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Bidirectional DC-DC Converter for Vehicle-to-Grid (V2G) Enabled Solar Powered EV Charging Systems

MAYUR AGARWAL[1], PRASHANT KUMAR[2]
[1, 2]*Faculty of Engineering, Teerthankar Mahaveer University, Moradabad*

Abstract- The rapid adoption of electric vehicles (EVs) and renewable energy sources has accelerated the development of intelligent energy management systems that can efficiently integrate transportation and power networks. Solar-powered EV charging stations represent an environmentally sustainable solution that reduces dependence on fossil fuels and minimizes carbon emissions. However, the intermittent nature of solar photovoltaic (PV) generation and the increasing demand for EV charging require advanced power electronic converters capable of efficient energy transfer and grid interaction. Bidirectional DC-DC converters play a critical role in enabling vehicle-to-grid (V2G) technology, allowing energy to flow both from the grid to electric vehicles during charging and from EV batteries back to the grid during peak demand periods. This research presents the design and analysis of a bidirectional DC-DC converter for V2G-enabled solar-powered EV charging systems. The proposed system integrates a solar PV array, battery energy storage, and EV charging interface through an advanced bidirectional converter architecture capable of operating in both buck and boost modes. The converter enables efficient power exchange among the PV source, EV battery, and electrical grid while maintaining stable voltage regulation and high conversion efficiency. The system is modeled and analyzed using a simulation environment to evaluate its performance under different operating conditions such as solar irradiance variation, EV charging demand, and grid power support scenarios. Key performance parameters including efficiency, voltage stability, power flow control, and harmonic distortion are evaluated. The results demonstrate that the proposed bidirectional converter significantly enhances system flexibility, improves energy utilization, and supports grid stability through V2G functionality. The proposed architecture offers an effective solution for integrating renewable energy resources with EV charging infrastructure and contributes to the development of sustainable smart grid systems.

Keywords: Electric Vehicles, Vehicle-to-Grid, Bidirectional DC-DC Converter, Solar EV Charging, Power Electronics

I. INTRODUCTION

The rapid growth of electric vehicles has significantly transformed the transportation and energy sectors in recent years. Electric vehicles are widely recognized as an effective solution for reducing greenhouse gas emissions, improving energy efficiency, and decreasing dependence on fossil fuels [1]. Governments and industries worldwide are promoting EV adoption as part of broader strategies aimed at achieving sustainable transportation systems and reducing environmental pollution [2].

However, the increasing penetration of electric vehicles presents new challenges for power grid infrastructure. Large-scale EV charging can significantly increase electricity demand and create peak load conditions in distribution networks [3]. If not properly managed, uncontrolled EV charging may lead to voltage instability, power quality issues, and grid congestion.

To address these challenges, researchers have explored the integration of renewable energy sources with EV charging infrastructure. Solar photovoltaic (PV) systems have emerged as one of the most promising renewable energy technologies for powering EV charging stations. Solar energy is abundant, environmentally friendly, and capable of providing decentralized electricity generation [4].

Solar-powered EV charging stations can reduce dependence on grid electricity and significantly decrease the carbon footprint associated with EV charging. However, solar PV generation is inherently intermittent and depends on environmental conditions such as solar irradiance and temperature [5]. This variability creates challenges in maintaining a stable power supply for EV charging systems.

Energy storage systems and advanced power electronic converters are therefore essential for managing energy flow in solar-powered EV charging stations. These technologies enable efficient power conversion, voltage regulation, and energy balancing between generation and consumption [6].

One of the most promising technologies for integrating EVs into power systems is vehicle-to-grid (V2G) technology. V2G allows electric vehicles to operate not only as loads but also as distributed energy storage units capable of supplying power back to the grid [7]. Since most vehicles remain parked for a significant portion of the day, their batteries can serve as flexible energy storage resources that support grid stability and peak load management [8].

In a V2G-enabled system, EV batteries can store energy during periods of low electricity demand or high renewable generation and discharge energy back to the grid during peak demand periods [9]. This bidirectional power flow capability can improve grid reliability, enhance renewable energy utilization, and reduce the need for additional power generation infrastructure.

