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Vehicle-to-Grid Power Transfer Method for Electric Vehicles using Off-Board Charger

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ABSTRACT- This article explores a power transfer technique from vehicle to grid (V2G) via the construction of an off-board charger for electric cars (EVs). The charger accommodates several charging modes, such as grid-to-vehicle (G2V), vehicle-to-vehicle (V2V), and vehicle-to-grid (V2G), facilitating efficient and adaptable energy management. In G2V mode, the charger utilizes grid power to recharge electric vehicle batteries, whilst V2V mode enables direct energy transfer between electric vehicles, circumventing the grid. The novel integration of G2V and V2V modes enables the concurrent use of grid electricity and energy from other electric vehicles, therefore diminishing grid reliance and enhancing power efficiency. The system has a three-phase pulse width modulation (PWM) rectifier that sustains a constant DC link voltage and attains a unity power factor on the grid side, therefore adhering to the IEEE 519 standard for total harmonic distortion (THD). Furthermore, a half-bridge bidirectional DC/DC converter guarantees consistent charging and discharging currents, hence improving the reliability and efficiency of the charging process. This holistic strategy enhances dynamic energy flow and grid stability while providing possible economic advantages to electric vehicle owners and operators via the integration of renewable energy sources and sophisticated management algorithms for improved energy use and storage.

Keywords: Vehicle-to-Grid, Grid-to-Vehicle, Vehicle-to-Vehicle, Off-board charger, Pulse width modulation rectifier, Bidirectional DC/DC converter, Energy management.

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1. INTRODUCTION

In recent years, the proliferation of electric vehicles (EVs) has surged due to environmental concerns and advancements in battery technology [1]. As the EV market expands, the need for efficient charging infrastructure becomes crucial. Traditional charging stations often rely solely on grid power for charging, but emerging technologies are exploring innovative approaches to maximize efficiency and flexibility [2]. One such innovation is the development of off-board chargers with grid connectivity and V2G, G2V, and V2V capabilities. The concept of V2G involves bidirectional energy flow between EVs and the electrical grid. It enables EVs not only to consume energy from the grid but also to feed surplus energy back into it [3]. This bidirectional energy exchange has the potential to revolutionize the electricity grid by providing grid stabilization services, peak shaving, and demand response capabilities. Moreover, V2G can offer economic incentives to EV owners by allowing them to monetize their vehicle's energy storage capacity [4].

Similarly, G2V charging involves the transfer of electrical energy from the grid to EV batteries. This mode of charging is essential for replenishing EV batteries and ensuring their usability for daily commutes and longer journeys. However, conventional G2V charging methods may strain the grid during peak demand periods, leading to inefficiencies and grid congestion [5]. Therefore, optimizing G2V charging processes is crucial for ensuring grid stability and minimizing energy wastage. Furthermore, the concept of V2V charging introduces a new dimension to EV charging infrastructure. It enables one EV to transfer energy directly to another EV, bypassing the need for grid intermediaries [6]. This peer-to-peer energy exchange can be particularly useful in scenarios where traditional charging infrastructure is unavailable or overloaded. Additionally, V2V charging fosters collaboration among EV owners, promoting community-based energy sharing and resilience. The integration of V2G, G2V, and V2V capabilities into off-board EV chargers represents a significant advancement in charging technology [7]. It not only enhances the efficiency and reliability of EV charging but also transforms EVs into dynamic grid assets. By leveraging bidirectional energy flow, these chargers facilitate energy optimization, grid support, and cost savings for both EV owners and grid operators [8].

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A key component of such chargers is the three-phase PWM rectifier, which serves as the front-end converter. This rectifier plays a crucial role in maintaining a constant DC link voltage and achieving unity power factor (UPF) at the grid side. By regulating the flow of grid power, the PWM rectifier ensures efficient energy conversion and minimizes harmonic distortion in the grid current [9]. *Figure 1* shows the Block diagram representation of the proposed system.

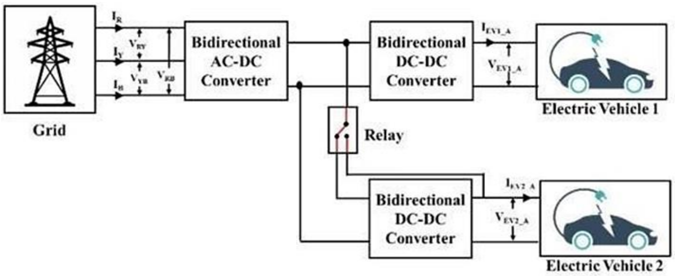

Figure 1. Proposed System Block Representation

To comply with industry standards and regulatory requirements, such as the IEEE 519 standard, the charger must maintain low total harmonic distortion (THD) in grid current. This ensures grid compatibility and prevents adverse effects on power quality [10]. By adhering to stringent THD limits, the charger mitigates the risk of grid instability and ensures seamless integration with existing grid infrastructure. Moreover, to enable seamless V2G, G2V, and V2V operations, the charger incorporates advanced control algorithms and communication protocols [11].

