AOI: 10.11234.2024.00024
ACT2024: Special Proceedings of Applied Computer Technology

Wireless Power Transfer for EV Charging Application using Half-Bridge LLC Resonant Converter

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ABSTRACT

This paper explores the integration of wireless power transfer (WPT) systems into electric vehicles (EVs) to address the growing demand for sustainable transportation solutions. Focusing on the application of a highly efficient half-bridge LLC resonant converter, the research aims to enhance the reliability and efficiency of EV charging systems through resonant operation. Employing MATLAB as the simulation platform, the investigation meticulously evaluates the performance of the WPT system under specified conditions, including a 230V AC input voltage and 1.1 kW output power. Critical parameters such as resonance frequency, output power, and power transfer efficiency are systematically examined to optimize the overall effectiveness and feasibility of the proposed WPT system within the context of electric vehicle applications. By addressing key technical aspects and utilizing advanced simulation tools, this research contributes to the ongoing discourse on sustainable transportation solutions. The findings presented herein offer valuable insights for the development of more efficient and reliable WPT systems in the pursuit of a greener and more sustainable future for electric vehicles.

Keywords: Wireless power transfer (WPT), Electric vehicles (EVs), Sustainable transportation, Half-bridge LLC resonant converter, MATLAB.

I. INTRODUCTION

In the realm of electric vehicle (EV) development, charging systems stand as pivotal contributors. Presently, two predominant charging technologies, namely plug-in charging (conductive charging) and wireless charging, shape the landscape. The use of high-power cables in conductive charging poses a primary challenge, as these cables, when plugged into EVs, can be cumbersome to handle and may give rise to safety concerns such as shocking hazards resulting from damaged cables or improper handling. In contrast, wireless charging eliminates the necessity for physical wires by facilitating the transfer of energy to the load seamlessly. The advantages of wireless charging over its conductive counterpart are manifold, encompassing the convenience of eschewing bulky power cords during EV charging, the avoidance of potential shocking hazards associated with cable usage, and a heightened resilience to environmental elements like dirt, water, and pollution. Wireless Power Transfer (WPT) achieves this feat through various coupling methods between two coils—designated as the transmitter and receiver coils. In the context of EV charging applications, transmitter coils are discreetly embedded in the road, while receiver coils find placement within the vehicle [1].

Fig.1 illustrates the fundamental concept of wireless EV charging.

Wireless charging technology can be categorized into three primary schemes: Static Wireless Charging (SWC), Quasi Wireless Charging (QWC), and Dynamic Wireless Charging (DWC). SWC offers the convenience of simply parking the vehicle on a designated charging pad, allowing drivers to effortlessly charge their electric vehicles before continuing with their day. This flexibility enables the installation of charging pads in various locations such as homes, garages, and parking lots. On the other hand, QWC optimizes electric vehicle charging during short parking intervals, such as at traffic lights, thereby enhancing the vehicle's range along its route and
d Fig.1 EV WIRELESS POWER TRANSFER CHARGING.
DWC represents an innovative approach by consistently charging electric vehicles while they are in motion, utilizing specified charging lanes on the road. This dynamic charging method contributes to an increased driving range and a reduction in the overall demand for battery capacity, thereby advancing the efficiency and sustainability of electric transportation.

Wireless Power Transfer (WPT) can be achieved via two ways: far-field and near-field transmissions. The far-field approach relies on electromagnetic radiation, enabling the transfer of power over considerable distances. However, this method is plagued by significant energy loss to the surrounding air, rendering it unacceptable. On the other hand, near-field transmission stands out as a more efficient and interference-resistant alternative, making it the preferred choice. Within near-field WPT, Capacitive WPT (CWPT) and Inductive WPT (IWPT) are prominent. CWPT, with its limited range, sees less widespread use compared to IWPT. IWPT, in turn, can further evolve into Resonant Inductive WPT (RIPT), representing an improved model with enhanced power-transferring capacity. Unlike traditional IWPT systems, RIPT incorporates compensating components, such as capacitors, inductors, or both, in series or parallel formations on both the transmitter and receiver sides of the coils. This strategic integration reduces additional losses, thereby significantly boosting efficiency [1] [2].

