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A NOVEL INTEGRATED WIRELESS CHARGING RECEIVER WITH DUAL INVERTER DRIVES FOR EV APPLICATIONS

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ABSTRACT

This study presents an advanced wireless charging system for electric vehicle (EV) applications by integrating a Fractional-Order Proportional-Integral-Derivative (FOPID) controller with a dual inverter drive configuration. Wireless Power Transfer (WPT) technology offers a contactless, safe, and convenient alternative to conventional plug-in charging; however, it suffers from challenges such as coil misalignment, load variations, and reduced efficiency under dynamic conditions. To overcome these limitations, the proposed system replaces the conventional PI controller with a FOPID controller, which introduces fractional-order tuning parameters for improved flexibility and control precision. The system is modeled and simulated using MATLAB/Simulink with a target output voltage of 360 V suitable for EV battery charging. The dual inverter architecture enhances power handling capability, ensures better load distribution, and improves overall system reliability. Simulation results demonstrate that the proposed system achieves faster dynamic response, reduced overshoot, minimal steady-state error, and significantly lower ripple compared to traditional methods. Additionally, the system exhibits strong robustness against coupling variations and coil misalignment, ensuring stable performance under practical operating conditions. Although the FOPID controller introduces slight computational complexity, its superior adaptability and efficiency make it a promising solution for next-generation wireless EV charging systems.

Keywords: Wireless Power Transfer, Electric Vehicle Charging, FOPID Controller, Dual Inverter, Voltage Regulation, System Stability, MATLAB Simulation

INTRODUCTION

The rapid growth of electric vehicles (EVs) has become a significant milestone in the global transition toward sustainable and eco-friendly transportation systems. Increasing concerns over greenhouse gas emissions, fossil fuel depletion, and environmental degradation have accelerated the adoption of EV technology worldwide. Governments and industries are actively promoting EV deployment through policy support, incentives, and infrastructure development. However, the efficiency and practicality of EV usage heavily depend on the availability of reliable and user-friendly charging systems. Conventional plug-in charging methods, although widely used, present several challenges such as physical wear of connectors, safety risks, and inconvenience in operation, particularly in adverse environmental conditions. These limitations have led to the emergence of wireless power transfer (WPT) technology as a promising alternative for EV charging applications, enabling contactless energy transfer and improved user convenience [1], [2], [3].

Wireless power transfer systems operate based on inductive coupling between transmitter and receiver coils, where electrical energy is transferred through a magnetic field without direct electrical contact. This technology eliminates the need for physical connectors, thereby reducing maintenance requirements and enhancing operational safety. In EV charging applications, WPT enables seamless energy transfer in both stationary and dynamic conditions, making it highly suitable for modern transportation systems. However, despite its advantages, WPT systems face several technical challenges, including sensitivity to coil misalignment, variations in coupling coefficient, and fluctuating load conditions. These factors significantly impact power transfer efficiency and system stability, leading to voltage fluctuations and reduced performance. Therefore, designing robust and efficient control strategies becomes essential to ensure consistent and reliable operation of wireless EV charging systems [4], [5], [6].

Control systems play a critical role in maintaining stable output voltage and ensuring efficient power transfer in wireless charging systems. Traditionally, proportional-integral (PI) controllers have been widely used due to their simplicity and ease of implementation. These controllers are effective for linear systems operating under steady-state conditions; however, their performance deteriorates in nonlinear and dynamic environments such as wireless EV charging systems. Issues such as high overshoot, longer settling time, steady-state error, and increased ripple content are commonly observed with PI controllers under varying operating conditions. These limitations highlight the need for advanced control strategies capable of handling system nonlinearities and uncertainties more effectively. Researchers have explored several alternative control techniques, including fuzzy logic, sliding mode control, and model predictive control, each offering certain advantages but often at the cost of increased complexity [7], [8], [9], [10].

Among the advanced control techniques, the fractional-order proportional-integral-derivative (FOPID) controller has gained significant attention due to its superior flexibility and enhanced performance characteristics. Unlike conventional PID controllers, the FOPID controller incorporates fractional calculus, allowing non-integer order integration and differentiation. This additional degree of freedom provides greater tuning flexibility, enabling precise control over system dynamics. As a result, FOPID controllers offer improved transient response, reduced overshoot, minimized steady-state error, and enhanced robustness against disturbances and parameter variations. These features make FOPID particularly suitable for wireless EV charging systems, where operating conditions are highly dynamic and unpredictable. The ability of FOPID controllers to adapt to changes in system parameters significantly improves overall performance and reliability [11], [12], [13].