A critical aspect of off-board EV chargers with V2G, G2V, and V2V capabilities is their ability to maintain consistent charging and discharging currents for EVs. This is achieved using bidirectional DC/DC converters, such as the half-bridge topology. These converters regulate the flow of energy between the EV batteries and the charger, ensuring optimal charging efficiency and battery health. The development of grid-connected off-board EV chargers with V2G, G2V, and V2V capabilities represents a significant milestone in the evolution of EV charging infrastructure. By enabling bidirectional energy flow, these chargers enhance grid flexibility, energy efficiency, and reliability [12]. The off-board charger enables V2G transmission of power by using a 3-phase inverter to discharge the stored electricity from the vehicle's batteries to the micro-grid during V2G operation [13]. The off-board charger enables V2G power transfer by allowing EVs to store and deliver energy, hence assisting grid tasks such as voltage regulation and total harmonic distortion reduction via optimal proportional-integral control [14]. The design utilizes a soft-switching dual active bridge (SS-DAB) converter, enabling efficient bidirectional power transmission and optimum control for vehicle-to-grid (V2G) applications, hence improving grid stability and energy management [15]. V2G power transfer employs bidirectional converters in external chargers, allowing electric cars to return stored battery energy to the grid, hence improving stability and load management [16]. The use of a dc-dc converter to elevate voltage, so allowing a three-phase voltage source inverter to enable active power transfer from the electric vehicle to the grid [17]. The V2G mode enables power transfer from the EV's batteries to the utility grid, utilizing a bidirectional charger that maintains sinusoidal current and unity power factor during discharging [18]. The off-board charger utilizes a three-phase PWM rectifier to facilitate V2G power transfer, maintaining a constant DC link voltage and ensuring compliance with IEEE 519 for harmonic distortion. The off-board charger utilizes a boost converter for AC grid connection, enabling efficient power transfer from the vehicle to the grid through bidirectional converters and sinusoidal PWM.

2. PROPOSED METHOD

The methodology employed in developing a grid-connected off-board electric vehicle (EV) charger with vehicle-to-vehicle (V2V) capability, utilizing hysteresis current control, encompasses a multifaceted approach that integrates various engineering disciplines, including power electronics, control systems, and electrical engineering. This comprehensive methodology aims to design, implement, and optimize the charger system to enable bidirectional power flow between EVs and the grid, while ensuring stable and efficient operation. The first phase of the methodology involves conceptualization and system design. This step entails defining the specifications and requirements of the charger system, considering factors such as charging capacity, voltage levels, and communication protocols. Based on these specifications, the system architecture is developed, outlining the components and their interconnections.

Once the system architecture is defined, the next step involves component selection and procurement. Key components such as power converters, sensors, and communication modules are carefully chosen to meet the system requirements and performance objectives. Considerations such as efficiency, reliability, and cost-effectiveness are taken into account during the selection process. With the components procured, the next phase of the methodology focuses on hardware design and fabrication. Circuit schematics are developed based on the system architecture, detailing the connections and functionalities of each component. Printed circuit boards (PCBs) are then designed to accommodate the circuitry and ensure proper layout and routing for optimal performance. Simultaneously, firmware and software development are undertaken to implement the control algorithms and communication protocols required for hysteresis current control and V2V capability. This involves programming microcontrollers or digital signal processors (DSPs) to execute the control logic and interface with peripheral devices such as sensors and communication modules.

Once the hardware and software components are developed, the system integration phase begins. The various subsystems are assembled and interconnected according to the system architecture, following best practices for electrical safety and reliability. Functional testing is conducted at each stage of integration to ensure proper operation and adherence to performance specifications. After successful integration, the charger system undergoes comprehensive testing and validation. This includes performance testing under various

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operating conditions, such as different charging loads, input voltages, and ambient temperatures. Additionally, interoperability testing is conducted to verify compatibility with different EV models and grid infrastructure. Once the charger system passes validation testing, it is ready for deployment and operation. Installation and commissioning activities are carried out to ensure proper installation, configuration, and calibration of the charger system. Operational procedures and maintenance protocols are established to support ongoing operation and ensure system reliability.