II. SYSTEM DESCRIPTION

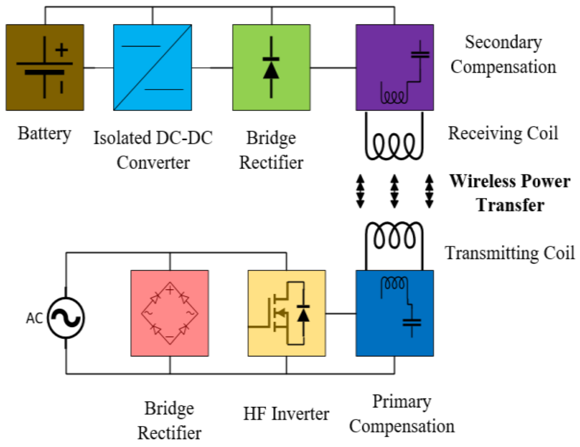

Fig.2 EV wireless power transfer system

Fig. 2 depicts a typical wireless EV charging system. It has multiple stages for wireless charging and mainly consists of two parts. One part is the transmitting part, which is put on the ground to transmit energy, and the other part is called the receiving part. Initially, the conversion process commences with a Full Bridge rectifier, tasked with transforming the incoming alternating current (AC) power, oscillating at 50 Hz, into a direct current (DC). Subsequently, an H-Bridge inverter steps into play, orchestrating the metamorphosis of the DC power back into AC power, albeit at a heightened frequency. This elevated-frequency AC power traverses through a coupling circuit and compensation network, facilitating its transmission to the recipient end. On the secondary end of the system, the received AC supply undergoes rectification to DC, orchestrated to charge the battery, a pivotal component of the setup. This rectified DC power is then channeled through an isolated DC-DC converter, ensuring an efficient and controlled transfer of energy to the battery, thereby completing the intricate cycle of power conversion and transmission within the system.

A. *Compensation topology*

The effectiveness of energy transfer in a Wireless Power Transfer (WPT) system is intricately linked to the mutual inductance between the transmitting and receiving coils. This essential factor facilitates the seamless transmission of energy, with the leakage inductance playing a more passive role in the overall power transfer process. The coupling factor, representing the degree of mutual coupling between the coils, tends to be modest—usually ranging from 5% to 30%. This percentage depends on various factors such as coil size, alignment, and the distance from one another due to the wide gap between them. Consequently, WPT systems exhibit a characteristic profile of small mutual inductance and substantial leakage inductance [3] [4].

The artistry of coil design assumes paramount importance in augmenting this coupling. Simultaneously, the compensation circuit emerges as a critical component in mitigating the impact of leakage inductance. Typically, a resonant circuit is meticulously crafted by introducing lumped or parasitic capacitors. This strategic integration is commonly known as the magnetic resonant technique, underscoring its pivotal role in optimizing the performance and efficiency of WPT systems. Establishing a seamless connection between power electronics converters and the transmitting and receiving coils is imperative for the efficacy of wireless power transfer (WPT) systems. In pursuit of enhanced efficiency, alternative topologies have been proposed. This particular system adopts an LCC/LCC resonant network for its resonant stage, incorporating components such as an inductor and a capacitor. The utilization of this configuration enables the achievement of soft switching by fine-tuning the characteristics of the compensation network. Furthermore, the implementation of the LCC compensation network at the secondary side facilitates the formation of a unit power factor pickup by compensating reactive power. This strategic integration not only optimizes the WPT system's performance but also highlights the versatility and sophistication of its design.

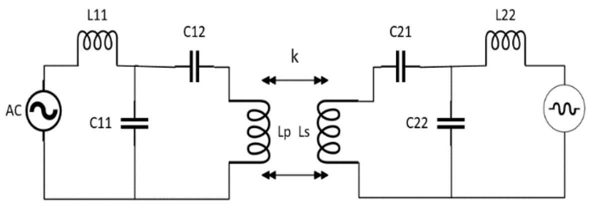

Fig.3 LCC/LCC Resonant Circuit

Figures 3 depict, the LCC/LCC resonant circuit.