In addition to advanced control strategies, the power conversion architecture plays a crucial role in determining the efficiency and performance of wireless charging systems. Conventional systems typically employ a single inverter configuration, which may limit power handling capability and flexibility. To address these limitations, dual inverter drive configurations have been proposed, offering improved power distribution, enhanced efficiency, and better control over energy flow. By integrating a FOPID controller with a dual inverter architecture, the proposed system aims to achieve superior performance in terms of voltage regulation, dynamic response, efficiency, and robustness. This integrated approach provides a comprehensive solution to the challenges associated with wireless EV charging systems, paving the way for the development of reliable and high-performance charging infrastructure for future electric mobility applications [14], [15].

LITERATURE SURVEY

The development of wireless power transfer (WPT) technology for electric vehicle (EV) charging has attracted significant research attention due to its potential to eliminate physical connectors and enhance user convenience. Early studies primarily focused on inductive coupling mechanisms, where energy is transferred between transmitter and receiver coils through a magnetic field. These foundational works established the feasibility of contactless power transfer and demonstrated its advantages in terms of safety, reduced maintenance, and operational flexibility. Researchers further explored resonant inductive coupling techniques to improve power transfer efficiency and extend transmission distance. The growing demand for EVs has accelerated advancements in WPT systems, with emphasis on achieving high efficiency, reliability, and scalability for real-world applications. Despite these developments, challenges related to power losses, electromagnetic interference, and system integration continue to be areas of active research [1], [2], [3].

Significant efforts have been directed toward improving coil design and compensation topologies to enhance the performance of wireless charging systems. Various coil geometries, such as circular, rectangular, and double-D configurations, have been investigated to optimize magnetic coupling and reduce leakage flux. Compensation networks, including series-series (SS), series-parallel (SP), and parallel-parallel (PP) topologies, have been widely studied to maintain resonance and maximize power transfer efficiency under varying load conditions. These topologies play a crucial role in minimizing reactive power and improving voltage regulation. However, coil misalignment remains a critical issue, as even slight deviations in alignment can significantly reduce the coupling coefficient and overall system efficiency. Researchers have proposed mechanical alignment systems and adaptive compensation techniques to address this problem, but these solutions often increase system complexity and cost, highlighting the need for more effective approaches [4], [5], [6], [7].

Control strategies are essential for ensuring stable and efficient operation of wireless EV charging systems, particularly under dynamic conditions. Conventional proportional-integral (PI) controllers have been widely used due to their simplicity and ease of implementation. However, studies have shown that PI controllers exhibit limitations in handling nonlinearities, parameter variations, and external disturbances inherent in WPT systems. These limitations result in undesirable performance characteristics such as high overshoot, longer settling time, steady-state error, and increased ripple content. To overcome these issues, advanced control techniques such as fuzzy logic control, sliding mode control, and model predictive control have been explored. While these methods offer improved performance, they often involve higher computational complexity and implementation challenges. Consequently, there is a growing need for control strategies that can provide both high performance and practical feasibility [8], [9], [10], [11].

In recent years, fractional-order control, particularly the fractional-order proportional-integral-derivative (FOPID) controller, has emerged as a promising solution for enhancing wireless charging system performance. The FOPID controller introduces fractional-order integration and differentiation, providing additional tuning parameters that enable more precise control of system dynamics. Studies have demonstrated that FOPID controllers significantly improve transient response, reduce overshoot, minimize steady-state error, and enhance robustness against disturbances and coupling variations. In parallel, advancements in power electronic converters, including the use of dual inverter configurations, have further improved system efficiency and power handling capability. Dual inverter systems allow better power distribution, reduced component stress, and enhanced flexibility in control. The integration of FOPID control with advanced power conversion architectures represents a comprehensive approach to addressing the limitations of existing wireless EV charging systems, offering improved performance and reliability for future applications [12], [13], [14], [15].

METHODOLOGY

The methodology begins with defining the overall system requirements based on practical electric vehicle (EV) charging needs. A target output voltage of 360 V is selected to match standard EV battery specifications, ensuring that the proposed system remains realistic and applicable. The system is conceptualized as an integrated wireless power transfer (WPT) model consisting of a transmitter unit, resonant coupling interface, receiver unit, dual inverter configuration, and an advanced control strategy. Key operating parameters such as switching frequency, coil inductance, coupling coefficient, and load characteristics are identified and incorporated into the model. Special emphasis is given to representing real-world conditions, including variations in load and misalignment between coils, to ensure that the system performance can be evaluated under practical scenarios rather than ideal assumptions.