Throughout the development process, documentation and documentation are maintained to track design decisions, component specifications, test results, and operational procedures. This documentation serves as a reference for future development iterations, troubleshooting activities, and system upgrades. The methodology for developing a grid-connected off-board EV charger with V2V capability using hysteresis current control encompasses conceptualization, design, procurement, fabrication, integration, testing, deployment, and documentation. By following this systematic approach, engineers can design and deploy robust and efficient charger systems that enable bidirectional power flow between EVs and the grid, contributing to the advancement of sustainable transportation infrastructure. The THD in V2V mode is not controlled to the same level as other modes due to the onboard charger's filtering and rectification capabilities, DC-DC converter tolerance, and specific operating conditions. However, maintaining reasonable THD levels remains crucial for efficient and reliable power transfer. While THD control may be relaxed, it's still essential to maintain reasonable THD levels to ensure:

1. Efficient power transfer
2. Minimized electromagnetic interference (EMI)
3. Compliance with regulatory standards (e.g., IEEE 519, IEC 61000-3-2)

Typical THD limits for V2V mode: IEEE 519: **15% to 20% THD.**

3. RESULTS AND DISCUSSION

3.1 G2V Mode of Operation

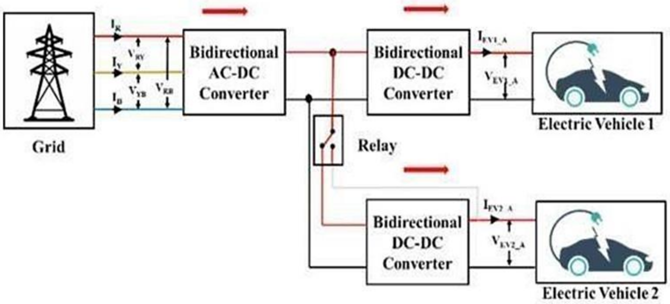

Figure 2. G2V Mode of operation

In G2V mode, the EV charger draws power from the grid to charge the vehicle's battery. The 440V grid supplies AC power, which is converted to DC by the VSC. The bidirectional buck boost converter interfaces between the VSC and the lithium-ion battery pack. During charging, the converter boosts the voltage to match the battery's charging requirements, while regulating the current flow to prevent overcharging. This mode allows efficient charging of EVs from the grid, supporting rapid replenishment of energy for extended driving ranges. *Figure 2* shows the grid to vehicle mode of operation.

V2G Mode of Operation: Conversely, in V2G mode, the EV functions as a distributed energy resource, capable of supplying power back to the grid when needed. The bidirectional buck boost converter facilitates this mode by converting DC power from the battery to AC power suitable for grid integration. The VSC controls the power flow direction and synchronizes the EV's output with the grid's voltage and frequency. This mode enables EVs to contribute to grid stabilization, load balancing, and peak shaving, enhancing the overall efficiency and reliability of the electrical grid.

Figure 3 shows the simulation diagram of grid to vehicle mode of operation.

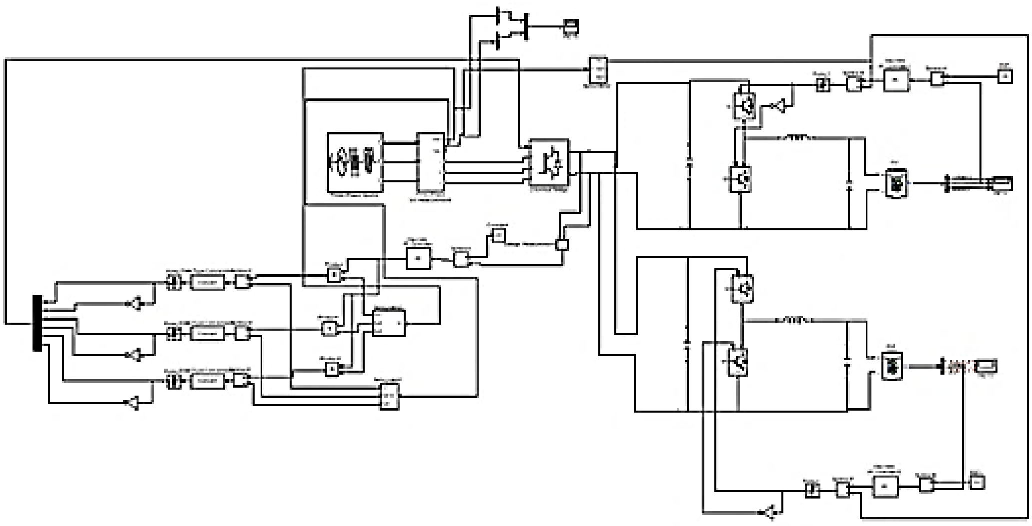

Figure 3. Simulation Diagram G2V Mode

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The 440V grid serves as the primary power source, providing AC electricity to the charging infrastructure. A three-phase VSC acts as the interface between the grid and the EV system, converting AC power to DC and vice versa with high efficiency and controllability. The bidirectional buck boost converter plays a crucial role in managing power flow between the VSC and the lithium-ion battery pack, adjusting voltage and current levels as required by the charging or discharging process. The lithium-ion battery serves as the energy storage device, storing electricity for EV operation and grid interaction. *Figure 4* shows the vehicle to grid mode of operation.

