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Design and Development of Bidirectional Converter based on V2G and G2V Operation

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Abstract. The rapid growth of electric vehicles (EVs) in the transportation sector presents challenges related to increased peak energy demand on existing grid infrastructures. Vehicle-to-grid (V2G) and grid-to-vehicle (G2V) technologies play a crucial role in mitigating these demands by enabling bidirectional energy transfer. This study proposes a solar-powered bidirectional converter for V2G and G2V operations, facilitating efficient energy exchange between EVs, the grid, and renewable sources. A bidirectional buck-boost converter, integrated with an H-bridge AC/DC converter, is analyzed alongside a control strategy that optimizes power flow. The proposed system leverages solar energy to enhance grid stability and reduce dependency on conventional power sources. Performance and efficiency are evaluated using a MATLAB/SIMULINK-based simulation model under various operating conditions. The results demonstrate the effectiveness of the proposed converter in ensuring stable, efficient, and renewable-powered energy transfer..

1. Introduction

The increasing popularity of electric vehicles (EVs) is driven by the global shift toward sustainable transportation, as fossil fuel resources continue to deplete. This transition is primarily motivated by the need to reduce greenhouse gas emissions and minimize carbon footprints. EVs offer significant advantages over conventional internal combustion engine vehicles, including lower emissions and reduced operational costs. However, their widespread adoption is hindered by several challenges, such as high initial costs, limited charging infrastructure, and constrained driving ranges [1].

The integration of EVs into power grids introduces additional complexities. Large-scale EV charging places substantial demands on electricity supply, intensifying the imbalance between energy consumption and generation, particularly given the intermittency of renewable energy sources such as wind and solar power. To address this issue, bidirectional EV chargers have emerged as a viable solution, enabling both Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations. These chargers facilitate energy exchange between EV batteries and the grid, thereby enhancing grid stability and overall efficiency.

Battery energy storage systems (BESS) play a crucial role in supporting V2G and G2V functionalities, ensuring efficient energy flow. The integration of EV chargers with smart grids further enhances grid reliability by enabling rapid charging capabilities and intelligent energy management. V2G technology mitigates grid stress by allowing EV batteries to discharge power during peak demand periods, offering potential financial incentives for vehicle owners contributing stored energy to the grid [2]. Consequently, research efforts have focused on developing compact, bidirectional chargers suitable for both fully electric and hybrid vehicles. These chargers are expected to alleviate grid strain while reinforcing the dual functionality of EVs as both energy storage units and transportation solutions.

In pursuit of this objective, various researchers have proposed and explored different technological approaches. For instance, the authors in [3] designed and simulated a bidirectional buck-boost converter for a plug-in hybrid electric vehicle (PHEV) system, incorporating a ripple compensation circuit to enhance performance. Further, in [4], the impact of V2G operations on battery lifespan was examined, highlighting challenges associated with continuous charge-discharge cycles. Additionally, [5] introduced a small-signal analysis and state-space modeling approach to evaluate the converter's steady-state and dynamic performance, achieving high efficiency and low total harmonic distortion. Lastly, [6] investigated buck converter specifications, detailing key parameters such as input and output voltage, duty cycle, inductor, and capacitor values required for optimal operation.

This study builds upon these research efforts by proposing a bidirectional power conversion system tailored for V2G and G2V applications. The proposed system integrates a bidirectional buck-boost converter with an H-bridge AC/DC converter, offering a reduced topology for enhanced efficiency. The effectiveness of this approach is evaluated

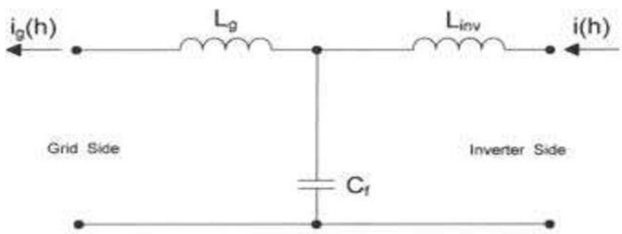

Fig. 2. LCL Filter circuit

through MATLAB/SIMULINK simulations, demonstrating its viability under various operational conditions.

2. System Implementation

To realize the proposed system, a comprehensive block diagram has been developed, as illustrated in Fig. 1. This diagram represents the system integration of the bidirectional converter for Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations, demonstrating the interconnections between the various components. The proposed system consists of two bidirectional converters along with a filtering circuit designed to minimize harmonic distortions. To achieve DC voltage regulation and maintain a bus voltage of 400V, a controller for the variable DC/DC converter stage is employed.

System Components and Their Functionality

The system is designed around a single-phase 230V AC grid, which serves as the primary energy interface. During G2V operation, the grid acts as the power source, facilitating battery charging. Conversely, in V2G mode, the grid functions as a load, receiving power from the EV battery.