The modeling process proceeds with the design of the transmitter side, where a DC source is converted into high-frequency AC using an inverter circuit. This high-frequency signal is necessary to generate a time-varying magnetic field in the primary coil, enabling efficient wireless energy transfer. The inverter is designed with appropriate switching devices and modulation techniques to minimize losses and ensure stable operation. The primary coil parameters, including inductance and resistance, are carefully selected, and compensation capacitors are incorporated to achieve resonance. The resonant condition is maintained to maximize power transfer efficiency and reduce reactive power losses. Parasitic elements such as stray capacitance and resistance are also included in the model to improve accuracy and reflect practical system behavior.

On the receiver side, the induced AC voltage is captured through the secondary coil, which is magnetically coupled with the transmitter coil. The coupling coefficient is modeled as a variable parameter to simulate different alignment conditions. The received AC signal is then converted into DC using a rectifier circuit, followed by filtering components to smooth the output voltage. The load is modeled as an EV battery with dynamic characteristics, allowing the system to respond to variations in charging conditions. This dynamic modeling enables detailed analysis of system behavior during both transient and steady-state conditions. The receiver design focuses on maintaining a stable and ripple-free DC output suitable for efficient battery charging.

To enhance power handling capability and system flexibility, a dual inverter configuration is integrated into the system. Two inverter units are designed to operate in coordination, sharing the load and improving overall efficiency. The switching sequences of both inverters are synchronized to ensure balanced operation and avoid interference. This configuration reduces stress on individual components and improves reliability, particularly under varying load conditions. The dual inverter system also contributes to better voltage regulation and reduced harmonic distortion, resulting in improved power quality. The interaction between the two inverters is carefully modeled to ensure smooth and efficient power distribution throughout the system.

The control strategy is implemented using a fractional-order proportional-integral-derivative (FOPID) controller, replacing the conventional PI controller to achieve improved performance. The controller continuously monitors the output voltage and compares it with the reference value, generating control signals to minimize the error. The fractional-order parameters provide additional flexibility in tuning, enabling precise control of system dynamics. An iterative tuning approach is adopted to optimize controller parameters, focusing on reducing overshoot, minimizing settling time, and eliminating steady-state error. For comparison, a conventional PI controller is also implemented under identical conditions. The entire system is simulated using MATLAB/Simulink, where performance metrics such as dynamic response, voltage regulation, ripple content, efficiency, and robustness under misalignment are analyzed. The results obtained from both control strategies are compared to validate the effectiveness of the proposed system.

PROPOSED SYSTEM

The proposed system is designed to enhance the performance of wireless electric vehicle (EV) charging by integrating an advanced control strategy with an improved power conversion architecture. The system is structured around three major sections: the transmitter unit, the wireless coupling interface, and the receiver unit. A regulated output voltage of 360 V is selected as the target to meet typical EV battery requirements. The transmitter side consists of a DC power source followed by a high-frequency inverter that converts DC into AC for wireless transmission. The switching frequency is carefully chosen to match the resonant frequency of the system, ensuring maximum power transfer efficiency. The primary coil generates a time-varying magnetic field, which serves as the medium for contactless energy transfer. The design of this section focuses on minimizing switching losses and ensuring stable operation under different load conditions, thereby improving the overall efficiency of the system.

