows EV batteries to be charged during moments of minimal energy need or high renewable generation (Venkata Govardhan Rao et al., 2022) and then discharge stored energy reintegrated into the grid when needed. This flexibility aids in system frequency support, providing services like fast frequency response and spinning reserve to mitigate sudden load changes. Moreover, V2G offers longer-term flexibility for load smoothing and peak reduction profile optimization (Águila-León et al., 2020; Tripathi & Agarwal, 2021; Vineel Kumar & Deepa, 2022). Central to the implementation of V2G is the bidirectional power converter, which acts as the interface between the EV battery pack and the grid. These converters enable both V2G and Grid-to-Vehicle (G2V) operations with high efficiency, low cost, and safe operation (Al Attar et al., 2022; Heydari-doostabad & O'Donnell, 2021). They play a crucial role in matching the battery voltage when it is low in the EV with the high voltage of the grid. However, existing converter topologies face limitations such as restricted voltage gain, complexity, and high component count. To address these limitations, a new step-down/step-up bidirectional converter is proposed. This converter offers a wide and high voltage gain range, allowing dynamic matching between the battery voltage and the grid voltage (Vineel Kumar & Deepa, 2022). With no voltage gain restrictions and a common ground between input and output terminals, it ensures safe and efficient operation. Furthermore, the proposed converter boasts a simple structure, low power stress on semiconductor devices, and a high utilization factor, making it a promising solution for V2G applications. In the realm of V2G and G2V services, the electrification of transport, coupled with increased renewable generation, plays a pivotal role in decarbonising the energy system (Heydari-doostabad & O'Donnell, 2021). EV charging introduces significant additional electricity demand, emphasizing the importance of power conversion efficiency. However, EV batteries also offer a valuable resource for aiding renewable integration through V2G. Bidirectional converters facilitate this integration by enabling efficient energy transfer linking EVs with the grid, supporting services like frequency regulation and peak shaving (Equbal & Bhargava, 2012). While conventional bidirectional converters have been widely adopted, they often have limitations in voltage gain ratios. Higher voltage gain ratios are desirable for reducing switch voltage and current stresses and minimizing losses (Panchanathan et al., 2023; Rajalakshmi et al., 2021). Additionally, bidirectional buck-boost converters equipped with step-down and step-up voltage gain ratios have become popular for regulating battery and dc-link voltages under diverse source conditions (González-Castaño et al., 2021; Haque et al., 2020; Yadagiri et al., 2024). A hybrid converter, combining switched capacitor and inductor-based converters, addresses the limitations of conventional converters and offers higher and wider voltage gain ratios. This innovation enables efficient energy transfer between the battery and the dc-link, paving the way for enhanced V2G capabilities. As the electric vehicle market growth persists exponentially, the integration of V2G and V2H technologies into smart grids will be instrumental in achieving energy autonomy (Trivedi & Sant, 2022). These technologies not only offer benefits for grid stability and renewable integration but also empower consumers to manage their energy usage more effectively. With advancements in on-board bidirectional chargers, EVs can play a pivotal role in shaping the future of energy management and sustainability (Mavila & Nisha, 2016). Figure 1 shows the Layout of an EV Electrical System.

1. Literature Review

Equbal and Bhargava (2012) review electric vehicle charging stations with G2V and V2G using Dual Active Bridge (DAB) converters. The surge in electric vehicle (EV) use demands advanced charging infrastructure for efficient energy transfer and grid stability. This review paper analyzes Electric Vehicle Charging Stations (EVCS) that use DAB converters, emphasizing their role in fast and bidirectional charging. It covers the evolution of EVCS, the advantages of DAB converters over traditional systems, and improvements in efficiency, control, and renewable energy integration. By examining recent studies, the paper evaluates the performance, reliability, and cost-effectiveness of DAB converters in various scenarios, including Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) interactions. It also explores regulatory frameworks and future developments, highlighting the impact of DAB

