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An Inductive EV Charging Topology with ZVS and ZCS Support using 3-Level Isolated DC-DC Converter

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Abstract

To enhance the transmission range of wireless power, advanced high-frequency converter architectures in inductive power transfer (IPT) setups frequently adopt Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS) techniques, aiming to retain a quasi-sinusoidal current waveform. Nevertheless, realizing complete ZVS or ZCS across all switching devices in IPT frameworks poses a notable obstacle. This study presents a refined IPT configuration that accomplishes both Zero Voltage and Zero Current Switching (ZVZCS). The suggested method employs an auxiliary branch to achieve ZCS, while ZVS is realized by adapting the traditional series compensation technique. MATLAB/Simulink-based simulations validate the improved switching approach under resistive and battery-driven loading scenarios.

Keywords: Wireless Power Transfer, Soft Switching with Zero Voltage Switching, Soft Switching with Zero Current Switching, Magnetic Inductive Power Transfer, Electric Vehicles

I. Introduction

The swift decline in petroleum reserves and the escalating severity of environmental issues represent critical challenges facing today's global economy. These factors have accelerated the shift toward sustainable technologies focused on minimizing key sources of greenhouse gas emissions, notably within the transportation sector. In this regard, electric vehicles (EVs) have emerged as a viable solution to mitigate the harmful environmental consequences associated with fossil fuel consumption[1]. Additionally, EVs present more economical mobility choices for users. Historically, the growth of the EV industry was significantly restricted by shortcomings in battery systems and power electronics control.

Nevertheless, remarkable advancements in battery technologies have yielded higher energy capacities, reduced size, and better performance. Combined with intelligent power regulation systems, these batteries improve the functional efficiency of EVs. Presently, intensive R&D efforts are concentrated on the development of DC-DC converters aimed at lowering energy dissipation, boosting robustness, ensuring consistent energy flow and prolonging the charge-discharge lifespan.

In this context, rapid charging solutions are also being implemented to overcome range limitations, especially in low-capacity vehicles where insufficient energy storage could present safety concerns. To further elevate converter efficiency and reduce total impedance, compensation circuitry is embedded within the architecture. Still, incorporating additional passive and active components may lead to greater circuit complexity. A highly optimized approach can enhance driving range, reduce upkeep demands, decrease emissions, and yield cost savings for users. Hence, the proper selection of power conversion systems is essential to the advancement of e-mobility technologies.

Among various topologies, the series-series compensated inductive power transfer (IPT) configuration remains a popular option due to its uncomplicated layout and dependable operation, even when subject to coil misalignment[2]. Despite being cost-effective, it may encounter problems like diminished transmission efficiency, limited power capacity, and poor control under varying load conditions. To counter these shortcomings, phase angle modulation is proposed to broaden bandwidth usage, although this method adds complexity to frequency control. Operating the system within an optimal frequency zone helps mitigate these issues and ensures consistent performance.

Recent developments feature an innovative coil arrangement utilizing dual L-C series compensation on both the sender and receiver ends. This setup repositions the coils onto the transmitter side, significantly minimizing onboard weight. It also simplifies the control scheme and computational overhead, while maintaining strong magnetic linkage even with coil displacement. Furthermore, integrating an H-Bridge high-frequency transformer with an L-C resonant circuit effectively resolves the constraints found in legacy IPT designs needing distinct resonant paths.

II. Wireless Power Transfer

The idea of Wireless Power Transfer (IPT) is not a modern-day breakthrough. Its roots trace back to the late 1800s when Nikola Tesla pioneered experiments to deliver electrical energy without the use of physical conductors. Since then, particularly from the 1960s onward, there has been a resurgence of interest in WPT, initially for powering biomedical implants, and later, from the early 2000s, for charging everyday portable gadgets like mobile phones and laptops. At present, WPT has matured into a commercially feasible technology, especially after the Wireless Power Consortium launched the “Qi” standard, with over 130 member firms participating globally.