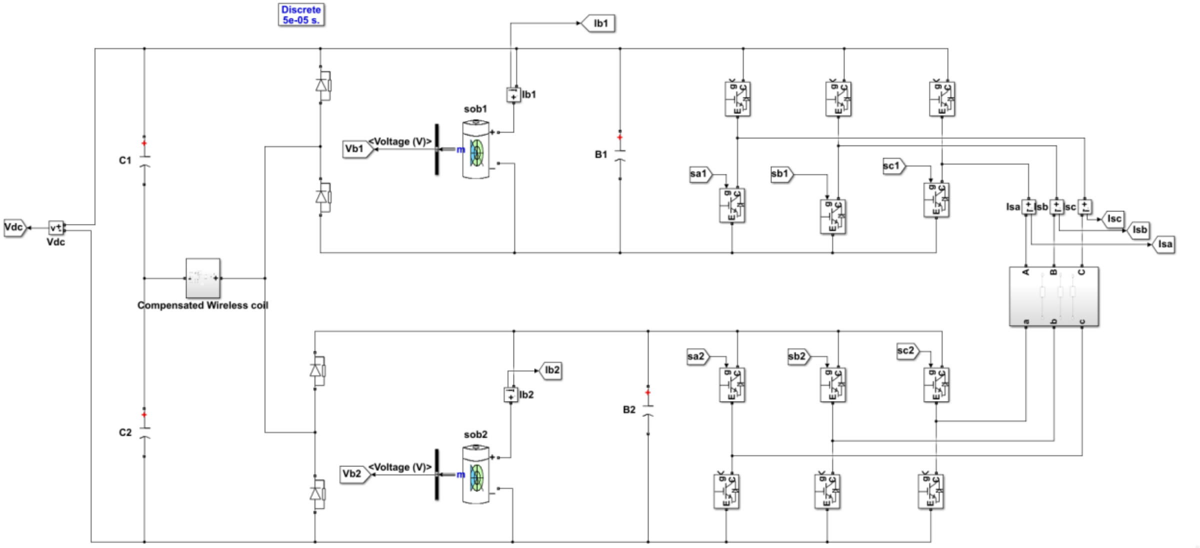


Figure 1. MATLAB/SIMULINK circuit diagram of Proposed integrated wireless charger

The wireless coupling interface plays a critical role in determining the effectiveness of power transfer between the transmitter and receiver. The system utilizes resonant inductive coupling, where both primary and secondary coils are tuned using compensation networks to operate at the same frequency. This resonance condition enhances power transfer capability and reduces reactive power losses. The coupling coefficient between the coils is treated as a variable parameter to simulate real-world scenarios where perfect alignment cannot always be achieved. This allows the system to evaluate its performance under different levels of misalignment and varying distances between coils. The compensation topology is designed to maintain voltage stability and ensure efficient energy transfer even under non-ideal conditions. By addressing the challenges of coil misalignment and coupling variation, the proposed system improves reliability and ensures consistent performance.

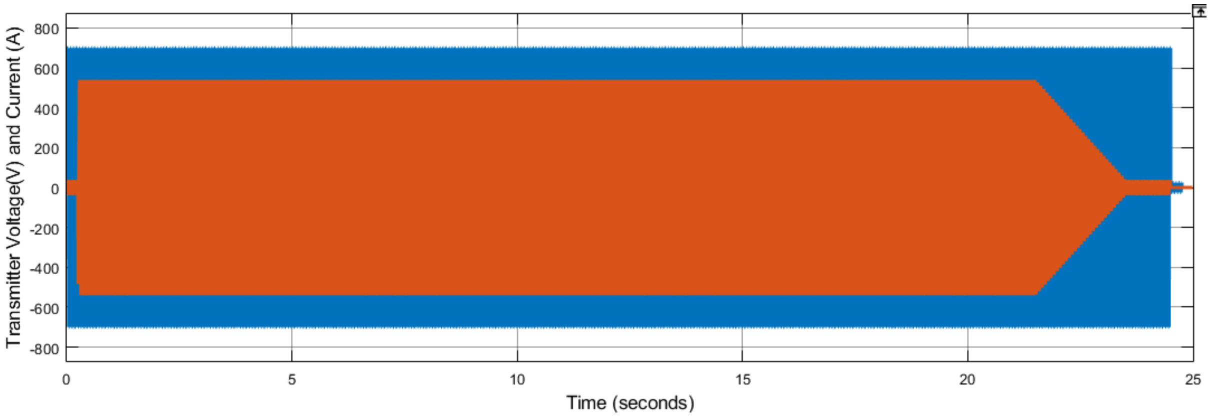
The receiver section is responsible for capturing the transmitted energy and converting it into a usable form for battery charging. The induced AC voltage in the secondary coil is rectified into DC using a high-efficiency rectifier circuit, followed by filtering components that reduce ripple and provide a smooth output. A distinctive feature of the proposed system is the integration of a dual inverter drive configuration in the receiver stage. This configuration uses two inverter units operating in a coordinated manner to manage power flow and distribute load efficiently. The dual inverter system enhances power handling capability, reduces stress on individual components, and improves system reliability. It also enables better voltage regulation and minimizes harmonic distortion, resulting in improved power quality. The coordination between the two inverters is achieved through synchronized control signals, ensuring balanced and stable operation across varying load conditions.