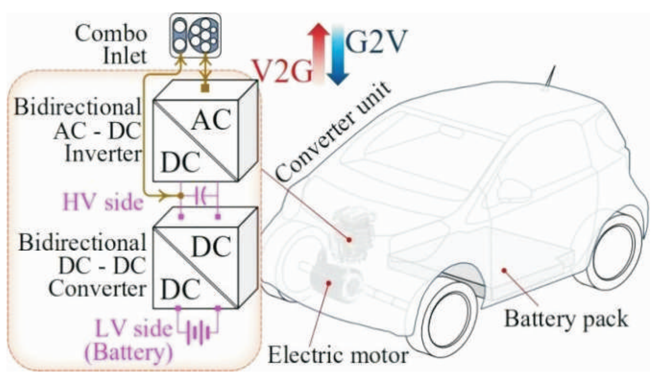

Figure 1. Layout of an EV Electrical System

technology on smart grids and sustainable transportation.

Lukianov et al. (2023) discuss the empowerment of traction grid-powered chargers in their article, Power Systems Research and Operation. Electric Vehicles (EVs) have been rapidly increasing, now comprising about 10% of the global automotive market and benefiting urban environments. To maximize these benefits, it is essential to use renewable energy for charging, strategically place charging stations, and manage charging processes efficiently. However, installing infrastructure for charging stations, particularly in densely populated areas, is costly and challenging. Public slow chargers using existing low-voltage grids provide some relief, but fast chargers can strain the network. Solutions include optimizing charger connections, using smart energy management systems, and leveraging EV batteries for grid support through vehicle-to-grid (V2G) technologies. These approaches can enhance grid stability and power quality, especially in areas with unstable or non-existent centralized power networks.

Yadagiri et al. (2024) describe about the design and development of bidirectional converter based on V2G and G2V operation. The rise of Electric Vehicles (EVs) could strain existing energy grids, highlighting the need for Vehicle-to-Grid (V2G) technology to manage peak demand (Khasim & Dhanamjayulu, 2021). To address this, a new "Bidirectional Converter Based on V2G and G2V Operation" is proposed. This system uses bidirectional converters for energy transfer between vehicles and the grid. The authors analyzed a bidirectional buck-boost converter with an H bridge AC/DC converter and tested its efficiency using a MATLAB/SIMULINK simulation model, which performed well under various conditions.

2. System Implementation

2.1 Existing System

Current bidirectional DC-DC converters used in HEV chargers often rely on traditional topologies with limited voltage gain. These converters struggle with efficient power conversion and encounter difficulties in accommodating the broad range of input and output voltage levels necessary for V2G and G2V operations. Furthermore, bidirectional power flow can lead to power losses that affect overall efficiency.

2.2 Proposed System

The proposed wide-range DC-DC converter with significant voltage gain and bidirectional capability introduces an innovative topology that combines advanced control strategies with optimized power circuit design (Saravanan & Babu, 2017). This converter overcomes the constraints of existing approaches by achieving higher voltage gains, ensuring efficient power conversion over a wide voltage range, and enabling bidirectional power flow with reduced losses. Figure 2 shows the proposed Bidirectional Converter.

2.3 Modelling

The configuration of the DAFB-based bidirectional EV battery charging system is shown in Figure 3. The setup primarily consists of a bidirectional DC/AC converter, which is followed by a high-frequency transformer that supplies a bidirectional AC/DC converter, ultimately charging the EV battery. The bidirectional power flow between the grid and the battery in the DAFB system is managed by adjusting the phase shift (φ) between the gate control signals of the two bridges. Additionally, an outer control loop employs a proportional–integral (PI) controller to maintain the state of charge (SoC%) of the EV battery.

3. Control Algorithm

The control algorithms of the two converters is different in each of the two possible operation modes (G2V, V2G).