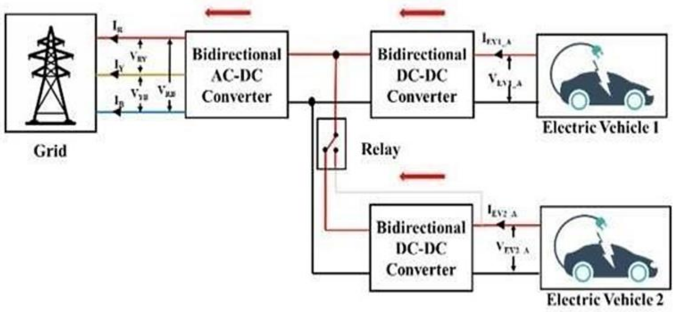

Figure 4. V2G Mode of operation

The 440V grid serves as the primary power source, providing AC electricity to the charging infrastructure. A three-phase VSC acts as the interface between the grid and the EV system, converting power of AC to DC and vice versa with high efficiency and controllability. The bidirectional buck boost converter plays a crucial role in managing power flow between the VSC and the lithium-ion battery pack, adjusting voltage and current levels as required by the charging or discharging process. The lithium-ion battery serves as the energy storage device, storing electricity for EV operation and grid interaction. *Figure 5* shows the voltage, current and state of charge in grid to vehicle and vehicle to grid for EV1.

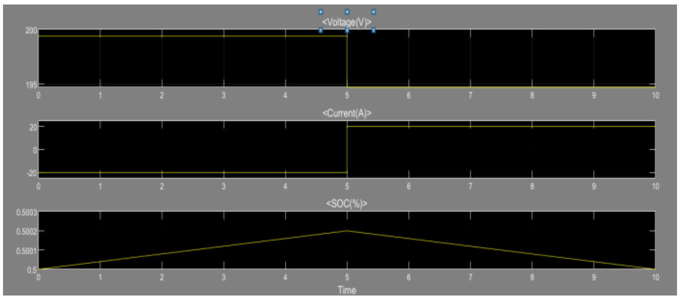

Figure 5. EV1 Battery Voltage, Current and SOC in G2V and V2G

Efficient operation of G2V and V2G modes requires careful control and coordination of power flow between the grid, the VSC, the bidirectional buck boost converter, and the lithium-ion battery. Control algorithms govern the charging and discharging processes, ensuring optimal performance, battery health, and grid compatibility *figure 6*. Simulation Diagram of V2G Mode Additionally, safety measures such as voltage and current monitoring, overcurrent protection, and fault detection are implemented to safeguard the system and its components against potential hazards. Fig 7 shows the voltage, current and state of charge in grid to vehicle and vehicle to grid for EV2.