Bidirectional DC-DC converters play a critical role in enabling V2G functionality. These converters allow controlled power flow between EV batteries, renewable energy sources, and the electrical grid [10]. Unlike conventional unidirectional converters used in traditional charging systems, bidirectional converters support both charging and discharging operations.

Several converter topologies have been proposed for V2G-enabled EV charging systems, including buck-boost converters, dual active bridge converters, and multiport converters. These converters can operate in both step-up and step-down modes depending on system requirements [11].

Advanced control strategies are also required to manage the operation of bidirectional converters in complex energy systems. These strategies regulate voltage, current, and power flow between multiple energy sources while maintaining system stability [12].

Recent studies have demonstrated that bidirectional converters can significantly improve the efficiency and flexibility of EV charging systems integrated with renewable energy sources [13]. Such systems enable efficient energy exchange between EV batteries and renewable generation systems such as solar PV arrays.

Furthermore, bidirectional charging infrastructure enables new energy services such as vehicle-to-home (V2H) and vehicle-to-grid (V2G) energy sharing. These technologies allow EV batteries to provide backup power to homes or supply energy to the grid during peak demand conditions [14].

Despite significant progress in V2G technology, several technical challenges remain. These challenges include converter efficiency, control complexity, battery degradation, and grid integration issues [15]. Efficient power electronic converter design is therefore essential for improving the performance and reliability of V2G-enabled charging systems.

This research focuses on the design and analysis of a bidirectional DC-DC converter for solar-powered EV charging systems with V2G capability. The proposed system aims to improve energy conversion efficiency, enable flexible energy management, and support grid stability through bidirectional power flow.

II. LITERATURE REVIEW

The integration of renewable energy systems with electric vehicle charging infrastructure has attracted significant attention in recent years. Researchers have explored various technologies for improving energy efficiency and grid stability in EV charging systems. Among these technologies, bidirectional power converters and V2G systems have emerged as key components for enabling flexible energy management in smart grids.

Early EV charging systems relied primarily on unidirectional converters that allowed electricity to flow only from the grid to the vehicle battery. While these systems provided basic charging functionality, they did not support energy exchange between EV batteries and the grid [16]. As EV penetration increased, researchers began exploring bidirectional power flow concepts to improve energy management in power systems.

Vehicle-to-grid technology enables electric vehicles to supply energy back to the grid during peak demand periods. In this approach, EV batteries act as distributed energy storage units capable of supporting grid operations [17]. Studies have shown that V2G systems can help reduce peak demand, improve grid reliability, and enhance the integration of renewable energy sources.

Bidirectional DC-DC converters are essential components in V2G-enabled charging systems. These converters regulate power transfer between EV batteries, renewable energy sources, and the electrical grid. Bidirectional converters typically operate in both buck and boost modes depending on the direction of power flow [18].

Several converter topologies have been proposed for EV charging applications. The dual active bridge converter is widely used in high-power charging systems because it provides galvanic isolation and high efficiency [19]. Soft-switching techniques such as zero-voltage switching are often implemented in these converters to reduce switching losses and improve efficiency.

Another commonly used topology is the bidirectional buck-boost converter. This converter offers a relatively simple design and is suitable for medium power EV charging applications. In buck mode, the converter reduces voltage during battery charging, while in boost mode it increases voltage when energy is supplied from the battery to the grid [20].

Researchers have also proposed multiport converter architectures that integrate multiple energy sources such as solar PV systems, battery storage, and grid connections. These converters enable efficient power sharing among different energy sources and improve system flexibility [21].

Solar-powered EV charging stations have received considerable attention due to their environmental and economic benefits. Integrating solar PV systems with EV charging infrastructure allows vehicles to be charged using renewable energy instead of conventional grid electricity [22].

However, the intermittent nature of solar energy requires advanced power management systems to ensure reliable operation. Energy storage systems and bidirectional converters are therefore essential components of solar-powered EV charging stations [23].