3.1 Grid-to-Vehicle (G2V) Operation Mode

In this mode of operation, the full-bridge AC-DC bidirectional converter acts as an active rectifier,

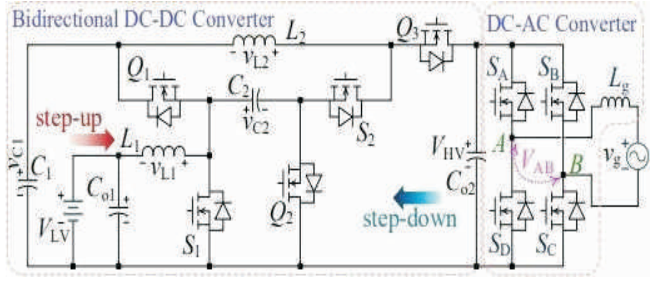

Figure 2. Proposed Bidirectional Converter

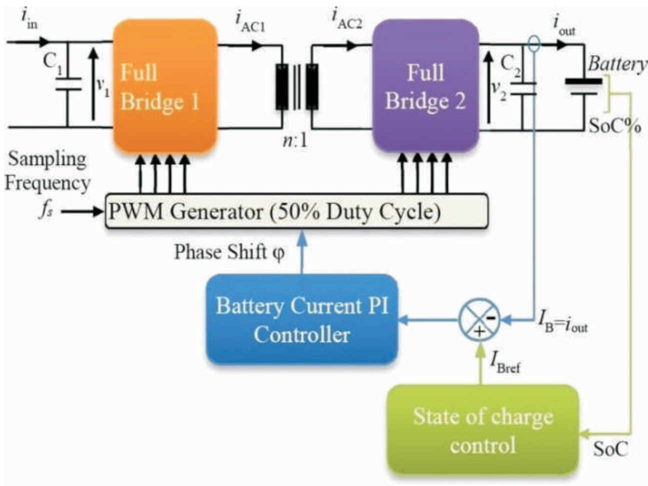

Figure 3. Modelling

delivering sinusoidal current and achieving a unit power factor. The reversible DC-DC converter, on the other hand, operates as a buck converter. The reversible DC- DC converter operates as buck converter. In order to accomplish with the maximum amplitude of the individual current harmonics specified by IEC 61000-3- 2 standard, it is mandatory that the full-bridge AC- DC bidirectional converter controller should be coordinated with the fundamental voltage of the power grid (Yadagiri et al., 2024). Therefore, a single-phase Phase-locked Loop (PLL) is the first algorithm implemented by the digital controller. To accomplish with this requirement a single-phase PLL in the α-β coordinates is used. This algorithm produces two sine-waves with unitary amplitude shifted by 90°: pllα and pllβ (Tripathi & Agarwal, 2021). When the PLL is coordinated with the power grid, the signal pllα corresponds to the direct component of pertaining to the power grid's base voltage. This signal is used as input to the subsequent digital control algorithms. The second control algorithm is responsible to calculate the reference current for the full-bridge AC- DC bidirectional converter (Equbal & Bhargava, 2012). To achieve the amplitude of the reference current, the reference active power is divided by the power grid voltage, with adjustments made by the plla signal. The reference active power is controlled by a PI controller that ensures the DC link voltage remains regulated. The control block diagram to generate the current reference (iS*) is shown. This current control uses the circuit model parameters and the information from previous samplings to calculate and can be resumed. The reversible DC-DC converter operates under both constant current and constant voltage modes. In the constant current mode, the reference current (iTB) is compared with the actual current (iTB)*. The current error obtained is fed into a PI controller, which adjusts the output duty cycle via a PWM modulator with a 20 kHz triangular carrier. Once the maximum voltage limit recommended by the battery manufacturer is achieved, the control algorithm switches to the constant voltage stage. In this stage, a second PI controller maintains the output voltage (vTB) of the reversible DC-DC converter at the voltage reference (vTB) (Haq & Ali, 2021).*