WPT coils with transmitting and receiving side inductances L_P, L_S and coupling factor k can be written as

$$L_M = k\sqrt{L_P L_S} \tag{1}$$

$L_{l,p}$ Represents the leakage inductance of the transmitting side and $L_{l,s}$ for the receiving side

$$L_{l,p} = L_P - L_M, \tag{2}$$

$$L_{l,s} = L_S - L_M. \tag{3}$$

Primary $Z_{P,eq}$ and secondary $Z_{S,eq}$, and mutual $Z_{M,eq}$ equivalent impedances can be expressed by

$$Z_{P,eq} = j\omega L_{11} + \left[\frac{1}{j\omega C_{11}} // \left(\frac{1}{j\omega C_{12}} + j\omega L_{l,p} + j\omega L_M\right)\right], \tag{4}$$

III. CONVERTER AND ITS WORKING PRINCIPLE

A significant trend in the present electric vehicle (EV) market is the emphasis on high power density. To align with this trend, it is essential to employ topologies characterized by a high capability for switching frequency and efficiency. Nonetheless, it is worth noting that high frequencies can lead to switching losses, particularly in terms of the secondary diode reverse recovery loss and the primary switch turn-off loss

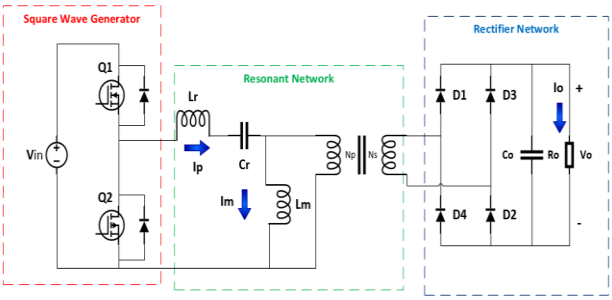

Fig.4 Half-Bridge LLC Resonant Converter Circuit

LLC resonant converters have attracted significant interest owing to their uncomplicated design, high power density, minimal switching losses at elevated frequencies, superior efficiency, soft switching phenomena (ZVS) and (ZCS), reduced electromagnetic interference (EMI), and the elimination of reverse recovery in output rectification diodes. These converters exhibit lower losses and are well-suited for high-power applications, thanks to their sinusoidal behavior and ability to function at high frequencies. Additionally, they contribute to the reduction in size of reactive components [5].

A. *Architecture of the converter*

Figure 4 illustrates the circuit diagram of the Half-bridge LLC Resonant Converter, a complex system comprising various crucial parameters. Among these, the resonant inductor (Lr), resonant capacitor (Cr), and magnetic inductance (Lm) play pivotal roles in determining the converter's performance. The diagram delineates three key components essential to the converter's functionality:

- **Square Wave Generator**: At the core of the system is the Square Wave Generator, responsible for producing the input waveform that initiates the resonant process. This component lays the foundation for the subsequent resonant and rectification stages.
- **Resonant Network:** The Resonant Network is a critical element designed to facilitate efficient energy transfer. Comprising components such as the resonant inductor (Lr) and resonant capacitor (Cr), this network enables resonant switching, minimizing losses and optimizing power conversion.
- **Rectifier Network:** The Rectifier Network, depicted in the diagram, functions to convert the resonantly generated waveform into a usable and stable output. This stage completes the conversion process, ensuring that the electrical energy is delivered in a suitable form for the intended application.

Understanding the interplay between these three components is essential for comprehending the overall operation of the Half-bridge LLC Resonant Converter, highlighting the intricate balance and synergy required for efficient power conversion [6].

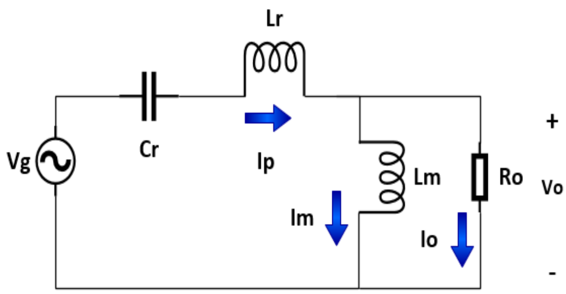

Fig.5 First Harmonic Approximation (FHA)

The resonant converter's gain (M), obtainable from the circuit illustrated in Fig. 5, represents the transfer function of the converter, where Vo denotes the output voltage and Vg signifies the fundamental voltage [7].