A bidirectional AC-DC converter ensures seamless interaction with the power grid. In G2V mode, this converter operates as an active rectifier, producing a sinusoidal current while maintaining a unity power factor (UPF). In V2G mode, it transitions into an inverter, acting as a Constant Current Source (CCS) to supply the required power back to the grid [7].

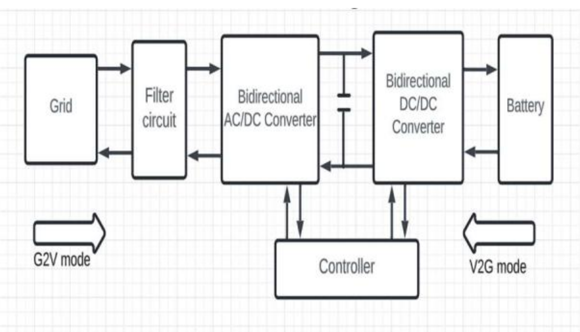

Fig. 1. Block Diagram of system intégration

The bidirectional DC-DC converter plays a crucial role in energy transfer between the battery and other system components. In G2V mode, it operates as a buck converter, stepping down the grid voltage to match the battery's charging requirements while regulating voltage and current. Conversely, during V2G operation, the converter functions as a boost converter, increasing the battery voltage to facilitate energy transfer back to the grid [10].

A lithium-ion battery rated at 170V, 12A is chosen to represent the electric vehicle's energy storage system. In G2V mode, the battery undergoes charging, whereas in V2G mode, it discharges, supplying power to the grid.

The controller in the bidirectional converter is responsible for managing energy flow between the EV battery and the grid, ensuring efficient operation during both V2G and G2V transitions.

Further advancements in bidirectional converter technologies have been explored by various researchers. In [11], a three-level hybrid active filter was developed for EV applications. Similarly, researchers in [12, 13] integrated renewable energy sources into their system designs to facilitate efficient power transfer between sources and loads.

3. Bidirectional Power Flow and Converter Design

Bidirectional power flow converters play a crucial role in enhancing power quality by ensuring a high power factor and low total harmonic distortion (THD) for both consumer and grid applications [8]. To optimize the performance of Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations, a bidirectional converter is proposed.

As illustrated in Fig. 2, an LCL filter is incorporated into the system to reduce the THD level by minimizing current distortion on the grid side. Effective energy exchange between the grid and the converter is essential for both G2V and V2G modes. The current direction in the converter is defined as positive when energy is transferred from the grid to the vehicle. The system design is guided by the mathematical formulations presented in [9].

The bidirectional converters utilized for both charging (G2V) and discharging (V2G) operations are depicted in Fig. 3 and Fig. 4.

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System Specifications

The key electrical specifications of the proposed system are as follows:

- Grid Voltage & Frequency: 230V, 50Hz
- DC Bus Voltage: 400V
- Capacitance (C): 6.23µF
- Inductance Values: 4.36mH and 4.06mH
- Bus Capacitance: 5.6mF

Operation of the Bidirectional Converter

The bidirectional converters, shown in Fig. 3 and Fig. 4, function in both charging (G2V) and discharging (V2G) modes:

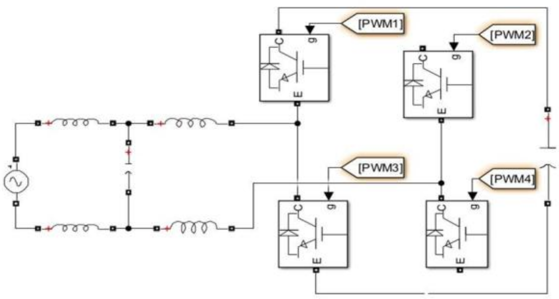

Fig .3 Bidirectional AC/DC Converter

Fig.4. Bidirectional DC/DC Converter

- Charging Mode (G2V Operation):
  - The converter operates as a buck converter, reducing the input voltage to match the battery's charging requirements.
  - When the switch is activated, current flows through the inductor, switch, and battery, initiating the charging process.
  - This mode facilitates power transfer from the grid to the electric vehicle battery.
- Discharging Mode (V2G Operation):
  - The converter functions as a boost converter, stepping up the battery voltage (170V) to match the DC bus voltage (400V).
  - When the bottom switch of the converter is turned on, current flows through the capacitor, anti-parallel diode, and inductor, allowing energy transfer.
  - Power is fed back from the electric vehicle battery to the grid, contributing to the stability and efficiency of the electrical system.

This bidirectional converter design ensures efficient energy flow while maintaining grid stability and reducing harmonic distortion.

4. Control Algorithm

The control scheme of the proposed technique is discussed in this section. The control circuits operate based on grid conditions, battery state of charge (SOC), and the availability of solar power. The system dynamically manages bidirectional energy transfer between the electric vehicle (EV), grid, and solar photovoltaic (PV) source..