3.2 Vehicle-to-Grid (V2G) Operation Mode

The full-bridge AC-DC bidirectional converter operates as inverter with sinusoidal current and unitary power factor, and the reversible DC-DC converter operates as a boost converter (Barzegarkhoo et al., 2017). As in the G2V operation mode, in the V2G mode the full-bridge AC-DC bidirectional converter must be synchronized with the power grid fundamental voltage. As noted earlier, synchronization is accomplished through a single-phase α-β PLL operating in α-β coordinates. The amount of active power to be provided to the power grid is defined as an external input parameter transmitted through a serial communication port, enabling the cooperative integration of the EV into a smart grid environment. Consequently, the control algorithm used in the V2G mode is similar to the one used in the G2V mode (Al Attar et al., 2022; Singirikonda et al., 2022). Predictive current control was employed to generate the reference current corresponding to the active power to be delivered. To allow the full-bridge AC-DC bidirectional converter to feed energy back to the power grid, the DC link voltage must be slightly higher than the peak power grid voltage. To meet this requirement, the reversible DC-DC converter must act as a boost converter if the traction batteries' voltage is lower than the necessary DC link voltage. Given that the voltage of the traction batteries remains fairly constant over short durations, the regulation of the active power returned to the power grid can be achieved by absorbing a steady current from the batteries. When the battery voltage drops throughout the discharging process, it is essential to raise the reference current to maintain constant active power. Dividing the reference active power (P) by the traction batteries' voltage (vTB) yields the reference current for the traction batteries (iTB). The error between this reference current (iTB*) and the actual current (iTB) is processed by a PI controller, which then adjusts the duty cycle for a 20 kHz PWM modulator. Figure 4 shows the energy flow during operating modes.

4. Control Algorithm

4.1 Topology

The use of this topology is advised for applications where automatic bidirectional power flow, along with power density, reliability, efficiency, and cost, are critical design elements. The DAFB consists of a bidirectional DC/AC H-bridge converter, followed by a High-Frequency (HF) transformer that supplies a bidirectional AC/DC H-bridge converter, which then charges the EV battery. In the DAFB system, bidirectional power flow between the grid and the battery is regulated by adjusting the phase shift (φ) between the gate control signals of the two bridges. Figure 5 shows the general topology.

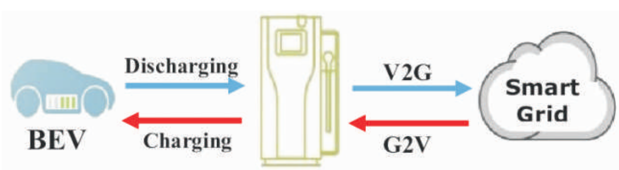

Figure 4. Energy Flow during Operating Modes

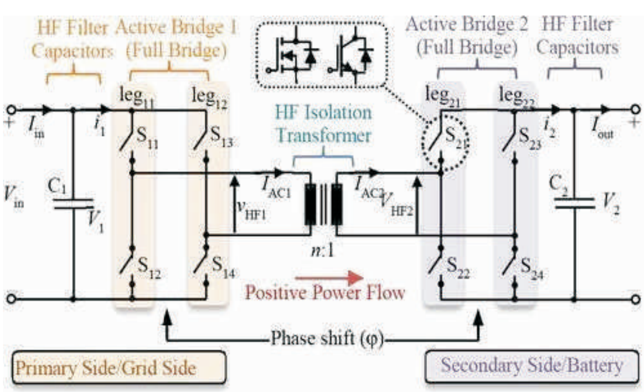

Figure 5. General Topology

4.2 Battery Lifetime Considerations

To ensure safe operation and prevent battery damage from overcharging or over-discharging, the system needs to monitor the SoC% of the battery to choose the appropriate operation mode. Figure 6 shows the various SoC% levels and their associated V2G or G2V operation modes. Within the 15–80% range, the operation priority is established by the user. Meaning that, in normal operation, V2G mode would be set bya command that is provided by the SG; unless, the EV user predefined G2V priority for EV charging.

5. Analytical Studies

Supplemental information for "A Versatile High Voltage Gain DC-DC Converter for Bidirectional V2G and G2V Hybrid Electric Vehicle Charging" is available here (Fan et al., 2022; Trivedi & Sant, 2022).

5.1 Variation of the Battery Side Voltage

Nominal voltage is determined by the anode and cathode materials and impedance. Voltage measurements are calculated by finding the midpoint between the full charge of 4.20 V/cell and the 3.0 V/cell cut-off with a 0.5A load. Therefore, the voltage across a lithium-ion battery varies with changes in discharge capacity or State of Charge (SoC). The expected variation of the voltage with SoC for a nominal 3.7 V/cell lithium-ion battery is from 4.2 V at full charge to a discharge cut-off voltage of 3.0 V. Therefore, for the application considered in this work, if the maximum value of the LV side voltage is 40 V, the voltage might be expected to vary within a range of 28 V to 40 V. As shown in Figure 7, by changing the voltage value of the low-voltage side (VLV), the duty cycle in both step-down and step-up modes varies. Therefore, the total maximum current and voltage values of semiconductor devices vary within an expected range.