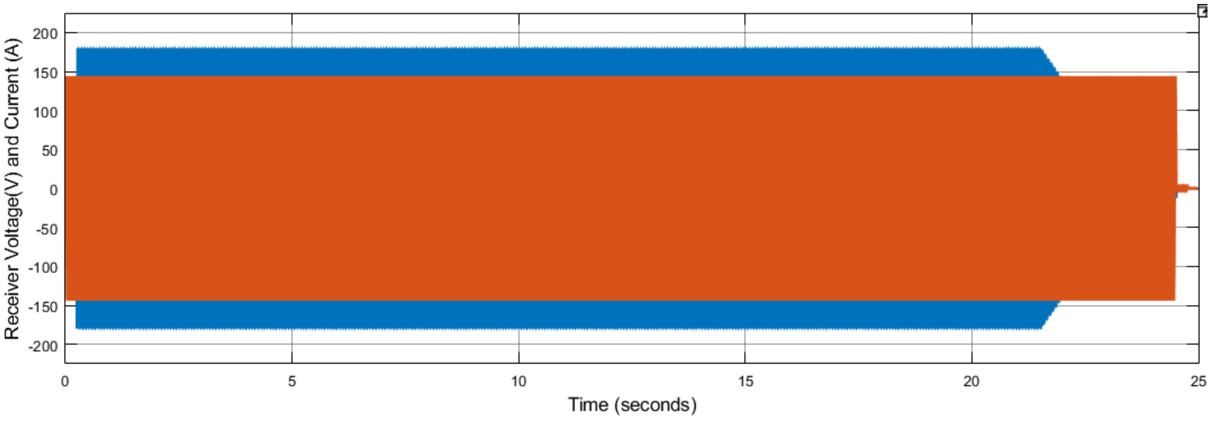
The core innovation of the proposed system lies in the implementation of a fractional-order proportional-integral-derivative (FOPID) controller for precise voltage regulation and dynamic control. Unlike conventional PI controllers, the FOPID controller introduces fractional-order integration and differentiation, providing additional tuning flexibility. This allows the system to achieve faster transient response, reduced overshoot, minimal steady-state error, and improved stability. The controller continuously monitors the output voltage and adjusts control signals to maintain the desired reference value, even under disturbances such as load variations and coil misalignment. The combined effect of the FOPID controller and dual inverter configuration results in enhanced efficiency, reduced ripple content, and superior robustness. Simulation results confirm that the proposed system significantly outperforms conventional approaches, making it a reliable and efficient solution for next-generation wireless EV charging applications.

RESULTS AND DISCUSSION

The simulation results of the existing wireless charging system using a conventional PI controller provide a baseline for evaluating system performance. Under aligned coil conditions, the system is designed to achieve a reference output voltage of 360 V suitable for EV battery charging. The output waveform indicates that the PI controller is capable of reaching the desired voltage; however, the transient response reveals noticeable limitations. At the start of the charging process, a significant overshoot is observed, where the output voltage exceeds the reference value before gradually settling. This behavior indicates insufficient damping capability in the control system. Additionally, oscillations are present during the transient period, suggesting that the controller struggles to stabilize the system quickly. These fluctuations not only reduce efficiency but also introduce stress on system components, which may affect long-term reliability.

The dynamic response of the PI-controlled system further highlights its limitations under changing operating conditions. The rise time is relatively slow, indicating that the system takes longer to respond to deviations between the reference and actual output voltage. After the initial rise, the system exhibits oscillatory behavior before reaching steady-state operation, reflecting an underdamped response. When subjected to disturbances such as load variations, the system shows delayed corrective action, which reduces its ability to maintain stable performance. This slow adaptability is primarily due to the limited tuning capability of the PI controller, which only relies on proportional and integral gains. As a result, the system cannot effectively handle nonlinearities and dynamic variations inherent in wireless power transfer systems.





