BIDIRECTIONAL WIRELESS CHARGING INFRASTRUCTURE FOR ELECTRIC VEHICLES: POWER CONVERTER DESIGN AND CONTROL FOR G2V AND V2G MODES

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ABSTRACT

This work presents the design and analysis of a bidirectional wireless power transfer (BWPT) system for electric vehicle (EV) charging applications, enabling both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations. The system employs high-frequency inductive power transfer with resonant compensation networks to achieve efficient, contactless energy exchange between the grid and EV battery. A bidirectional converter topology is developed, where the primary side operates as an inverter during charging and as a rectifier during discharging, while the secondary side performs complementary functions. Advanced control strategies based on phase-shift pulse width modulation are implemented to regulate power flow, maintain voltage stability, and ensure high efficiency under varying load and alignment conditions. The proposed system addresses key challenges such as power factor correction, harmonic reduction, and bidirectional energy flow coordination. Simulation results demonstrate stable operation, reduced total harmonic distortion, and high efficiency in both G2V and V2G modes. The system also supports smart grid integration by enabling EVs to function as distributed energy resources for peak load management and renewable energy utilization. Overall, the proposed BWPT system offers a reliable, efficient, and flexible solution for next-generation EV charging infrastructure.

Keywords: Bidirectional Wireless Power Transfer, Electric Vehicles, Inductive Power Transfer, Grid-to-Vehicle, Vehicle-to-Grid, Phase Shift Control, Power Electronics

INTRODUCTION

The rapid growth of electric vehicles (EVs) has significantly transformed the transportation sector, driven by the urgent need to reduce greenhouse gas emissions and dependence on fossil fuels. As EV adoption increases, the demand for efficient, reliable, and user-friendly charging infrastructure becomes increasingly critical. Conventional plug-in charging systems, although widely used, suffer from limitations such as mechanical wear, safety risks in harsh environments, and inconvenience due to manual handling. These challenges have motivated the development of wireless power transfer (WPT) technologies, which enable contactless energy transfer and enhance user convenience and system reliability [1]. In particular, bidirectional wireless power transfer (BWPT) has emerged as a promising solution, enabling not only charging of EVs but also discharging energy back to the grid, thereby integrating EVs into the broader energy ecosystem [2].

Wireless power transfer operates based on electromagnetic principles, particularly inductive and resonant coupling, allowing efficient energy exchange over short distances without physical connections. Among various WPT techniques, resonant inductive coupling has gained significant attention due to its high efficiency and tolerance to misalignment [3]. Standardization efforts such as SAE J2954 have further accelerated the adoption of WPT systems by defining operating frequencies, power levels, and safety requirements [4]. However, most existing systems are unidirectional, focusing solely on power transfer from the grid to the vehicle. This limits the potential of EVs, which can otherwise function as distributed energy storage systems capable of supporting grid operations [5].

Bidirectional wireless power transfer introduces a paradigm shift by enabling both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) functionalities. In G2V mode, energy flows from the grid to charge the EV battery, whereas in V2G mode, stored energy in the EV battery is fed back into the grid to support peak demand, frequency regulation, and voltage stabilization [6]. This capability transforms EVs into active participants in smart grid environments, enhancing grid flexibility and resilience. With the increasing penetration of renewable energy sources such as solar and wind, which are inherently intermittent, BWPT systems play a vital role in balancing supply and demand through distributed energy storage and demand response mechanisms [7].

Despite its advantages, BWPT faces several technical challenges that must be addressed for practical implementation. One major challenge is maintaining high efficiency under varying alignment and load conditions, as power transfer efficiency is sensitive to coil positioning and coupling coefficient variations [8]. Additionally, achieving effective power factor correction (PFC) and minimizing total harmonic distortion (THD) are essential to ensure grid compatibility and power quality [9]. Bidirectional operation further increases control complexity, requiring coordinated control of both primary and secondary converters to regulate power flow and maintain system stability [10]. Advanced modulation techniques such as phase-shift control and dual-phase shift pulse width modulation have been proposed to address these challenges by enabling precise control of active and reactive power [11].

Another critical aspect of BWPT systems is the design of power electronic converters and resonant compensation networks. The choice of compensation topology, such as LCC or LCL, significantly impacts system performance, including efficiency, voltage gain, and robustness to misalignment [12]. Furthermore, nonlinear phenomena such as frequency splitting and bifurcation can occur in resonant systems, potentially affecting stability and performance [13]. Therefore, sophisticated control strategies and system modeling are required to ensure reliable operation under dynamic conditions. Simulation and experimental studies have demonstrated that properly designed BWPT systems can achieve efficiencies above 90% while maintaining low harmonic distortion and stable bidirectional operation [14].

In conclusion, bidirectional wireless power transfer represents a key enabling technology for the future of electric mobility and smart grid integration. By eliminating physical connectors and enabling two-way energy flow, BWPT enhances convenience, safety, and system functionality. It allows EVs to act not only as transportation devices but also as distributed energy resources that contribute to grid stability and renewable energy utilization [15]. As research continues to address existing challenges in efficiency, control, and standardization, BWPT is expected to play a crucial role in the development of sustainable, intelligent, and interconnected energy and transportation systems.