5.2 Comparison of Calculated Efficiency

The supplementary information of "A Versatile High

Figure 6. Operation modes based on Battery SoC%

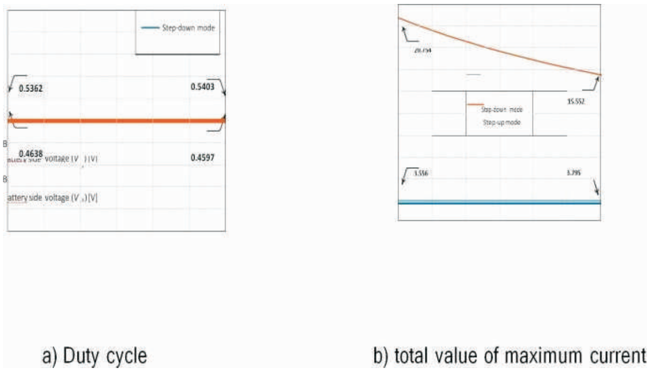

Figure 7. DC-DC Converters

Voltage Gain DC-DC Converter for Bidirectional V2G and G2V Hybrid Electric Vehicle Charging" is given here.

The comparison is based on calculations of losses in the various components of each converter, under the assumptions that all circuits use the same semiconductor devices, the inductors and capacitors equivalent series resistance is 100mΩ and 50mΩ, respectively. All the voltage and current of elements are obtained from the simulation at different power levels. Calculating the performance of the power converter is very important to adequately design the cooling system (Sharma et al., 2020), additionally, where the proposed topology has the maximum/minimum efficiency. The power loss of the converter PLoss is described by (A.1), where PM (con), PM (sw), PL(con), PL(core), PC(con)and PA are the conduction and switching losses of the five MOSFETs, the conduction and core losses of the two inductors, the losses associated with conduction in the three capacitors and auxiliary power loss, respectively. Figure 8 shows the calculated efficiency at different power levels.

Ploss = PM(con)+PM(sw)+PL(con)+PL(cor)+PC(con)+PA

5.3 Comparison of Voltage Gain

The main features of proposed converter rather than all published bidirectional converters are provided the proposed converter offers the highest-wide voltage gain ratio than all of the other converters, which make the proposed converter a novel solution for V2G and G2V applications (Saxena & Kumar, 2021). Figure 9 shows the comparison of voltage gain.