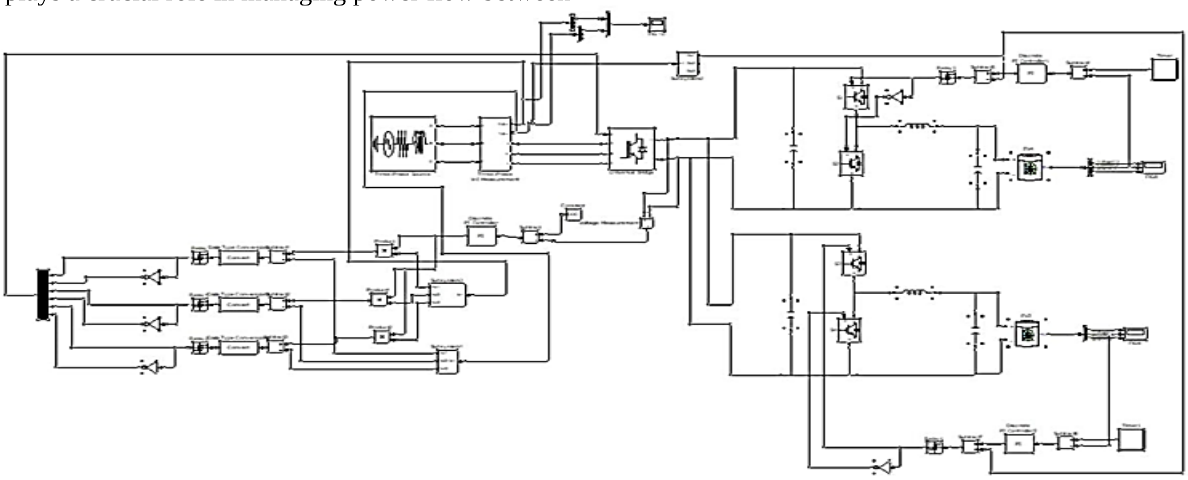

Figure 6. Simulation Diagram of V2G Mode

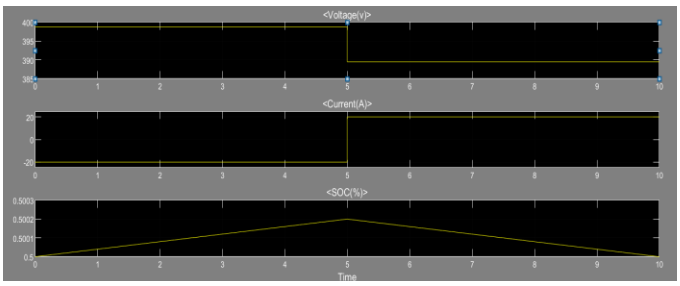

Figure 7. EV2 Battery Voltage, Current and SOC in G2V and V2G

Integration with a 440V grid presents specific challenges and opportunities for G2V and V2G operations. The high voltage level allows for efficient power transmission and distribution, enabling fast charging of EVs and bidirectional power exchange with the grid. However, grid compatibility, voltage regulation, and harmonic mitigation become critical considerations to maintain system stability and meet regulatory requirements. Advanced control strategies and grid synchronization techniques are employed to address these challenges and ensure seamless integration with the grid infrastructure.

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G2V and V2G modes offer numerous benefits to both EV owners and grid operators. G2V mode enables convenient and rapid charging of EVs, extending their driving range and promoting widespread adoption of electric transportation. V2G mode empowers EVs to participate in grid services, enhancing grid flexibility, resilience, and sustainability. Applications include peak load management, renewable energy integration, emergency backup power, and demand response programs, unlocking new revenue streams and cost-saving opportunities for EV owners and utilities alike. *Figure 8* shows the R-phase Voltage and Current in G2V and V2G mode.

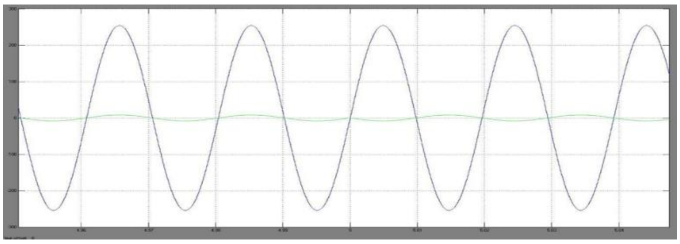

Figure 8. R-phase Voltage and Current in G2V and V2G

G2V and V2G modes play integral roles in modern electric vehicle charging infrastructure, enabling efficient energy transfer between the grid and EVs. Within a 440V grid environment, coupled with a three-phase VSC, bidirectional buck boost converter, and lithium-ion battery system, these modes facilitate rapid charging, grid stabilization, and demand-side management. By harnessing the capabilities of EVs as mobile energy assets, G2V and V2G operations contribute to the advancement of sustainable transportation and smart grid integration, shaping the future of energy and mobility ecosystems.

3.2 G2V and V2V Mode of Operation

The integration of EVs with the electrical grid has catalyzed the development of advanced charging technologies, notably G2V and V2V modes. This exploration examines these charging modes in the context of a 440V grid system, utilizing a three-phase Voltage Source Converter (VSC), a bidirectional buck-boost converter, and a sophisticated lithium-ion battery setup.

G2V Mode: In G2V mode, EVs draw power directly from the grid for charging. The 440V grid serves as the primary energy source, delivering power to the EV through a three-phase VSC. This VSC is crucial in managing the power flow from the grid to the EV, ensuring it aligns with the vehicle's onboard charging requirements. The bidirectional buck-boost converter plays a pivotal role, acting as an intermediary that adjusts the voltage and current to suit the battery's specific needs.

The lithium-ion battery system within the EV stores the energy drawn from the grid. Comprised of multiple lithium-ion cells arranged in series and parallel configurations, it meets the required voltage and capacity. Advanced Battery Management Systems (BMS) meticulously monitor the state of charge (SoC), state of health (SoH), and temperature of the battery pack, guaranteeing safe and efficient charging operations. *Figure 9* shows the block diagram of G2V and V2V Mode of Operation.