$$M = \frac{V_O(s)}{V_g(s)} \tag{5}$$

$$M = \frac{sLm \,||\, Ro}{(sLm \,||\, Ro) + sLr + 1/sCr} \tag{6}$$

B. *Converter parameters*

TABLE I
PARAMETERS AND FORMULA OF CONVERTER

Variable	Formula	Parameter
F_n	$\frac{fo}{fsw}$	Normalized frequency
f_o	$\frac{1}{2\pi\sqrt{LrCr}}$	Resonance frequency series
f_p	$\frac{1}{2\pi\sqrt{(Lm+Lr)Cr}}$	Resonance frequency parallel
Q_0	$\frac{\sqrt{LrCr}}{Re}$	Quality factor
R_e	$\frac{8}{\pi^2}\frac{Np^2Ro}{Ns^2}$	Reflected load resistance
L_m	$\frac{2\pi f_r mQN_S^2}{N_P^2Ro}$	Magnetizing Inductor
m	$\frac{Lm}{Lr}$	Inductance ratio
L_r	$\frac{1}{(2\pi fr)^2Cr}$	Resonant Inductor
C_r	$\frac{1}{2\pi Qf_rRe}$	Resonant Capacitor
k	$\frac{M}{\sqrt{L_1L_2}}$	Coupling Coefficient
R_O	$\frac{V_O^2}{P_O}$	Load resistance

TABLE II
HALF-BRIDGE LLC RESONANT CONVERTER PARAMETER VALUES

Circuit Parameters	Values
L_r	22.6 µH
C_r	112 nF
L_m	79.1 µH
R_o	5 ohm

From Table II, we consider a specific configuration for the Half-Bridge LLC resonant converter with an input voltage of 267 volts, a switching frequency of 80 kHz, and a resonant frequency of 100 kHz.

TABLE III
LCC COMPONESATION PARAMETERS

Symbol	Value	Parameter
L_{11}	15 µH	Primary series inductor
C_{11}	220 nF	Primary parallel capacitor
C_{12}	50 nF	Primary series capacitor
L_P	74 µH	Primary coil self-inductance
k	0.17	Coupling coefficient
L_s	85 µH	Secondary coil self-inductance
C_{21}	50 nF	Secondary series capacitor
C_{22}	220 µF	Secondary parallel capacitor
L_{22}	15 µH	Secondary series inductor

Table III Shows the Design specification of the LCC compensation network with carefully chosen inductor (L), capacitor (C1), and capacitor (C2) components for optimal impedance matching and resonance

By adhering to this design specification, the LCC compensation system aims to optimize wireless power transfer efficiency and to adapt to varying load conditions.

IV. DESIGN SPECIFICATIONS

- Develop a wireless power transfer system utilizing a Half-Bridge LLC resonant converter, implemented and simulated using MATLAB, to achieve efficient and reliable energy transmission.
- Implement resonant coupling for efficient wireless power transfer between the transmitter and receiver coils.
- Utilize a half-bridge LLC resonant converter as the core topology for the wireless power transfer system.
- Optimize the LLC resonant converter to operate at a specified frequency range for maximum efficiency.
- Design the converter to handle a specific power level based on application requirements.
- Define the voltage and current ratings considering input and output requirements.
- Define simulation parameters such as input voltage, load conditions, and resonant frequency for accurate representation [8].

V. RESULTS and DISCUSSIONS

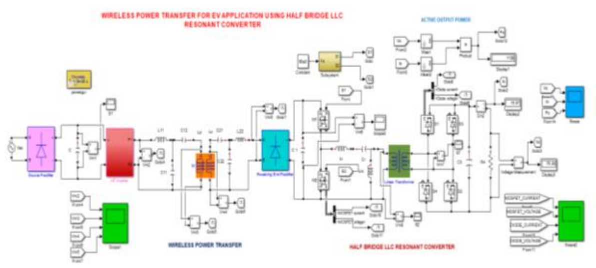

Fig.6 Simulink Model Of WPT System

The illustrated Figure 6 offers a visual representation of the comprehensive Simulink model encapsulating the Wireless Power Transfer System, employing the Half-Bridge LLC DC-DC Resonant Converter. This intricate model incorporates various power conversion elements, notably featuring bridge rectifiers and H-bridge inverters tailored for different power conversion requirements. Through the amalgamation of these components, the Simulink model embodies a sophisticated interplay of technologies, exemplifying a versatile and efficient Wireless Power Transfer System. This holistic approach not only underscores the intricacies of the design but also highlights the adaptability of the system to diverse power conversion scenarios.