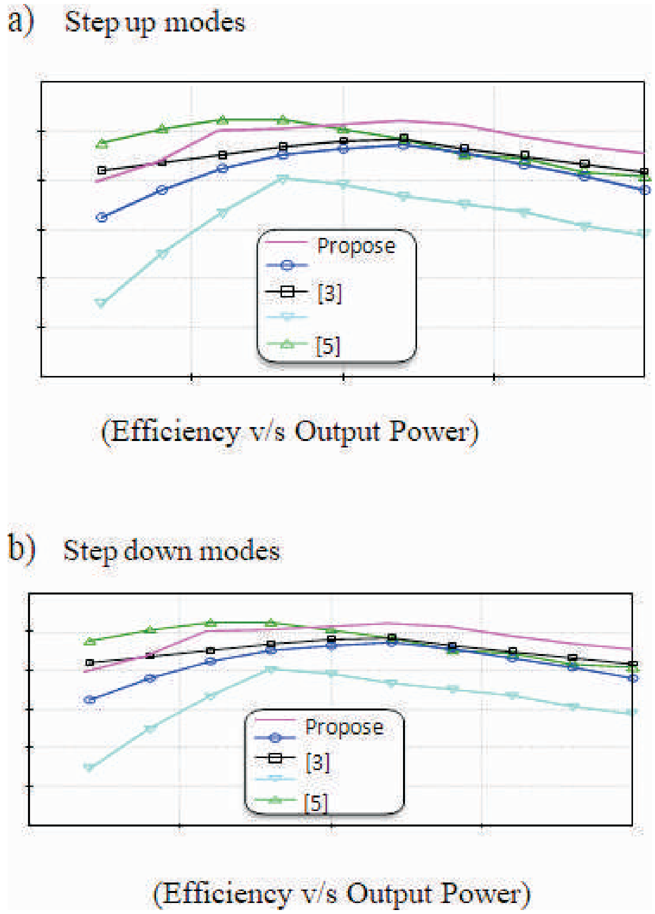

Figure 8. Calculated Efficiency at Different Power Levels

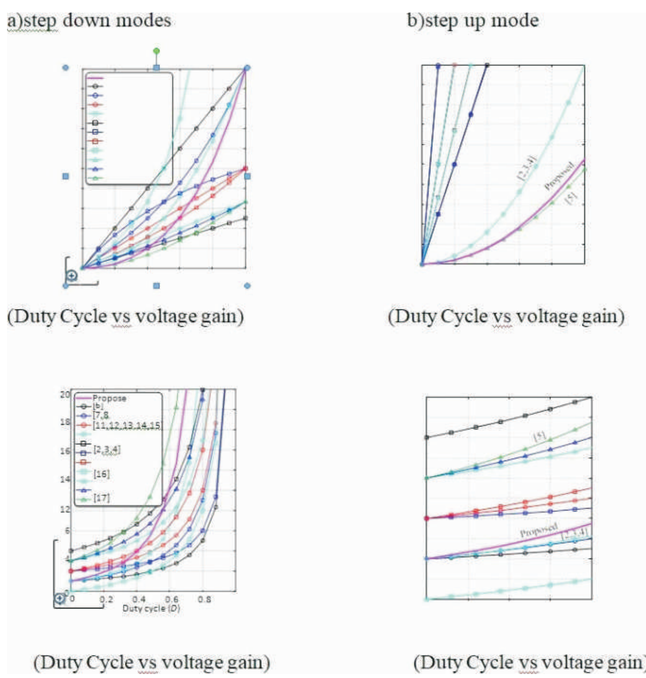

Figure 9. Comparison of Voltage Gain

6. Results

6.1 Simulation Results

The simulation results for the proposed model reveal a comprehensive view of the system's performance across various operational modes. Figure 10 shows the Simulation Diagram. As shown in Figure 11, the AC grid input voltage is stabilized at 230V, while Figure 12 shows the battery voltage maintained at a consistent 42V. The gate pulses, shown in Figure 13 and Figure 14 demonstrate the precise timing required for optimal performance. Figure 15 shows the battery charging output is effectively managed in step-down mode, ensuring efficient energy transfer. When transitioning to step-up mode, as shown in Figure 16 the DC voltage is successfully increased from 42V to 250V, which is corroborated by the AC voltage measurement in Figure 17. This simulation highlights the system's ability to handle voltage conversion effectively and maintain stable outputs across different modes.