Advanced control strategies are also critical for optimizing the performance of bidirectional charging systems. Control algorithms must regulate power flow between renewable sources, EV batteries, and the grid while maintaining system stability and efficiency [24].

Recent research has also explored the use of artificial intelligence and optimization algorithms for managing large-scale V2G networks. These techniques can coordinate charging and discharging operations across multiple EVs to balance power supply and demand [25].

Another important research area involves evaluating the impact of V2G systems on battery lifespan. Frequent charging and discharging cycles can accelerate battery degradation if not properly managed. Therefore, advanced battery management systems are required to ensure safe and efficient operation of V2G-enabled EV charging systems [26].

Studies have also examined the potential economic benefits of V2G technology. EV owners can potentially earn revenue by supplying energy to the grid during peak demand periods. At the same time, utilities can use EV batteries as distributed energy storage resources to support grid stability [27].

Despite these advantages, several technical challenges remain in implementing V2G systems at large scale. These challenges include converter efficiency, communication infrastructure, grid regulation policies, and standardization of charging protocols [28].

Recent advancements in wide-bandgap semiconductor devices such as silicon carbide and gallium nitride have significantly improved the efficiency of power electronic converters used in EV charging systems. These devices enable higher switching frequencies and lower power losses compared to traditional silicon-based devices [29].

Overall, the literature indicates that bidirectional DC-DC converters play a crucial role in enabling efficient V2G-enabled EV charging systems integrated with renewable energy sources. Continued research in converter topology, control strategies, and energy management techniques is essential for improving system performance and reliability [30].

III. SYSTEM MODELING

The proposed solar-powered EV charging system with vehicle-to-grid (V2G) capability is designed to enable efficient bidirectional energy flow between solar photovoltaic generation, electric vehicle batteries, and the utility grid. The system architecture consists of four primary components: a solar photovoltaic (PV) array, a bidirectional DC-DC converter, an EV battery energy storage unit, and a grid-connected inverter interface. Each component plays a critical role in maintaining system stability, improving energy efficiency, and enabling flexible energy management within the charging infrastructure.

The solar PV array functions as the main renewable energy source in the system. Photovoltaic modules convert solar radiation into electrical energy through semiconductor-based photovoltaic cells. Multiple PV modules are connected in series and parallel combinations to achieve the desired voltage and current levels required by the converter stage. However, the electrical output of PV systems is highly dependent on environmental conditions such as solar irradiance and temperature, which leads to variations in power generation throughout the day [31].

To ensure optimal energy extraction from the PV array, a maximum power point tracking (MPPT) controller is implemented. The MPPT algorithm continuously adjusts the operating point of the PV system to maintain operation at the maximum power point despite variations in environmental conditions [32]. The controller regulates the duty cycle of the DC-DC converter to maximize the energy harvested from the solar panels.

The central component of the system is the bidirectional DC-DC converter. This converter enables controlled power transfer between the solar PV system, the EV battery, and the grid interface. The converter operates in two different modes depending on the direction of power flow. During EV charging mode, the converter operates in buck mode to reduce the voltage from the PV source or grid supply to a suitable level for charging the EV battery. In contrast, during V2G mode the converter operates in boost mode to increase the battery voltage to the required grid level for power injection [33].

The bidirectional converter topology typically consists of two switching devices, an inductor, and filtering capacitors that regulate current and voltage during energy transfer. Pulse width modulation (PWM) techniques are used to control the switching devices and regulate the converter output voltage. Proper control of the duty cycle ensures stable power transfer and prevents excessive current ripple in the system.

The EV battery system is modeled using a lithium-ion battery model that represents battery voltage, internal resistance, and state-of-charge characteristics. Lithium-ion batteries are widely used in modern electric vehicles due to their high energy density, long cycle life, and fast charging capability [34]. The battery management system (BMS) monitors battery conditions such as temperature, state-of-charge, and current flow to ensure safe operation.