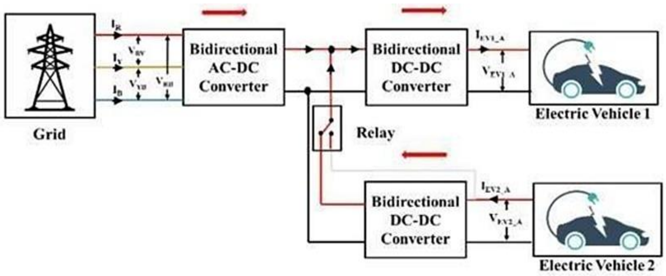

Figure 9. G2V and V2V Mode of Operation

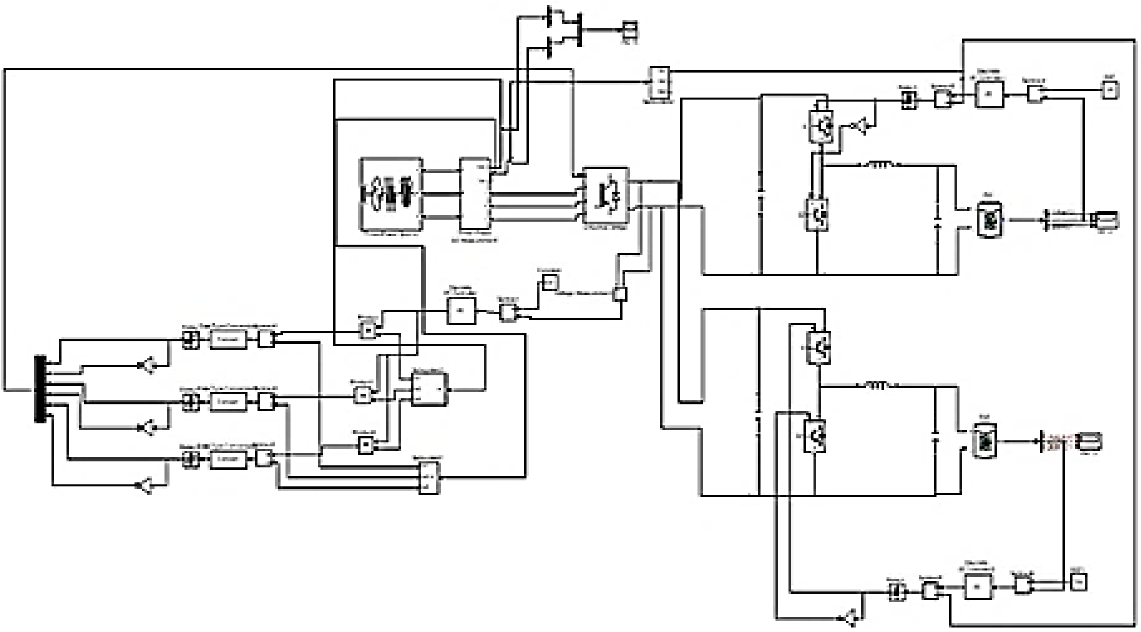

Figure 10. Simulation Diagram of G2V and V2V Mode

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V2V Mode: In V2V mode, EVs have the capability to share power directly with each other. This mode enables peer-to-peer energy transfer between vehicles, allowing one EV to provide energy to another. The VSC and bidirectional buck-boost converter facilitate bidirectional power flow, enabling seamless energy exchange between the participating vehicles. When an EV acts as the donor vehicle, its Li-ion battery discharges energy through the bidirectional buck-boost converter, converting the battery voltage to the required level for transmission. The VSC controls the power flow from the donor vehicle to the recipient vehicle, ensuring efficient energy transfer. Similarly, the recipient vehicle's VSC and buck-boost converter regulate the received power, facilitating charging of its Li-ion battery. *Figure 10* shows the Simulation Diagram of Grid to vehicle and Vehicle to vehicle mode. *Figure 11* shows the voltage, current and SOC of Grid to vehicle and Vehicle to vehicle mode.

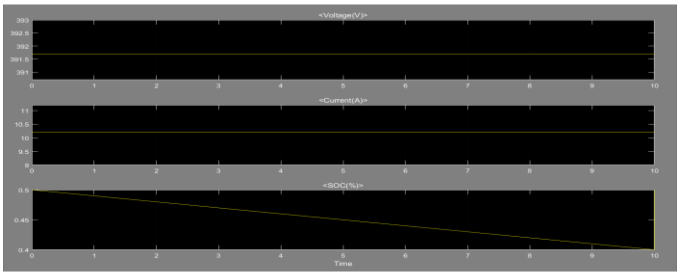

Figure 11. EV1 Battery Voltage, Current and SOC in G2V & V2V

Integration of Components: The successful implementation of G2V and V2V modes relies on the seamless integration of various components, including the grid connection, VSC, bidirectional buck-boost converter, and Li-ion battery system. The 440V grid serves as the primary energy source, with the VSC managing the interface between the grid and the EVs. The bidirectional buck-boost converter ensures voltage compatibility between the grid and the EV battery, enabling efficient power transfer in both directions.

The Li-ion battery system plays a crucial role in storing and distributing energy in both G2V and V2V modes. Its integration with the charging system, including the bidirectional buck-boost converter and BMS, ensures safe and reliable operation during charging and discharging cycles. Additionally, advanced control algorithms and communication protocols facilitate coordination between multiple EVs in V2V mode, optimizing energy transfer efficiency and balancing the load among participating vehicles. *Figure 12* shows EV2 Battery Voltage, Current and SOC in G2V &V2V mode of operation.