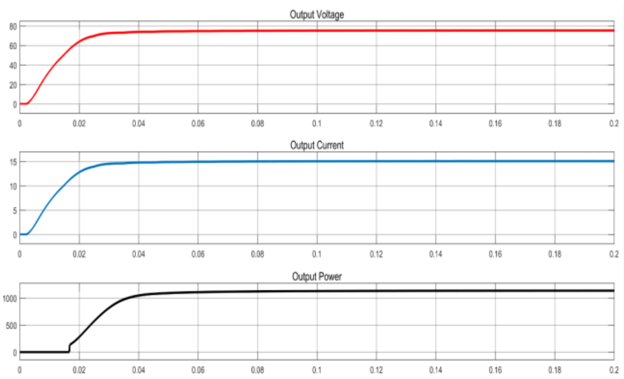

Fig.7 Output Waveforms Of The WPT System

Figure 7 serves as a comprehensive visual representation, offering a consolidated view of the output results within the entire Wireless Power Transfer (WPT) infrastructure. This insightful figure encapsulates key performance metrics, including Output Voltage, Output Current, and Output power.

The specification for the Wireless Power Transfer (WPT) system delineates a meticulous blueprint for its operational parameters. Set against a backdrop of a 230 V AC grid input voltage and a 50 Hz grid input frequency, the system showcases its technical prowess through a judiciously chosen inverter switching frequency of 91.5 kHz. The meticulously crafted output specifications reveal a finely tuned performance, with an output voltage of 75.33 V DC, a robust output current of 15 A, and an overall output power of 1.1 kW. This comprehensive framework not only underscores the precision in the selection of input parameters but also illuminates the system's capacity to efficiently transform and deliver power within the specified parameters, marking a significant milestone in the realm of wireless power transfer technology.

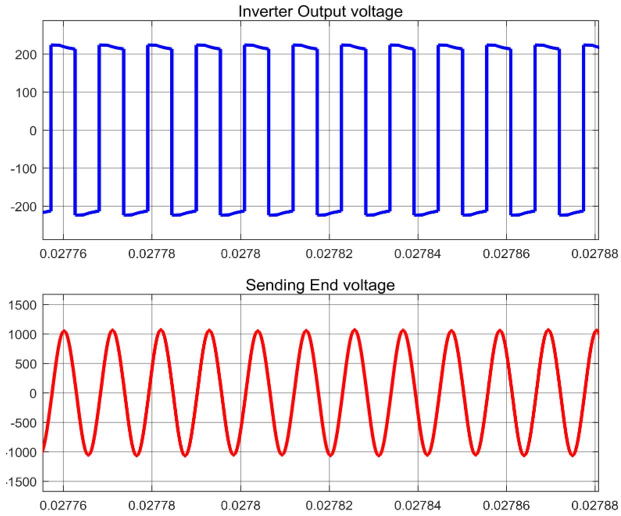

Fig.8 Inverter Output Voltage And Sending End Voltage

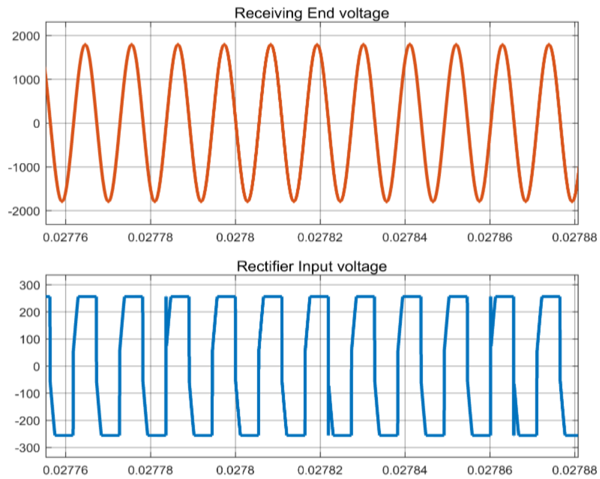

Fig.9 Receiving End Voltage And Rectifier Input Voltage

The above figure 8. and 9 illustrates the waveforms of the sending end voltage, which comes from the inverter output, and the receiving end voltage, which goes to the rectifier input. This gives a comprehensive understanding of the complex dynamics of wireless power transfer. This graphic depiction captures the essence of the energy transfer mechanism and shows how the sending and receiving ends interact harmoniously.