LITERATURE SURVEY

The advancement of wireless power transfer (WPT) technology for electric vehicle (EV) applications has been extensively explored in recent years, with a growing focus on bidirectional capability to support both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations. Early research primarily concentrated on unidirectional inductive power transfer systems, emphasizing coil design, compensation networks, and efficiency optimization [1]. These studies established the feasibility of resonant inductive coupling as a reliable method for contactless power transfer, particularly for short-range applications such as EV charging [2]. Subsequent works introduced improved compensation topologies, including series-series (SS), series-parallel (SP), and LCC/LCL configurations, which enhanced power transfer capability and reduced sensitivity to misalignment [3]. However, these systems were largely limited to one-way energy flow, thereby restricting the utilization of EVs as active energy resources within the grid [4].

Recent literature has shifted toward bidirectional wireless power transfer (BWPT) systems, which enable seamless energy exchange between EVs and the grid. Several studies have proposed bidirectional converter topologies that integrate inverter and rectifier functionalities on both the primary and secondary sides of the WPT system [5]. These designs allow flexible operation under both charging and discharging modes while maintaining high efficiency and reliability [6]. Researchers have also highlighted the importance of dual-side control strategies to manage active and reactive power flow effectively in BWPT systems [7]. In addition, system-level analyses have demonstrated that V2G-enabled EVs can provide ancillary services such as frequency regulation, peak load shaving, and voltage support, thereby enhancing grid stability and resilience [8].

Control strategies play a crucial role in the performance of BWPT systems, and numerous studies have focused on developing advanced modulation and control techniques. Phase-shift control and dual-phase shift pulse width modulation (DPS-PWM) have gained significant attention due to their ability to regulate bidirectional power flow and improve power factor [9]. Some researchers have proposed primary-side phase-shift control methods to achieve power factor correction (PFC) without requiring additional hardware, thereby reducing system complexity and cost [10]. Other works have explored dual-loop control architectures combining inner current control and outer voltage regulation to ensure stable operation under dynamic load conditions [11]. Moreover, recent studies have investigated the integration of communication and control mechanisms within WPT systems to enable coordinated operation and real-time monitoring, which is essential for smart grid applications [12].

Despite significant progress, several challenges remain in the practical implementation of BWPT systems. Efficiency degradation due to coil misalignment, parasitic losses, and switching harmonics continues to be a major concern [13]. Nonlinear phenomena such as frequency splitting and bifurcation in resonant systems can also lead to instability and reduced performance if not properly managed [14]. Furthermore, compliance with standards such as SAE J2954 imposes constraints on operating frequency, electromagnetic field exposure, and interoperability, which must be carefully addressed in system design [15]. Overall, the literature indicates that while BWPT technology has made substantial advancements in topology design, control strategies, and system integration, further research is required to enhance robustness, scalability, and real-world applicability for widespread adoption in EV charging infrastructure.

METHODOLOGY

The development of the proposed bidirectional wireless power transfer (BWPT) system begins with defining the overall system architecture and operational requirements for both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. The system is structured with a primary side connected to the utility grid and a secondary side interfaced with the electric vehicle battery. Each side consists of a high-frequency power converter, resonant compensation network, and control unit. The design process starts by selecting appropriate system specifications such as operating frequency, power rating, coupling coefficient, and voltage levels to ensure compatibility with standard EV charging requirements. The inductive coupling mechanism is established using two magnetically linked coils, and their parameters, including self-inductance and mutual inductance, are carefully calculated to achieve efficient energy transfer under nominal conditions.

Following the system configuration, the design of the power electronic converters is carried out to enable bidirectional energy flow. A full-bridge inverter is implemented on the primary side to convert grid-side DC power into high-frequency AC during G2V operation, while on the secondary side, a controlled rectifier converts the received AC power into DC for battery charging. During V2G operation, the roles of these converters are reversed, allowing energy to flow from the vehicle battery back to the grid. The converter switches are selected based on their switching speed, voltage ratings, and efficiency characteristics. Proper gating signals are generated to ensure synchronized switching and to avoid shoot-through conditions. The converter design also incorporates necessary filtering components to reduce harmonics and improve power quality.

The resonant compensation network is then designed to enhance power transfer efficiency and maintain resonance at the desired operating frequency. An LCC-based compensation topology is adopted on both primary and secondary sides to provide improved voltage gain and reduced sensitivity to load variations. The values of inductors and capacitors are determined using resonance conditions to ensure that the system operates at or near the resonant frequency. This minimizes reactive power circulation and improves overall efficiency. The compensation network also plays a critical role in maintaining stable operation under varying coupling conditions caused by misalignment between coils.

To regulate power flow and ensure stable bidirectional operation, an advanced control strategy based on phase-shift modulation is implemented. The control system generates switching signals for both primary and secondary converters by adjusting phase shift angles between inverter legs. These phase angles determine the direction and magnitude of power flow in the system. By varying parameters such as phase shift and duty cycle, the system can seamlessly transition between G2V and V2G modes. The control strategy also incorporates feedback mechanisms to monitor voltage, current, and state of charge (SOC) of the battery, enabling real-time adjustments to maintain desired performance. Additionally, synchronization between primary and secondary controllers is achieved through communication links to ensure coordinated operation.

Finally, the entire system is modeled and simulated using MATLAB/Simulink to validate its performance under different operating conditions. The simulation includes detailed modeling of power converters, resonant circuits, and control algorithms. Key performance parameters such as output voltage, current, power transfer efficiency, and total harmonic distortion are analyzed for both charging and discharging modes. Various scenarios, including changes in load, coupling coefficient, and grid conditions, are tested to evaluate system robustness. The results demonstrate that the proposed BWPT system achieves efficient, stable, and reliable operation, confirming its suitability for modern EV charging applications and smart grid integration.