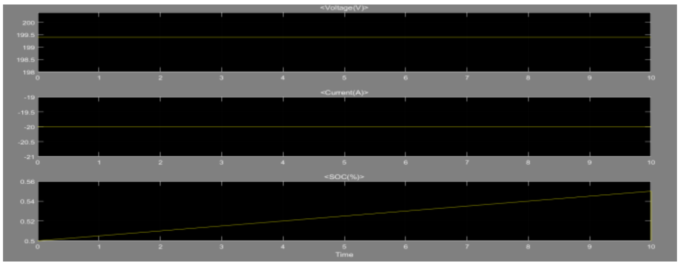

Figure 12. EV2 Battery Voltage, Current and SOC in G2V &V2V

Advantages and Challenges: The adoption of G2V and V2V modes offers several advantages, including enhanced grid flexibility, reduced dependency on centralized charging infrastructure, and improved energy efficiency. By leveraging the existing grid infrastructure, EVs can be charged conveniently and cost-effectively, while also supporting grid stability through V2G capabilities. However, several challenges must be addressed to realize the full potential of these modes. *Figure 13* shows the R-phase Voltage and Current in V2V & G2V.

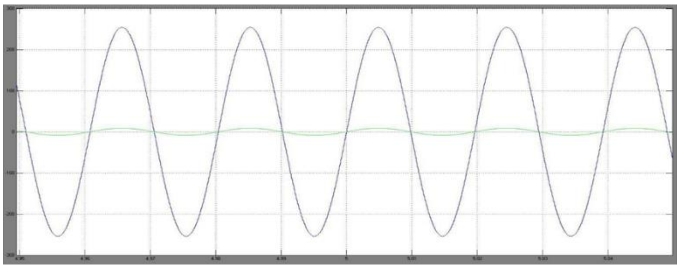

Figure 13. R-phase Voltage and Current in V2V & G2V

The description highlights the operation of G2V and V2V modes in the context of a 440V grid, utilizing a three-phase VSC, bidirectional buck-boost converter, and Li-ion battery system. These modes offer opportunities to optimize EV charging and energy management, supporting the transition towards sustainable transportation systems. Despite the challenges involved, continued research and innovation in this area are essential to unlock the full potential of grid-connected EV charging solutions.

V2V MODE OF OPERATION

The V2V mode of operation represents an innovative approach to electric vehicle (EV) charging, where one EV can share its power with another EV directly as shown in *figure 14*. In this mode, both EVs act as energy sources and sinks, enabling dynamic power exchange between them. This description will focus on V2V operation utilizing a 440V grid, a three- phase VSC, a bidirectional buck-boost converter, and Lithium-Ion (Li-ion) batteries.

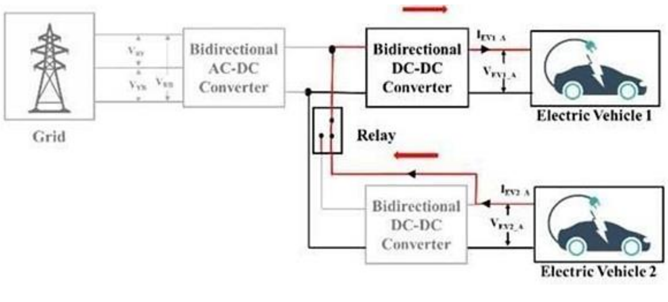

Figure 14. V2V Mode of Operation

V2V mode enables EVs to exchange electrical energy without relying solely on external charging infrastructure. This mode enhances the flexibility and resilience of the EV charging ecosystem by allowing peer-to-peer energy transfer. The 440V grid serves as the primary energy source for the EVs involved in V2V charging. This high-voltage grid facilitates efficient

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power transfer, reducing losses during transmission. By tapping into the 440V grid, EVs can access ample electrical energy for charging and discharging operations. *Figure 15* shows EV1 Battery Voltage, Current and SOC in V2V mode.

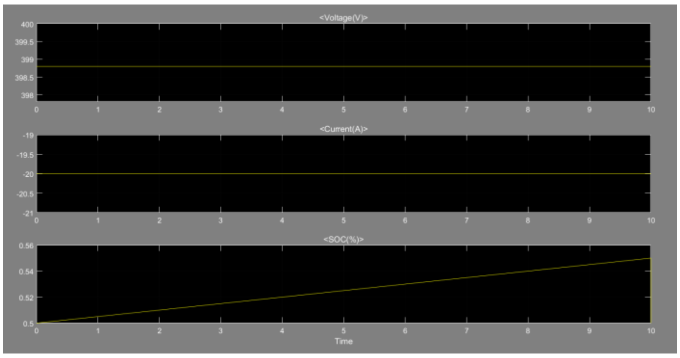

Figure 15. EV1 Battery Voltage, Current and SOC in V2V

The VSC serves as the interface between the 440V grid and the EV's power electronics system. It converts the AC power from the grid into a controllable DC voltage, which can then be utilized by the bidirectional buck-boost converter for charging or discharging the EV's battery. The three-phase configuration ensures balanced power flow and efficient operation, especially in systems with high-power requirements. The bidirectional buck-boost converter plays a crucial role in V2V charging by managing the power flow between the EV's battery and the VSC. *Figure 16* shows the EV2 Battery Voltage, Current and SOC in V2V mode.