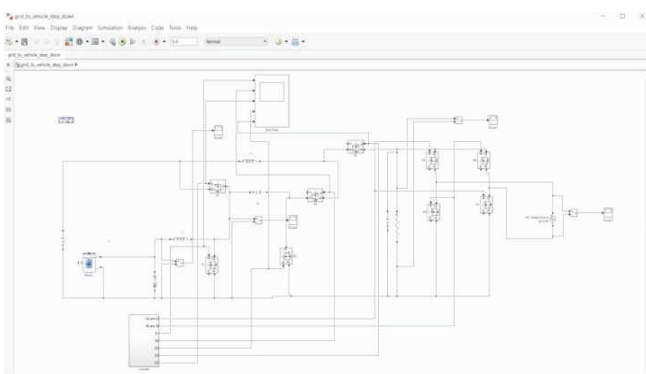

Figure 10. Simulation Diagram

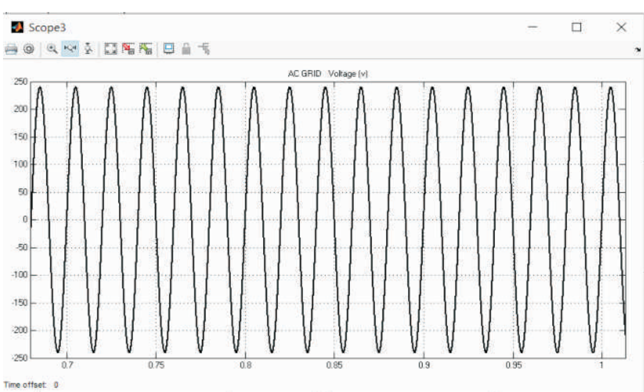

Figure 11. AC Grid Input voltage 230V

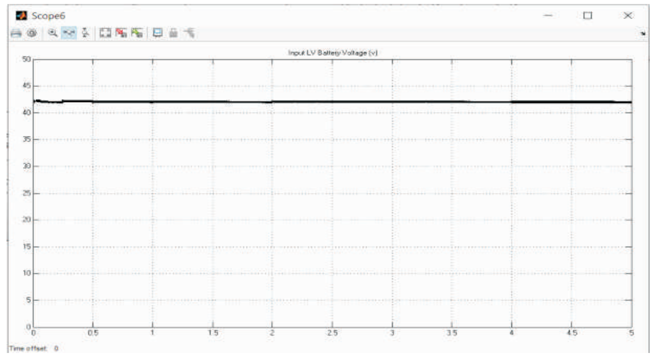

Figure 12. BatteryVoltage42V

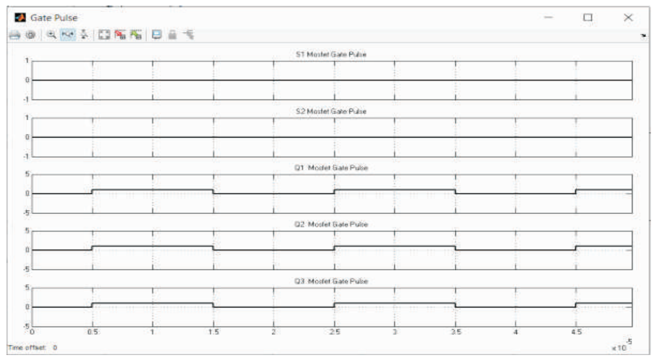

Figure 13. Gate Pulse

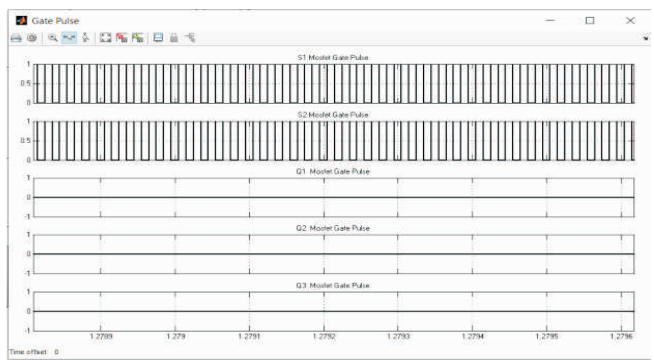

Figure 14. Gate pulse

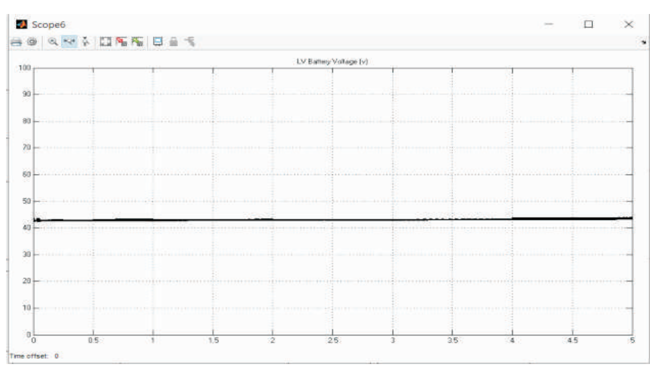

Figure 15. Battery Charging Output in Step down Mode

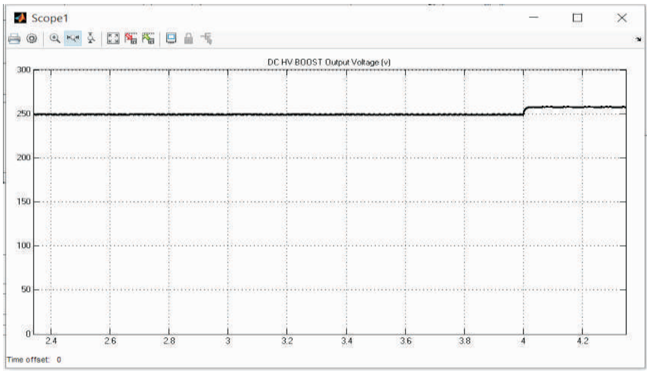

Figure 16. Step up DC Voltage 42-250V

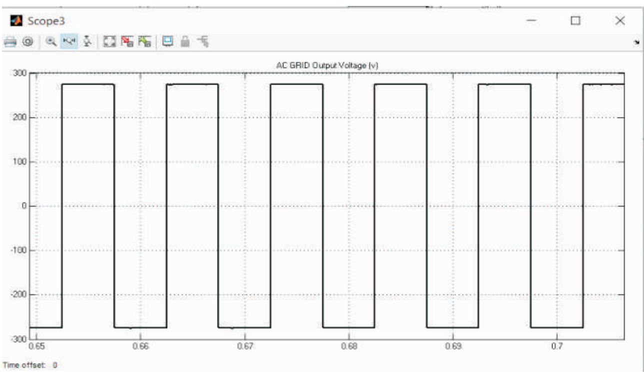

Figure 17. AC Voltage in Step up Mode

7. Discussion

The proposed wide-range DC-DC converter represents a significant advancement in Hybrid Electric Vehicle (HEV) charging technology, particularly through its bidirectional capabilities and substantial voltage gain. Unlike existing converters, which often struggle with limited voltage range and efficiency under varying operational conditions, this innovative design addresses these limitations by facilitating dynamic voltage matching and improved energy transfer between the grid and the vehicle. The converter's broad voltage gain range enables it to accommodate both low and high voltage scenarios effectively, which is crucial for the variable conditions inherent in Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations. Comparative analysis shows that this new converter offers superior efficiency, reduced power losses, and a simpler structure compared to traditional systems. The ability to support both charging and discharging with minimal efficiency losses positions this converter as a transformative solution for future HEV charging infrastructures, paving the way for enhanced energy management and integration into smart grid systems. This design not only supports the integration of renewable energy sources but also contributes to the development of more sustainable and resilient energy systems, addressing key challenges in energy management and smart grid technology.

Conclusion