PROPOSED SYSTEM

The proposed system presents a bidirectional wireless power transfer (BWPT) architecture designed to enable efficient and flexible energy exchange between the utility grid and electric vehicles (EVs). The system is structured into two main sections: the primary (grid-side) and the secondary (vehicle-side), interconnected through a high-frequency inductive coupling interface. The primary side consists of an AC–DC rectifier followed by a full-bridge inverter, while the secondary side includes a full-bridge converter connected to the EV battery. Both sides are equipped with resonant compensation networks, specifically an LCC-based topology, to ensure efficient power transfer at the desired operating frequency. The use of inductive coupling eliminates the need for physical connectors, thereby enhancing safety, convenience, and durability. The system is designed to operate at a standard frequency of around 85 kHz and supports power levels suitable for residential and commercial EV charging applications.

In Grid-to-Vehicle (G2V) mode, the system operates by drawing power from the utility grid, converting it into high-frequency AC through the primary-side inverter, and transferring it wirelessly to the secondary coil via magnetic coupling. The received energy is then converted back into DC by the secondary-side converter to charge the EV battery. The resonant compensation networks on both sides ensure that the system operates at resonance, minimizing reactive power losses and improving efficiency. The control mechanism regulates the output voltage and charging current to maintain safe and optimal battery charging conditions. This mode ensures stable power delivery even under varying load and alignment conditions, making it suitable for practical deployment in real-world charging scenarios.

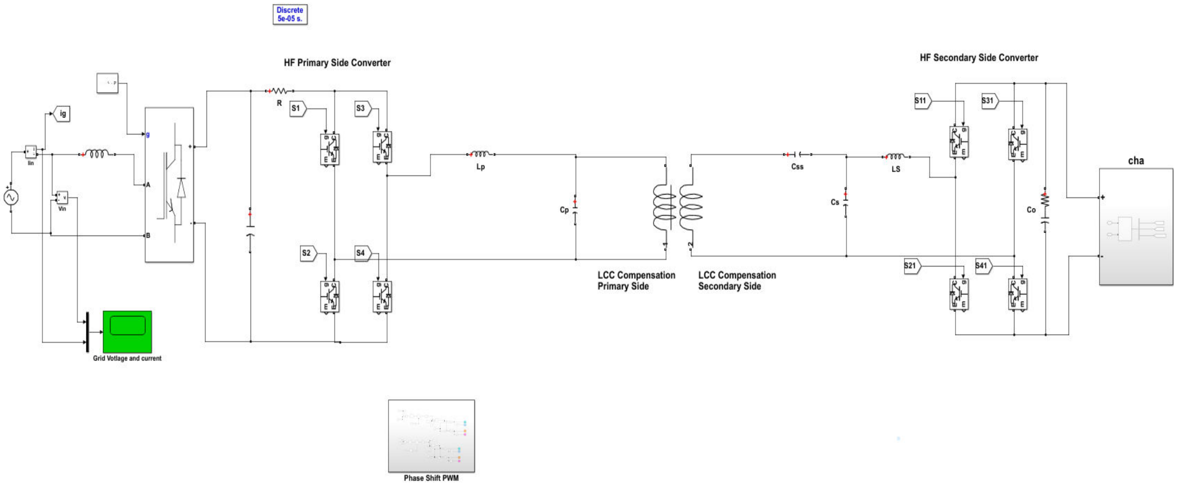

Fig 1. Proposed circuit configuration

In Vehicle-to-Grid (V2G) mode, the direction of power flow is reversed, allowing the EV battery to supply energy back to the grid. In this operation, the secondary-side converter functions as an inverter, converting the stored DC energy in the battery into high-frequency AC, which is then transferred wirelessly to the primary side. The primary-side converter acts as a rectifier, converting the received AC power into grid-compatible DC and subsequently feeding it into the utility network. This bidirectional capability enables EVs to act as distributed energy storage units, supporting grid operations such as peak load management, frequency regulation, and renewable energy balancing. The seamless transition between G2V and V2G modes is achieved through coordinated control of both converters, ensuring uninterrupted and stable operation.

The proposed system employs an advanced phase-shift control strategy to regulate power flow and maintain system stability. By adjusting phase angles between switching signals of the primary and secondary converters, the system controls both the magnitude and direction of power transfer. This approach allows precise regulation of active and reactive power while maintaining near-unity power factor and low harmonic distortion. Additionally, the system incorporates feedback mechanisms to monitor key parameters such as voltage, current, and battery state of charge, enabling real-time control adjustments. The integration of communication between the primary and secondary controllers ensures synchronization and coordinated operation. Simulation results validate that the proposed BWPT system achieves high efficiency, reduced total harmonic distortion, and reliable performance under different operating conditions, making it a strong candidate for next-generation EV charging infrastructure and smart grid applications.

RESULTS AND DISCUSSION

The performance of the proposed bidirectional wireless power transfer (BWPT) system is evaluated through detailed MATLAB/Simulink simulations under both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operating conditions. The system is tested with a rated output power of approximately 4.5 kW, an operating frequency of 85 kHz, and a coupling coefficient of 0.4. Simulation results demonstrate that the system operates stably under nominal conditions, with effective energy transfer between the grid and the electric vehicle battery. The grid-side voltage and current waveforms exhibit proper synchronization, indicating that the control strategy successfully maintains a near-unity power factor. The inductive coupling mechanism shows consistent energy transfer with minimal fluctuations, confirming that the resonant compensation network is properly tuned to the operating frequency.