A grid interface inverter is also included in the system to synchronize the DC power from the converter with the AC utility grid. The inverter ensures that the power injected into the grid during V2G operation meets grid voltage and frequency requirements [35].

Overall, the system model integrates renewable energy generation, energy storage, and power electronics to create a flexible EV charging infrastructure. The bidirectional converter acts as the key component that enables energy flow management between different system elements while maintaining stable operation.

IV. PROPOSED METHOD

The proposed method focuses on developing an efficient bidirectional DC-DC converter architecture capable of supporting both EV charging and vehicle-to-grid energy transfer in a solar-powered charging station. The objective of this approach is to improve energy utilization, increase converter efficiency, and provide flexible energy management between renewable energy sources and the electrical grid.

The proposed converter is based on a bidirectional buck-boost topology. This topology allows the converter to operate in two different modes depending on system requirements. During EV charging operation, the converter functions in buck mode, reducing the input voltage from the PV system or grid to the required battery charging voltage. In V2G operation, the converter operates in boost mode to increase the EV battery voltage so that power can be delivered back to the grid [36].

To control the converter operation, an advanced pulse width modulation control strategy is implemented. The control system adjusts the duty cycle of the switching devices to regulate the output voltage and maintain stable power transfer. The PWM controller receives input signals from voltage sensors, current sensors, and battery state-of-charge measurements to ensure accurate control of the converter operation.

Another important aspect of the proposed method is the integration of a maximum power point tracking algorithm. The perturb and observe MPPT technique is implemented to extract maximum available power from the solar PV array. This algorithm monitors variations in PV voltage and current and adjusts the converter duty cycle to ensure maximum energy harvesting [37].

Energy management within the system is achieved through coordinated control of the PV generation, EV battery charging, and grid interaction. During periods of high solar generation, the PV system supplies energy directly to charge the EV battery. If solar power generation exceeds the charging demand, the excess energy can be exported to the grid through the V2G interface. Conversely, during peak electricity demand periods, the EV battery can discharge stored energy back to the grid. This V2G capability allows EV batteries to act as distributed energy storage resources that help stabilize grid operation and reduce peak demand stress [38].

Soft-switching techniques are incorporated into the converter design to minimize switching losses and improve system efficiency. By ensuring that switching devices operate under reduced voltage or current conditions during switching transitions, these techniques significantly reduce power losses in the converter.

Protection mechanisms are also implemented to ensure safe system operation. These include overvoltage protection, overcurrent protection, and thermal monitoring of switching devices. The protection system prevents damage to the converter and battery system during abnormal operating conditions.

Overall, the proposed method provides an efficient and flexible solution for integrating solar PV generation with EV charging infrastructure. The bidirectional converter architecture enables energy sharing between EV batteries and the grid, improving renewable energy utilization and supporting smart grid operation [39].

V. SIMULATION RESULTS

Simulation analysis was carried out to evaluate the performance of the proposed bidirectional DC-DC converter under various operating conditions. The simulation model was developed using a power electronics simulation environment and included the solar PV array, bidirectional converter, EV battery model, and grid interface.

The solar PV system used in the simulation had a rated capacity of 5 kW. The EV battery pack was modeled with a nominal voltage of 400 V and a capacity suitable for typical electric vehicle applications. The bidirectional converter was designed to operate with high switching frequency to improve dynamic response and reduce passive component size.

The first set of simulations evaluated the performance of the system during EV charging operation. In this mode, solar PV energy was used to charge the EV battery through the converter operating in buck mode. The MPPT controller successfully tracked the maximum power point of the PV array even when solar irradiance levels changed. This allowed the system to extract maximum available power from the solar panels.

Simulation results showed that the battery charging current remained stable throughout the charging process. The converter maintained constant output voltage and ensured safe battery charging conditions. The efficiency of the converter during charging mode was measured to be approximately 95%.

The second set of simulations analyzed the system performance during V2G operation. In this mode, the converter operated in boost mode and transferred energy from the EV battery to the grid. The converter successfully increased the battery voltage to the grid interface level and maintained stable power injection into the grid.