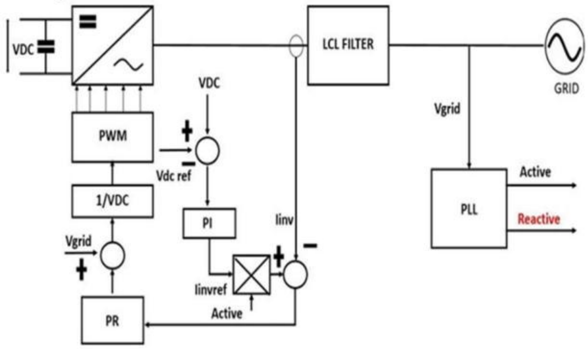

Fig. 5 Control diagram of Bidirectional AC/DC converter

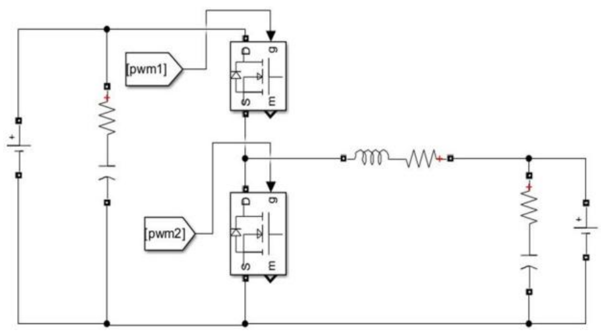

Fig. 5 illustrates the bidirectional power flow mechanism under various scenarios, integrating solar power into the control strategy. A current-mode controller regulates the AC-DC converter operation. The grid PI regulator manages the DC-link voltage error to generate the grid reference current. The Proportional-Resonant (PR) controller is employed to track AC components more accurately than a traditional PI controller. For grid-to-vehicle (G2V) operation, when excess solar power is available, the controller prioritizes direct solar charging of the EV battery. The Maximum Power Point Tracking (MPPT) algorithm is employed to optimize solar power utilization. If solar power is insufficient, the grid supplies the remaining charging power. For vehicle-to-grid (V2G) operation, when the grid demand is high, the controller facilitates power injection from the EV battery, regulated by the DC-link voltage controller. If solar energy is available, it supports power injection, reducing stress on the battery and optimizing energy flow.

The PWM generator produces gate pulses for switches S1 to S4, based on the error signal obtained from the PI controller, which compares the reference grid current with the actual grid current. A triangular carrier waveform is used for modulation, ensuring stable and efficient switching operation.

The objective of the PI controller is to maintain the control signal Vref, reducing the error Ve(k), which is often expressed as a voltage. The system dynamically switches between grid and solar power based on availability, enhancing overall efficiency and reliability.

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5. Results and Discussion

A MATLAB-based simulation model has been developed to facilitate Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) energy transfer within an electric power system while incorporating solar power integration. This simulation effectively demonstrates the operation of a single-phase AC-DC bidirectional converter in conjunction with a synchronous rectification DC-DC buck-boost converter, enabling efficient charging and discharging of the electric vehicle (EV) battery using both grid and solar energy sources.

Grid-to-Vehicle (G2V) Operation with Solar Integration

During **G2V mode**, the EV battery is charged using power from both the grid and solar photovoltaic (PV) sources. The control strategy prioritizes solar energy utilization through **Maximum Power Point Tracking (MPPT)**, reducing grid dependency and enhancing renewable energy utilization.

Key operational aspects in this mode include:

- **Solar priority charging:** When solar power is available, it directly charges the EV battery, minimizing grid power consumption.
- **Seamless grid integration:** If solar power is insufficient, the system automatically supplements charging with grid power.
- **Power flow synchronization:** The DC and AC waveforms remain in phase with a **0° phase difference**, ensuring seamless power transfer.
- **Current direction management:** The current direction is reversed within the battery to facilitate charging.
- **DC bus voltage stability:** The system maintains a **DC bus voltage of 400V**, ensuring stable and efficient operation.