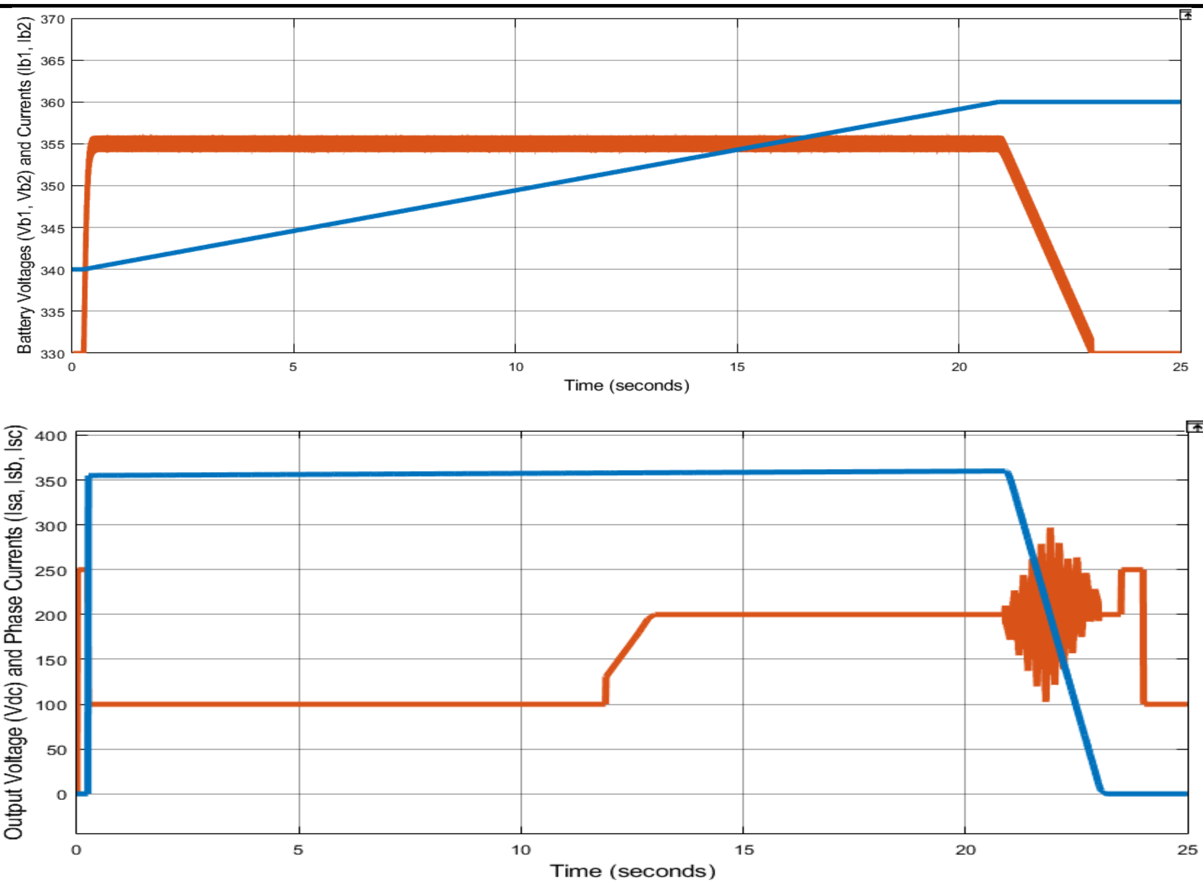
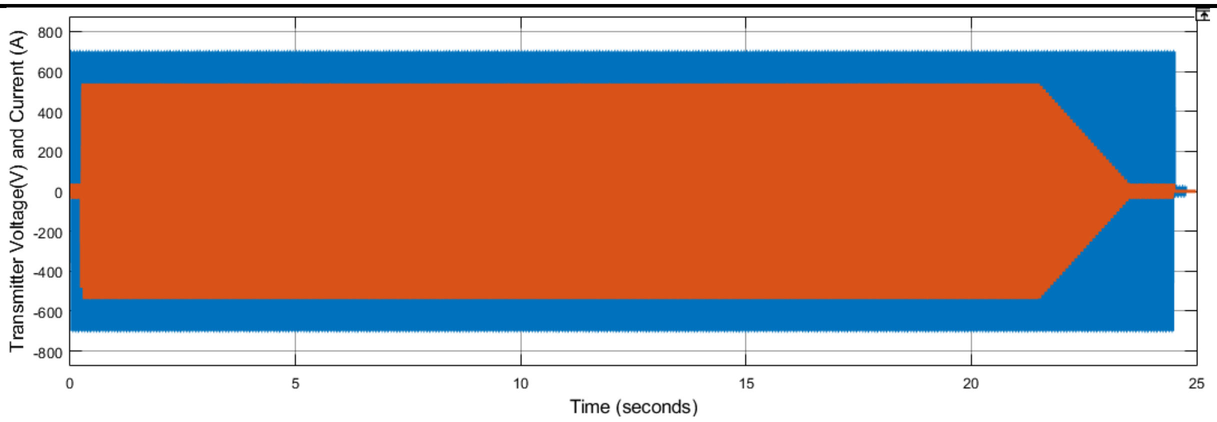
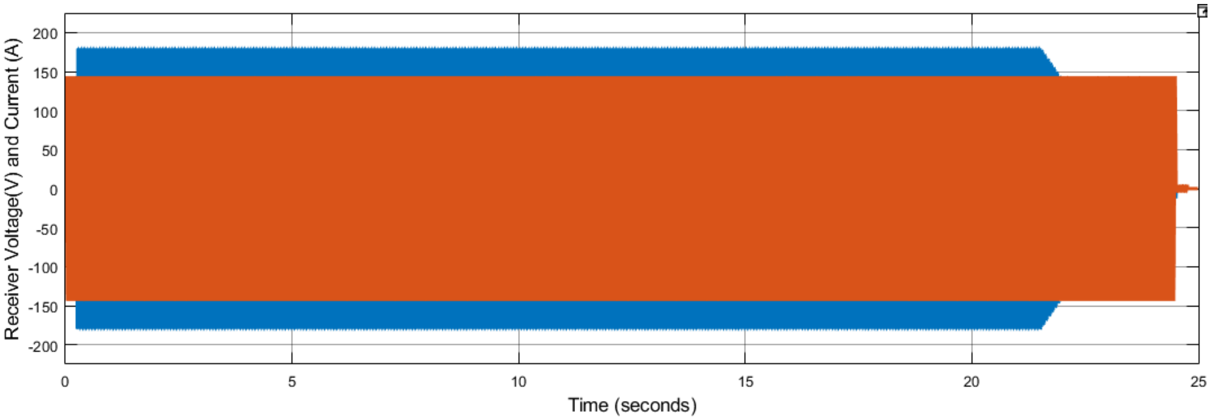