This paper presents a novel wide-range DC-DC converter with substantial voltage gain and bidirectional capability, specifically designed for Hybrid Electric Vehicle (HEV) chargers. The proposed converter significantly enhances both Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) functionalities, addressing the inherent limitations of existing converter topologies. Through a detailed comparative analysis, it is evident that the new converter offers superior performance in terms of efficiency, voltage range, and power flow flexibility.

The proposed converter's innovative design overcomes the constraints of traditional systems by providing an expansive voltage gain range, enabling effective operation across diverse voltage conditions. This is crucial for seamless integration between the HEV battery and the grid, facilitating efficient energy transfer whether the vehicle is charging from the grid or discharging back into it. The converter's simplified structure, coupled with reduced power losses and lower stress on semiconductor devices, makes it a more reliable and cost-effective solution compared to conventional converters. Furthermore, the advancements achieved with this converter support not only improved energy management and integration but also align with the growing demands for smart grid technology and sustainable energy systems. By enhancing the versatility of HEV chargers, this converter paves the way for the next generation of electric vehicle infrastructure, promoting more efficient and resilient energy systems.

The proposed wide-range DC-DC converter represents a significant advancement in HEV charging technology, providing a transformative solution that supports both the integration of renewable energy sources and the evolution towards smarter, more sustainable energy systems. Its ability to effectively manage bidirectional power flow and adapt to varying voltage conditions highlights its potential to drive forward the future of electric vehicle infrastructure.

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