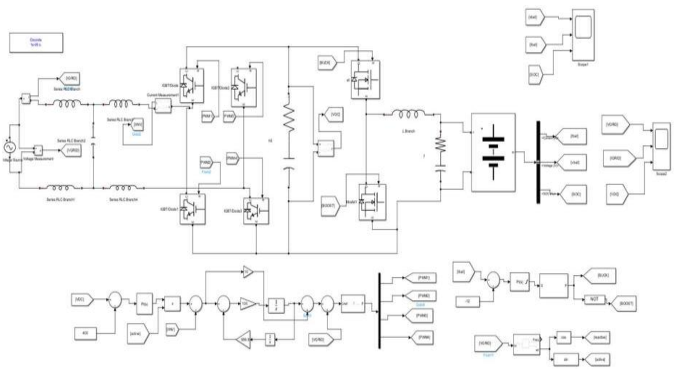

Fig. 6. Simulation diagram Bidirectional Converter The battery SOC The State of Charge (SOC) increases beyond its initial value, confirming that the battery is charging. The SOC validation is seamless, as the system efficiently directs current in the opposite direction during the charging process. The actual battery voltage varies based on the state of charge and load conditions. In the proposed system, solar energy is prioritized for charging, reducing grid dependency and improving energy efficiency.When solar power is available, the system dynamically adjusts charging based on Maximum Power Point Tracking (MPPT), ensuring optimal utilization of solar energy. If solar energy is insufficient, the grid supplies the required power to maintain continuous charging.

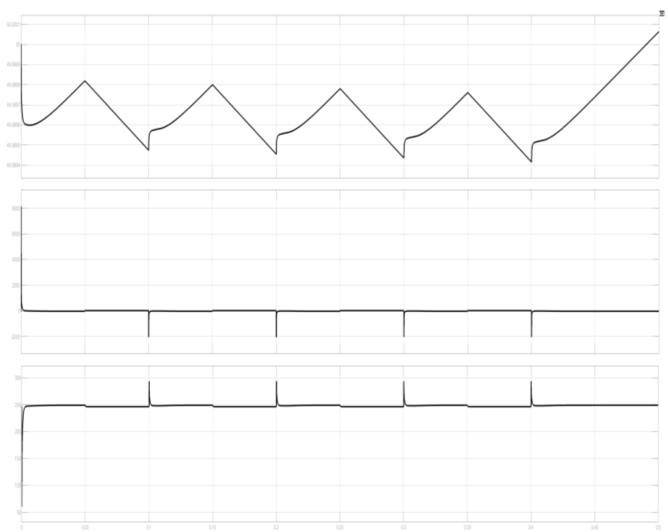

Fig. 7 Output waveforms of V2G mode operation at battery side

V2GMode: Fig. 9 illustrates battery measurements in V2G mode which power is transferred from vehicles to the grid That the vehicle is now supplying electricity to the grid is confirmed by the signs of the voltage and current waveforms being opposite.

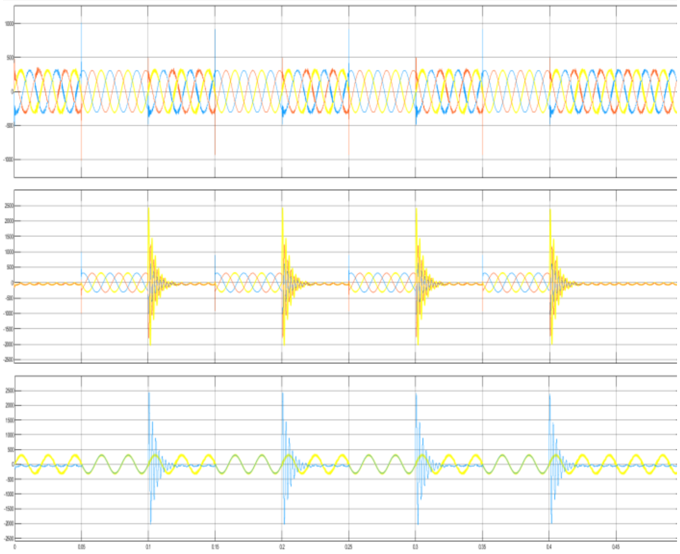

Fig. 8. Output waveforms of V2G and G2V mode Operation

In addition to maintaining the DC bus voltage at 400V, the battery current is positive and matches the reference value of 12A.Vehicle2Grid operation causes a decrease in the State of Charge relative to the initial value from the battery, which corresponds to the discharging process. The flow of the current direction (current discharging) is always seen as positive in the entire battery discharge process. The voltage of the battery remains constant during the V2G mode. In a nutshell, a vehicle during V2G operation behaves as a wide-spread energy source that feeds the grid directly when there is insufficient capacity.

6. Conclusion

The proposed bidirectional converter has been successfully tested for Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations under two different conditions. The results demonstrate that the system not only facilitates efficient bidirectional energy transfer but also reduces harmonic distortion, thereby enhancing overall power quality.The implementation of V2G functionality allows EV owners to contribute surplus energy back to the grid. This process is managed by a local aggregator, who oversees power distribution and control in exchange for a predetermined revenue share.

Impact on Grid Stability

Simulation results confirm that EV batteries can play a crucial role in grid stabilization by discharging stored energy during peak demand periods. By alleviating stress on the grid, V2G technology enhances grid resilience and improves energy efficiency, making it a valuable asset in modern smart grid systems.

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