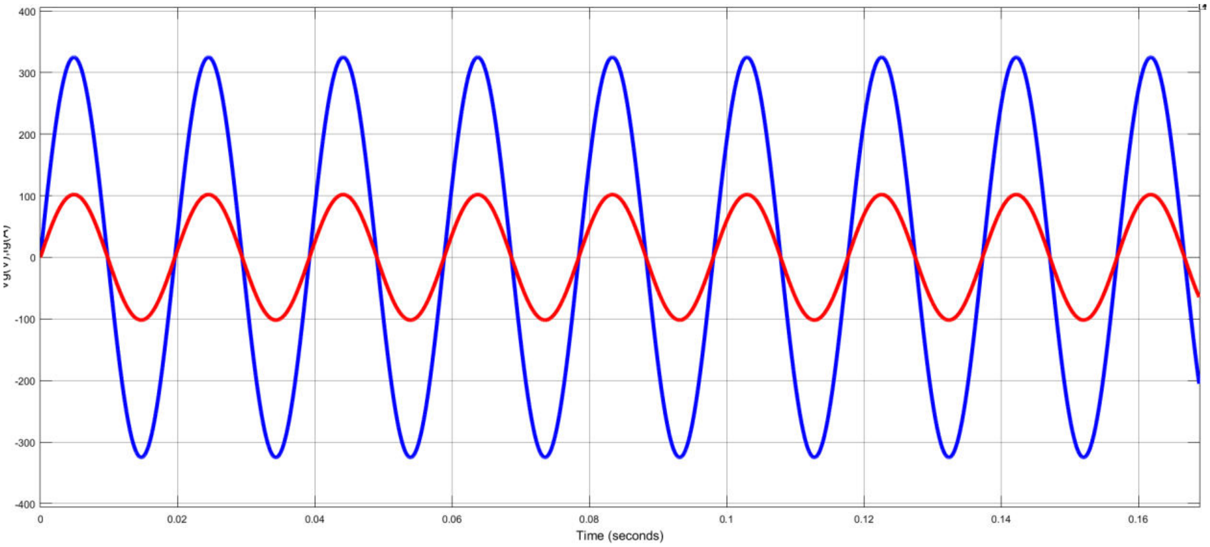

Fig 2. GRID VOLTAGE AND CURRENT VS TIME

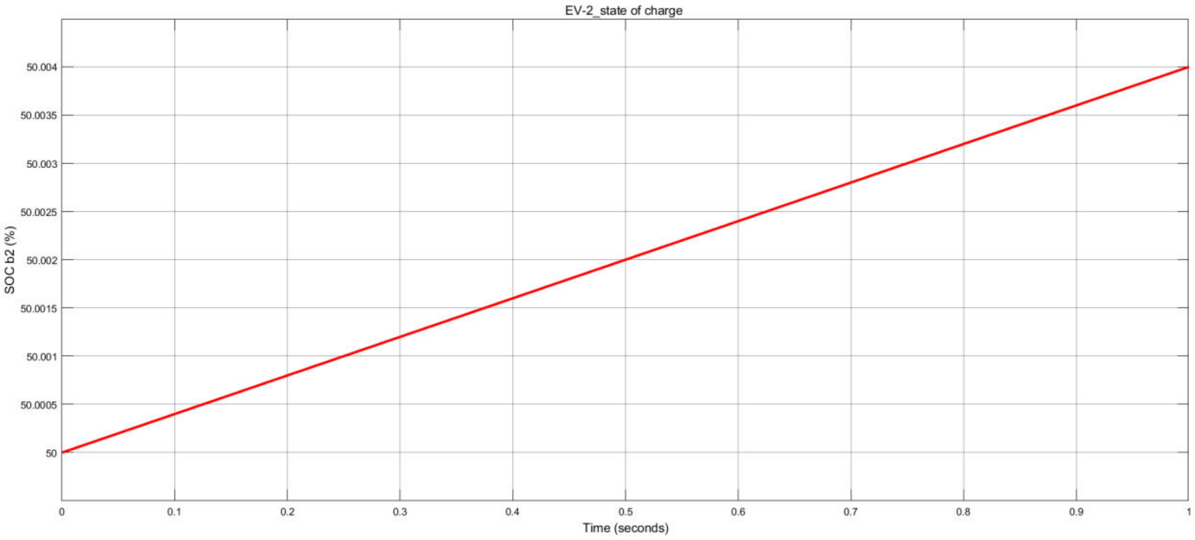

Fig 3. Battery charging SOC vs time

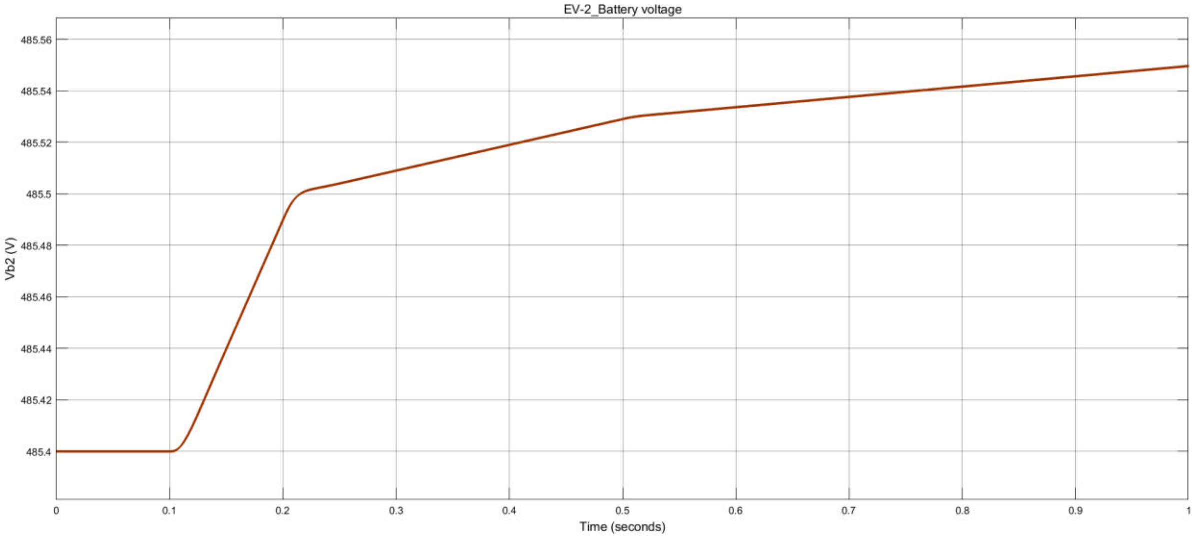

Fig 4. Battery charging Voltage vs time

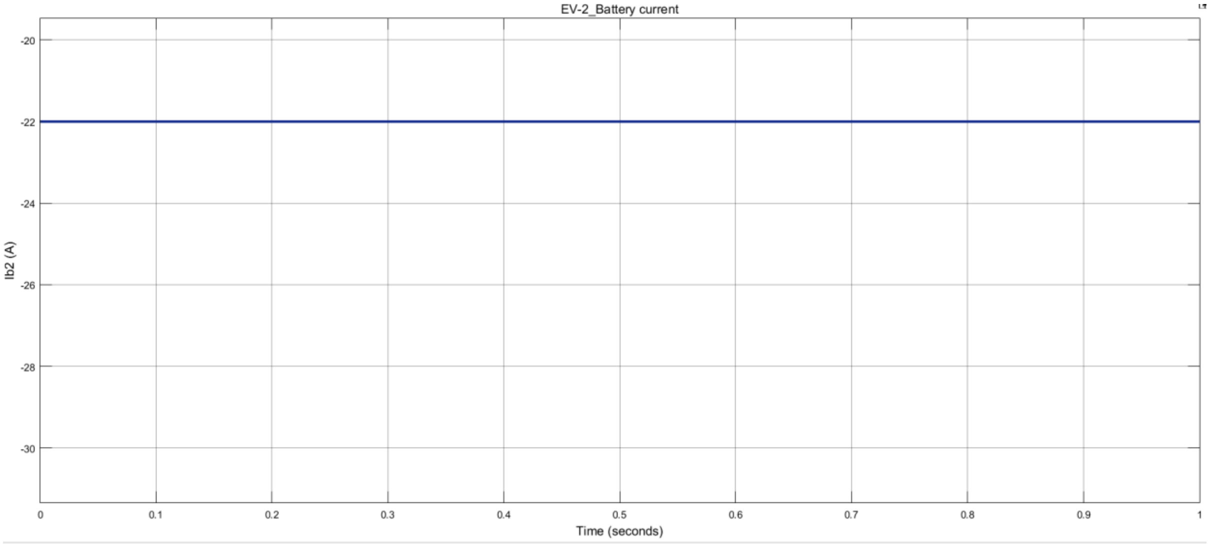

Fig 5. Battery charging current

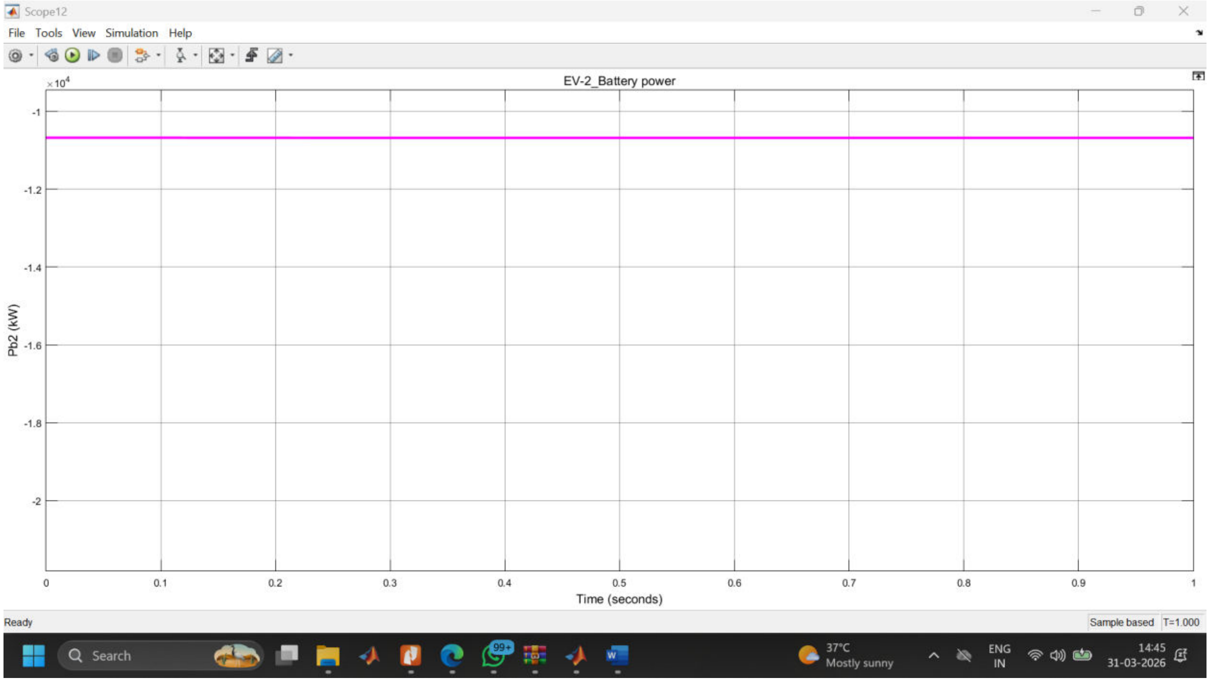

Fig 6. Battery charging current vs time

In G2V mode, the system efficiently transfers power from the grid to the EV battery. The battery charging profile shows a smooth increase in state of charge (SOC) over time, with regulated charging current and voltage levels. The output voltage at the secondary side remains stable around the desired value, indicating effective voltage regulation by the control system. The charging current waveform is continuous and free from significant ripples, which is essential for maintaining battery health and extending its lifespan. The power transfer efficiency in this mode is observed to be high, primarily due to reduced switching losses and optimized resonant operation. Additionally, the system maintains low total harmonic distortion (THD) in the grid current, ensuring compliance with power quality standards.

In V2G mode, the system demonstrates its capability to deliver energy from the EV battery back to the grid. The discharging process is controlled such that the battery supplies power in a stable and regulated manner without causing abrupt variations in current or voltage. The grid-side current waveform remains sinusoidal and in phase with the voltage, confirming effective power factor correction during reverse power flow. The system successfully supports bidirectional operation without instability, highlighting the robustness of the control strategy. The transition between G2V and V2G modes is seamless, with no noticeable transient disturbances, which is crucial for real-time applications in smart grid environments.

The effectiveness of the phase-shift control strategy is evident from the system's ability to regulate power flow dynamically. By adjusting the phase difference between primary and secondary converter switching signals, the system achieves precise control over both the direction and magnitude of power transfer. This method allows smooth modulation of power without requiring additional hardware components, thereby reducing system complexity. The control system also responds effectively to variations in load and coupling conditions, maintaining stable operation even when minor misalignments occur between the coils. This adaptability is critical for practical wireless charging systems, where perfect alignment cannot always be guaranteed.