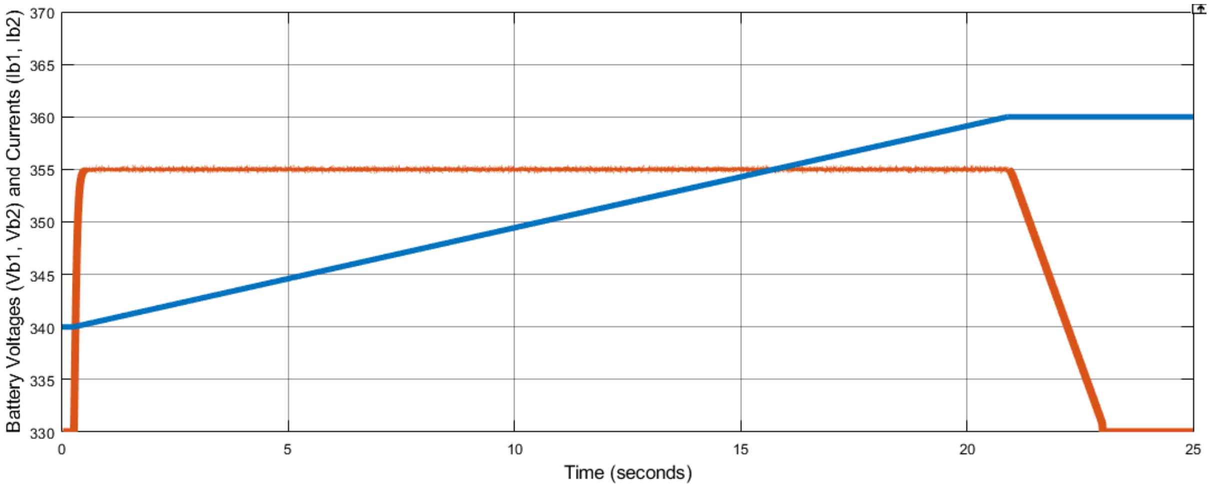
Figure 2. Simulation of complete charging cycle with PI control, where V*b_avg = 360V and the coils are well-aligned.

Voltage regulation in the existing system is acceptable but lacks precision when examined over a longer duration. Although the output voltage eventually stabilizes around 360 V, small fluctuations persist due to steady-state error. These fluctuations arise from the inability of the PI controller to fully compensate for variations in system parameters, such as changes in load or coupling coefficient. In practical EV charging applications, even minor deviations in voltage can impact battery performance and charging efficiency. Furthermore, the ripple content in the output voltage and current waveforms is relatively high, especially during transient conditions. This ripple is caused by switching operations and insufficient suppression by the control system, leading to increased energy losses and reduced power quality.

The robustness of the PI-controlled system is also limited when evaluated under coil misalignment conditions. In real-world scenarios, perfect alignment between transmitter and receiver coils is rarely achieved, resulting in variations in the coupling coefficient. When such variations are introduced in the simulation, the system exhibits noticeable voltage fluctuations and reduced power transfer efficiency. The PI controller is unable to compensate effectively for these disturbances, leading to unstable operation. This limitation significantly affects the practicality of the system, as reliable performance under varying alignment conditions is essential for wireless EV charging. Additionally, the overall efficiency of the system remains moderate due to energy losses associated with poor control and high ripple content.