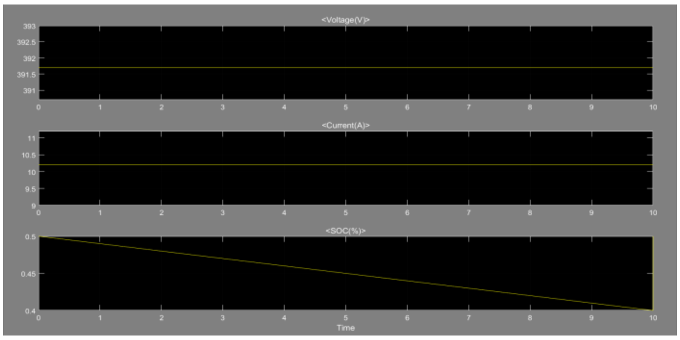

Figure 16. EV2 Battery Voltage, Current and SOC in V2V

During charging, it boosts the voltage from the VSC to match the battery's charging voltage, enabling energy transfer from the grid to the battery. Conversely, during discharging, it regulates the battery voltage to match the requirements of the VSC, allowing energy transfer from the battery to the grid or another EV. The bidirectional nature of the converter ensures flexibility and versatility in V2V operations. Li-ion batteries serve as the energy storage units in EVs, storing electrical energy for propulsion and auxiliary systems. In V2V mode, the Li-ion battery acts as both a source and sink of electrical energy, depending on the charging or discharging operation. The high energy density, fast charging capabilities, and long cycle life of Li-ion batteries make them well-suited for V2V applications, enabling efficient energy exchange between EVs. Effective control and communication systems are essential for coordinating V2V charging operations. The control algorithms govern the power flow between the EV's battery, the bidirectional buck-boost converter, and the VSC, ensuring efficient energy transfer while maintaining system stability and safety. Additionally, communication protocols facilitate data exchange between the EVs involved in V2V charging, enabling negotiation of power transfer parameters and status monitoring. *Figure 17* shows R-phase Voltage and Current in V2V mode.

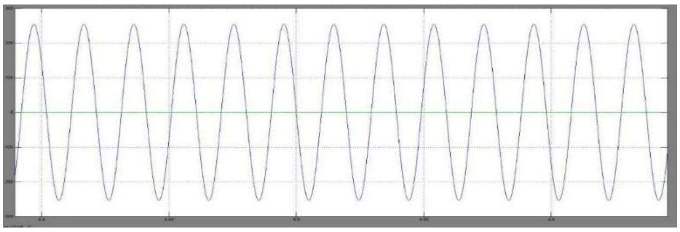

Figure 17. R-phase Voltage and Current in V2V

V2V mode offers several advantages over traditional charging methods. Firstly, it promotes energy sharing and resource optimization, allowing EVs to utilize surplus energy more effectively. Secondly, it reduces reliance on centralized charging infrastructure, enhancing grid resilience and reducing congestion in charging stations. Thirdly, it fosters a sense of community and collaboration among EV owners, encouraging peer-to-peer interactions and mutual support in energy management. Despite its potential benefits, V2V charging poses challenges related to interoperability, safety, and regulatory compliance. Standardization of communication protocols and power interfaces is crucial to ensure compatibility between different EV models and charging systems. Moreover, safety mechanisms must be implemented to prevent overcharging, overheating, or other hazards during V2V operations. Regulatory frameworks may need to evolve to accommodate V2V charging and address issues such as liability, billing, and grid integration. In summary, V2V mode represents a promising approach to EV charging, enabling dynamic energy exchange between vehicles without relying solely on traditional charging infrastructure. By leveraging a 440V grid, a three-phase VSC, a bidirectional buck-boost converter, and Li-ion batteries, V2V charging systems can facilitate efficient energy sharing, enhance grid resilience, and promote community-driven energy management in the electric mobility ecosystem.

4. CONCLUSION

The paper introduces a grid-connected off-board charger capable of versatile charging modes for EVs. In G2V mode, EVs are charged using grid power, while in V2V mode, EVs can share power with each other. Additionally, the system supports V2G mode, allowing EVs to feed power back into the grid. The proposed system also features a combined G2V and V2V mode, utilizing both grid and EV power to charge another EV. Grid voltage and current are regulated to unity power factor (UPF), meeting IEEE 519 standards with less than 5% total harmonic distortion (THD) in all modes except V2V. Moreover, EV charging/discharging occurs at a constant current of 20 A. Simulation of all modes validates the system's power balance.

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