The waveform analysis provides a visual representation of the smooth transfer of electrical energy over the wireless medium in addition to illuminating the temporal nuances. We can learn more about the system's responsiveness, efficiency, and the intricate details of the energy transfer process by examining these waveforms. This thorough representation is essential to understanding the intricate dynamics present in wireless power transfer.

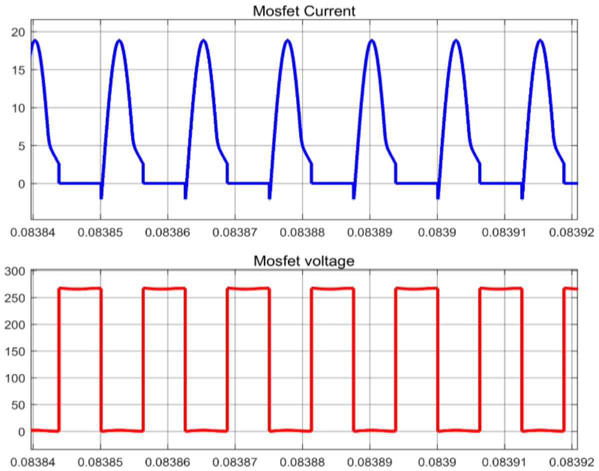

Fig.10 MOSFET current and MOSFET voltage

Figure 10 shows the MOSFET current and MOSFET voltage across the switch Q1 of the half-bridge LLC resonant converter. The meticulous analysis reveals a precisely measured peak current of 16.7 A, illuminating the dynamic nature of the system's electrical flow. Simultaneously, the voltage across the MOSFET is examined, revealing a significant 267.5 V. This insightful revelation not only demonstrates the system's components' resilience, but also emphasizes the MOSFET's critical role in handling substantial voltage levels. The symbiotic interaction of current and voltage, depicted in this figure, is critical to understanding the intricate nuances of the device's operational characteristics, providing invaluable insights for further optimization and refinement.

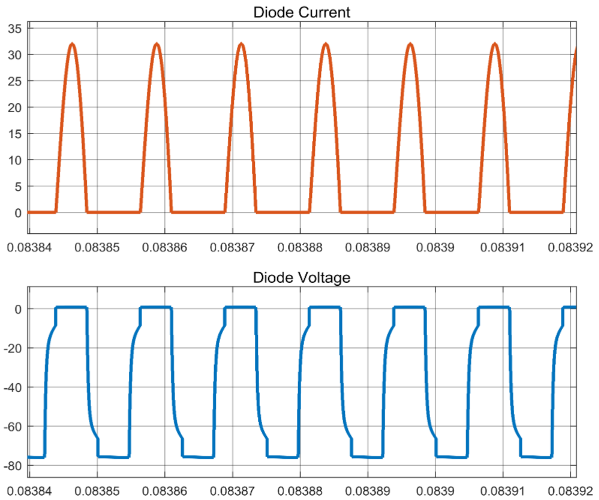

Fig.11 Diode Current And Diode Voltage

Within the secondary side of the Half-Bridge LLC Resonant Converter, in the rectifier circuit, Figure 11 shows the Diode current and Diode Voltage waveforms. The data reveals a peak current surge coursing through the diode, registering a robust 31.7 A simultaneously, the voltage across the diode is distinctly marked at 75.5 V. The interplay of current and voltage, as illustrated in the figure, not only highlights the robustness of the rectifier circuit but also serves as a pivotal reference for optimizing the converter's secondary side for enhanced efficiency and reliability in the broader context of the Half-Bridge LLC Resonant Convert

V. CONCLUSION

In conclusion, the Simulink model designed for wireless power transfer in electric vehicle (EV) charging successfully demonstrates the efficient conversion of a 230V input voltage at 50Hz frequency into a desired 75V output voltage, delivering a reliable output power of 1.1kW. The utilization of a suitable compensation topology ensures a significant and effective wireless power transfer between the sending and receiving coils. The incorporation of the Half-Bridge LLC resonant converter for charging further enhances the system's performance, achieving a harmonious resonance that optimizes power transfer and minimizes energy losses. This comprehensive simulation underscores the viability and effectiveness of the proposed wireless charging system, providing a robust foundation for real-world implementation in advancing electric vehicle technologies. The successful amalgamation of key components within the Simulink model underscores its potential to contribute to the evolution of wireless charging solutions for electric vehicles, paving the way for more sustainable and efficient transportation systems in the future.

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