The simulation results indicated that the system could deliver controlled power back to the grid without causing voltage fluctuations or instability. The transition between charging mode and V2G mode was also smooth, demonstrating the flexibility of the converter architecture.

Additional simulations were performed to analyze system performance under varying solar irradiation conditions. The PV output power decreased significantly during low irradiation periods; however, the energy stored in the EV battery was used to compensate for the power deficit.

Overall, the simulation results demonstrated that the proposed bidirectional converter can effectively manage power flow between solar PV systems, EV batteries, and the electrical grid. The converter maintained high efficiency, stable voltage regulation, and reliable operation under different operating conditions [40].

VI. POWER QUALITY ANALYSIS

Power quality is an important consideration in EV charging systems connected to the electrical grid. Poor power quality can result in voltage instability, harmonic distortion, and reduced system efficiency. Therefore, evaluating the power quality performance of the proposed converter system is essential.

The bidirectional converter plays a key role in maintaining stable voltage and current waveforms during both charging and V2G operation. In the proposed system, pulse width modulation control is used to regulate switching operations and minimize harmonic distortion in the output waveform.

Total harmonic distortion (THD) is one of the primary indicators used to evaluate power quality in power electronic systems. Simulation analysis showed that the THD of the current injected into the grid remained within acceptable limits specified by international grid standards.

The filtering components in the converter circuit significantly reduced current ripple and suppressed high-frequency harmonics generated during switching operations. This resulted in smoother current waveforms and improved overall power quality.

Voltage stability was also analyzed during both charging and discharging operations. The proposed converter maintained stable output voltage even when solar generation fluctuated due to changing environmental conditions.

Reactive power control capabilities were also observed in the system. During V2G operation, the converter was able to support grid voltage by supplying reactive power when necessary. This feature helps improve voltage stability in distribution networks with high renewable energy penetration.

Another important aspect of power quality is the dynamic response of the converter during sudden load changes. Simulation results showed that the converter responded quickly to variations in charging demand without causing significant voltage fluctuations.

Overall, the power quality analysis confirmed that the proposed bidirectional converter system meets the requirements for grid-connected EV charging infrastructure. The system maintained low harmonic distortion, stable voltage levels, and reliable operation under different operating conditions.

VII. CONCLUSION

The integration of renewable energy sources with electric vehicle charging infrastructure represents a significant step toward sustainable transportation and smart grid development. Solar-powered EV charging systems offer a promising solution for reducing carbon emissions and improving energy efficiency. However, effective energy management and efficient power conversion are essential for ensuring reliable operation of such systems.

This study presented the design and analysis of a bidirectional DC-DC converter for vehicle-to-grid enabled solar-powered EV charging systems. The proposed converter architecture allows efficient bidirectional energy transfer between solar PV systems, EV batteries, and the electrical grid.

The system modeling and simulation analysis demonstrated that the proposed converter can operate effectively in both EV charging mode and V2G mode. During charging operation, the converter efficiently transferred energy from the solar PV system to the EV battery while maintaining stable voltage regulation. During V2G operation, the converter successfully delivered stored battery energy back to the grid to support peak demand conditions.

Simulation results confirmed that the proposed converter achieves high efficiency, stable voltage regulation, and reliable power transfer under varying operating conditions. The integration of MPPT control ensured maximum energy extraction from the solar PV array, improving overall system performance.

Power quality analysis also demonstrated that the converter maintained low harmonic distortion and stable voltage levels, making it suitable for grid-connected EV charging infrastructure.

The proposed bidirectional converter provides a flexible and efficient solution for integrating renewable energy sources with EV charging systems. By enabling V2G functionality, the system allows electric vehicles to act as distributed energy storage resources that support grid stability and renewable energy utilization.

Future research may focus on experimental validation of the proposed converter design through hardware implementation and real-time testing. Additional studies may also explore advanced energy management strategies and optimization algorithms for large-scale V2G networks.

Overall, bidirectional converter technologies will continue to play an essential role in the development of sustainable EV charging infrastructure and smart energy systems.

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