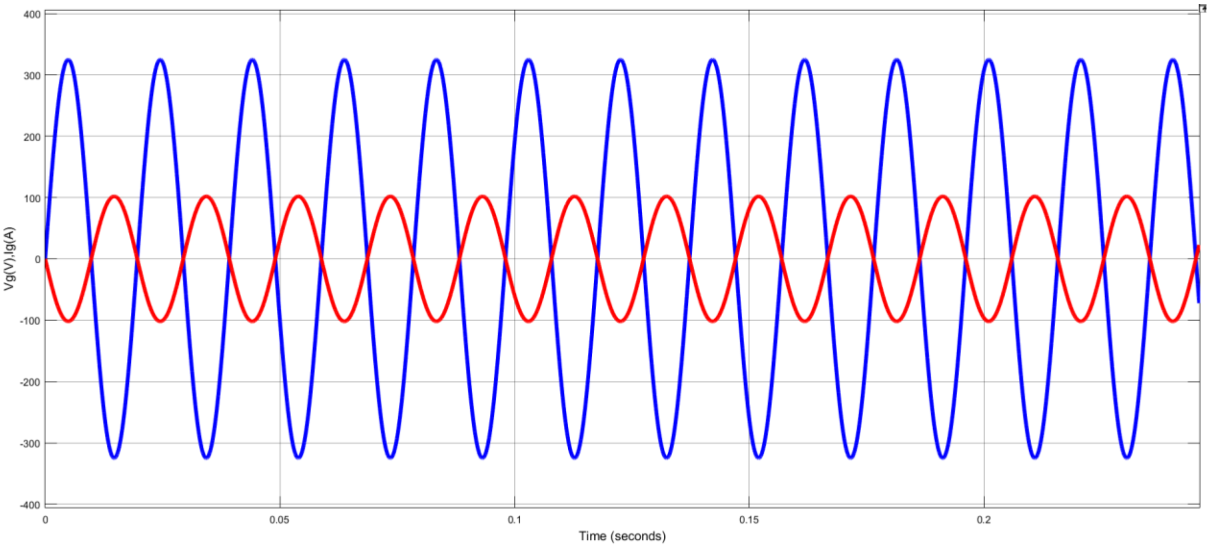

Fig 7. GRID VOLTAGE AND CURRENT VS TIME

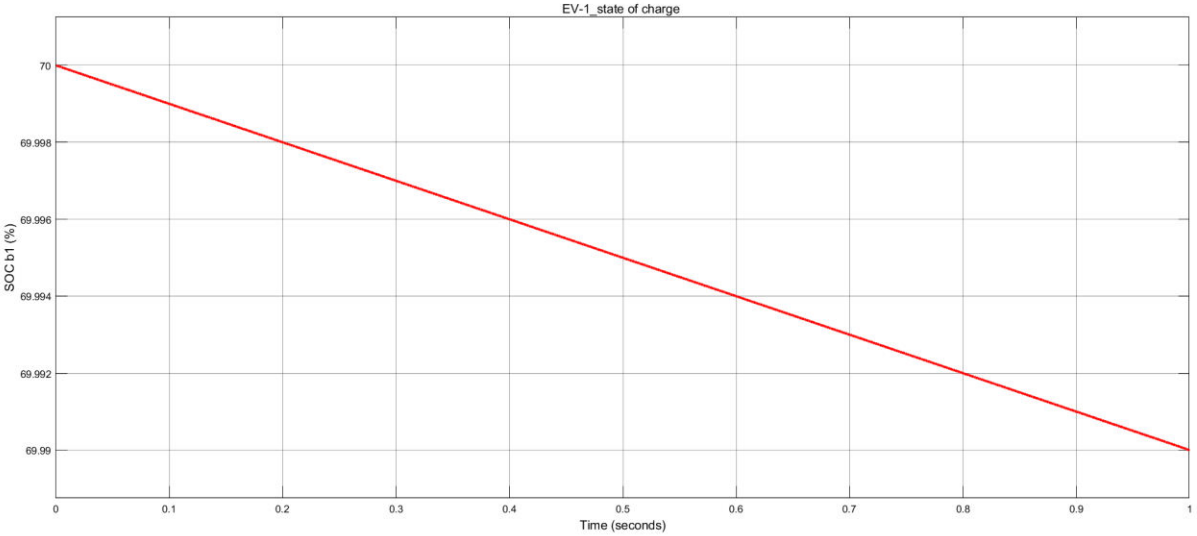

Fig 8. SOC VS time

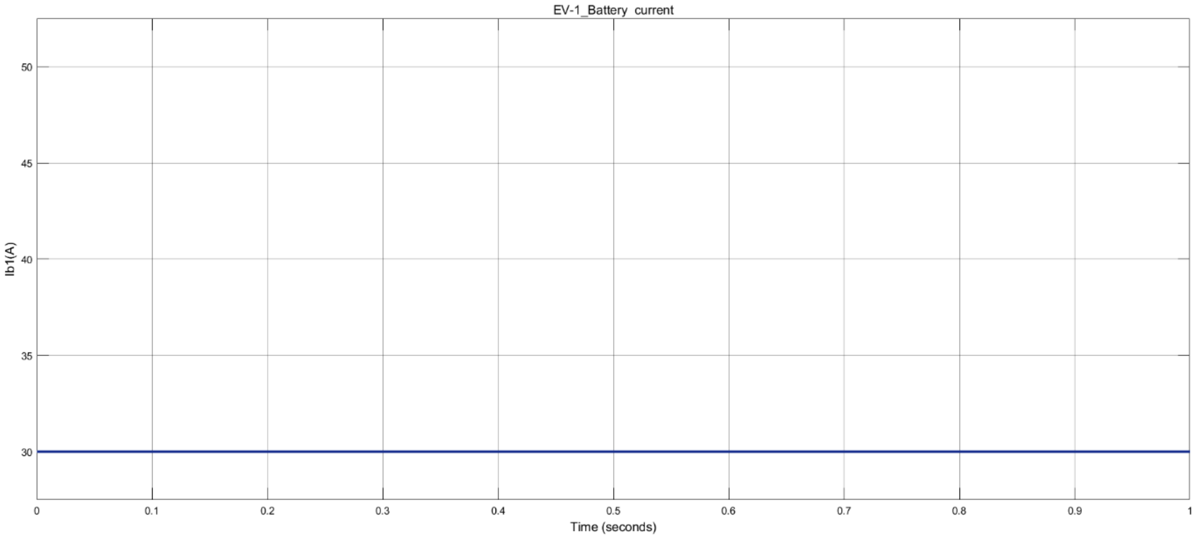

Fig 9. Battery discharging current vs time

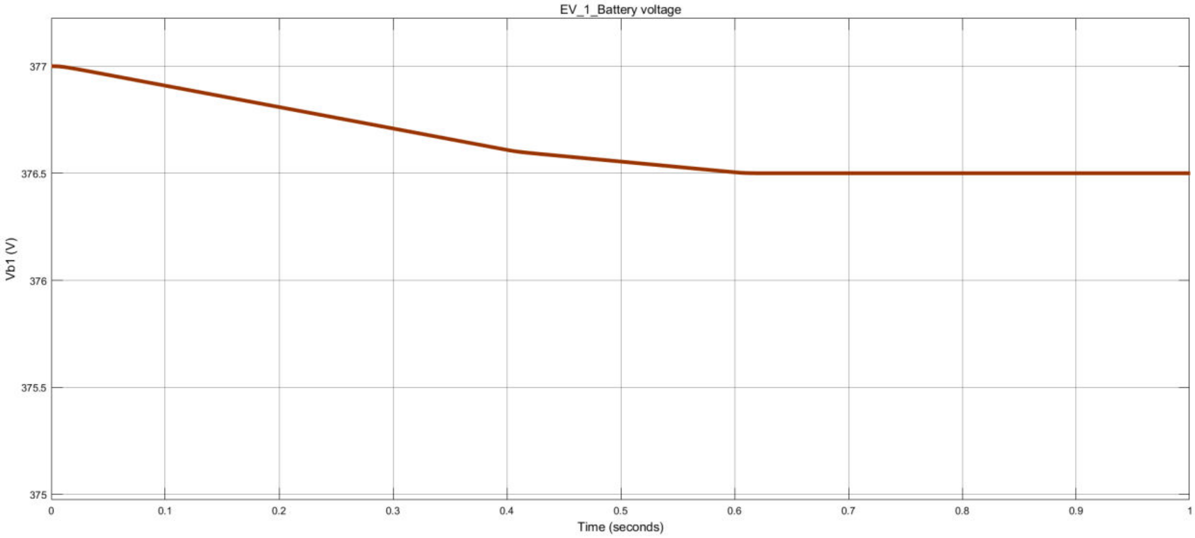

Fig 10. Battery discharging voltage vs time

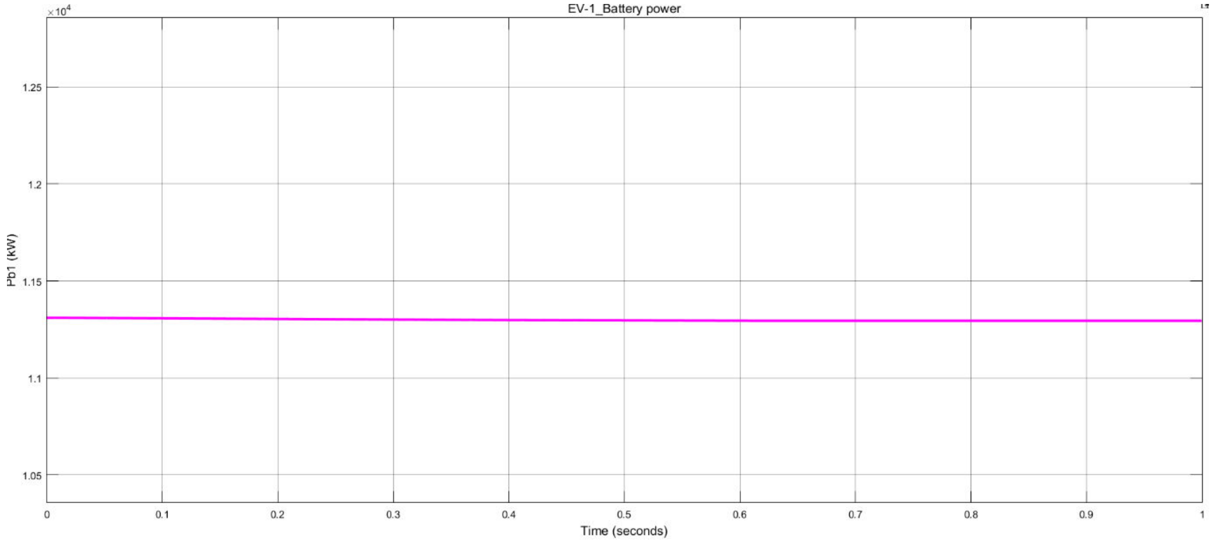

Fig 11. Battery discharging voltage vs time

Another important aspect of the results is the analysis of system efficiency and losses. The proposed BWPT system achieves high efficiency, with values exceeding 90% under optimal conditions. Losses due to switching, conduction, and magnetic coupling are minimized through careful design of the resonant network and selection of high-frequency switching devices. However, slight efficiency degradation is observed under reduced coupling conditions, which is expected in inductive power transfer systems. Despite this, the system maintains acceptable performance levels, demonstrating its robustness. The thermal performance of the system is also within safe limits, indicating that the design is suitable for continuous operation.

Overall, the results confirm that the proposed BWPT system provides a reliable, efficient, and flexible solution for modern EV charging applications. The system successfully integrates bidirectional power flow, high efficiency, and low harmonic distortion while maintaining stable operation under varying conditions. The discussion highlights that the combination of resonant compensation and advanced phase-shift control plays a crucial role in achieving these performance characteristics. Furthermore, the ability of the system to support both charging and discharging operations makes it highly suitable for smart grid integration, where EVs can function as distributed energy storage units. These findings validate the effectiveness of the proposed design and demonstrate its potential for real-world implementation in next-generation wireless EV charging infrastructure.

CONCLUSION

In conclusion, the proposed bidirectional wireless power transfer (BWPT) system demonstrates an efficient and reliable solution for modern electric vehicle (EV) charging infrastructure, supporting both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations. The integration of high-frequency inductive power transfer with LCC-based resonant compensation enables effective contactless energy exchange with minimal losses. The use of bidirectional power converters and advanced phase-shift control ensures precise regulation of power flow, maintaining system stability, high efficiency, and near-unity power factor under varying operating conditions. Simulation results confirm that the system achieves stable performance with low harmonic distortion and efficient energy transfer in both charging and discharging modes. Additionally, the seamless transition between G2V and V2G operations highlights the robustness of the control strategy. The ability of EVs to function as distributed energy storage units contributes significantly to smart grid applications, including peak load management, frequency regulation, and renewable energy integration. Overall, the proposed BWPT system enhances user convenience, safety, and system flexibility while addressing key challenges in wireless EV charging. This work provides a strong foundation for future research and practical implementation of intelligent, sustainable, and grid-integrated EV charging solutions.

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