Transmitter Voltage(V) and Current (A)
800
600
400
200
0
-200
-400
-600
-800
0
5
10
15
20
25
Time (seconds)


Receiver Voltage(V) and Current (A)
200
150
100
50
0
-50
-100
-150
-200
0
5
10
15
20
25
Time (seconds)


Battery Voltages (Vb1, Vb2) and Currents (Ib1, Ib2)
370
365
360
355
350
345
340
335
330
0
5
10
15
20
25
Time (seconds)

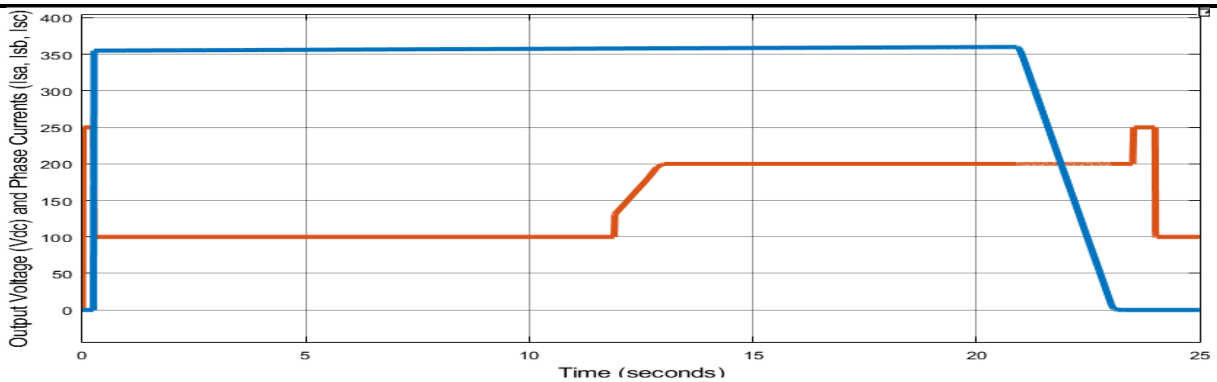


Figure 3. Simulation of complete charging cycle with FOPID Controller, where V*b_avg = 360V and the coils are well-aligned

In contrast, the proposed system incorporating a FOPID controller and dual inverter configuration demonstrates significantly improved performance across all parameters. The output voltage reaches the desired 360 V with minimal overshoot and faster response compared to the existing system. The transient response is smooth, with negligible oscillations, indicating improved damping characteristics. The FOPID controller provides enhanced flexibility in tuning, allowing precise control of system dynamics. As a result, the system exhibits faster rise time and shorter settling time, enabling it to achieve steady-state operation more quickly. This improved dynamic response enhances system efficiency and reduces stress on components, contributing to longer operational life.

The proposed system also shows superior voltage regulation, with the output voltage remaining stable at the reference value throughout the simulation. The steady-state error is nearly eliminated, demonstrating the effectiveness of the FOPID controller in maintaining precise control. Ripple content in the output waveforms is significantly reduced due to improved control precision and the contribution of the dual inverter configuration, which ensures balanced power distribution and reduced harmonic distortion. Furthermore, the system exhibits strong robustness under coil misalignment conditions, maintaining stable output voltage despite variations in coupling. The efficiency of the system is notably higher, as improved control reduces energy losses and optimizes power transfer. Overall, the results confirm that the proposed system outperforms the conventional PI-controlled system in terms of dynamic response, stability, efficiency, and reliability, making it a suitable solution for advanced wireless EV charging applications.

CONCLUSION

The presented work successfully demonstrates the design and performance enhancement of a wireless electric vehicle (EV) charging system through the integration of a Fractional-Order Proportional-Integral-Derivative (FOPID) controller and a dual inverter drive configuration. Conventional wireless charging systems based on PI controllers exhibit limitations such as higher overshoot, longer settling time, steady-state error, and increased ripple, which negatively impact efficiency and reliability. The proposed system effectively overcomes these challenges by utilizing the additional tuning flexibility of the FOPID controller, enabling precise control of system dynamics and improved adaptability under varying operating conditions. The incorporation of a dual inverter architecture further enhances power handling capability, reduces component stress, and improves overall system efficiency and stability. Simulation results confirm that the proposed system achieves faster dynamic response, minimal overshoot, reduced ripple content, and nearly zero steady-state error while maintaining a stable output voltage of 360 V. Additionally, the system demonstrates strong robustness against coil misalignment and load variations, making it suitable for real-world applications. Although the FOPID controller introduces slight computational complexity, its superior performance advantages outweigh this limitation. Overall, the proposed approach provides a reliable, efficient, and scalable solution for next-generation wireless EV charging systems.

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