The increasing popularity of electric vehicles (EVs) has infused new relevance and momentum into WPT development[6]-[8]. Techniques for transmitting power wirelessly can generally be distinguished either by transmission range or by their operational principles. Based on these functional concepts, WPT systems fall into three primary categories: radio frequency transmission, electromagnetic induction, and magnetic resonance coupling.

A notable and early real-world application of WPT lies in energizing implantable medical equipment, such as cardiac pacemakers. These compact devices help maintain normal heart rhythm by sending electrical impulses directly to the cardiac muscle. Given their continuous operation, powering such devices using traditional wired methods is both impractical and hazardous, with risks including infections and patient discomfort. Modern pacemakers depend on internal power sources, which are limited in volume and service life. Wireless energy transfer offers a safer, non-invasive alternative to prolong device functionality without repeated surgeries.

Nevertheless, WPT systems present greater complexity compared to traditional plug-and-play wired setups. In addition to their intricate design, these systems also face hurdles such as reduced energy efficiency, higher deployment expenses, lower versatility, and potential safety risks due to electromagnetic exposure. A major safety issue involves the presence of foreign or biological objects (FO/LO) within the power field. Energy transferred via magnetic flux through the air can unintentionally affect nearby metal items or living tissue[9]-[10]. This not only diminishes overall system performance—as more input power is needed to deliver the same output—but also introduces risks of overheating unintended objects.

Even under modest power outputs like 5 watts, noticeable heating can occur. Everyday materials including coins, metal wrappers, jewelry, or paper clips can absorb between 0.5 to 1 watt and still reach temperatures exceeding 80°C, which can be hazardous. Such thermal effects breach global safety norms and stress the need for advanced detection and regulation mechanisms in all WPT setups to prevent harm or unnecessary energy dissipation.

III. Existing Methodology

The converter features a traditional H-bridge configuration, where the primary side includes four active switches (S1 to S4), and the secondary side comprises four diodes (D5 to D8). Capacitors Ca1 and Ca2 serve as a voltage divider at the input stage, while auxiliary components LA and TA support soft-switching functionality, working in coordination with a blocking capacitor (BC).Coupling between the primary and secondary sections of the circuit is achieved using inductors L1 and L2, paired with capacitors C1 and C2 respectively. The overall operation is governed by a Modified Pulse Width Modulation (MPWM) control technique.

To simplify the analysis of the converter's functioning, the following assumptions are made:

1) All electrical components—whether active or passive—including the transformer, DC power source, switches, diodes, and capacitors, are assumed to operate under ideal conditions. This includes internal diode and capacitive effects within the switches.

2) Series resistance in inductors and the inter-winding capacitance of the transformer are considered negligible.

3) The voltage divider capacitors (where Ca = Ca1 = Ca2) and filter capacitor (CF) are assumed to have sufficiently large values to sustain constant voltage levels at both the input and output terminals.

4) The influence of the magnetizing inductance of the transformer's auxiliary winding (TA) is ignored for simplicity.

IV. PROPOSED METHODOLOGY

The power conversion strategy proposed in this study is aimed at improving the efficiency and reliability of wireless electric vehicle (EV) charging systems[3]-[5]. It integrates a diode bridge rectifier, a boost inductor for power factor correction, and a three-level isolated DC–DC converter. To address losses associated with hard-switching at high frequencies, this design incorporates both Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS). ZVS is applied to the primary-side switches, while ZCS is implemented on the secondary-side diodes, significantly improving the system's overall performance in terms of reduced EMI, thermal stress, and energy losses. The operation is governed by a carefully crafted switching strategy that not only supports soft switching but also simplifies circuit complexity compared to conventional multi-stage designs[11]-[14].

The overall converter topology is depicted in Fig. 2. It combines a basic diode bridge, a single boost inductor Lb, and four main switches arranged in a three-level full-bridge configuration. This hybrid design ensures that switches S1 through S4 are shared between the PFC boost stage and the isolated DC–DC stage. In this arrangement, no additional switches are required for the boost function. When switches S2 and S3 are turned ON together, the input inductor Lb stores energy from the input voltage. During this time, the body diodes of switches S1 and S4 conduct naturally, effectively creating a unidirectional current path without needing additional diodes. The converter generates three voltage levels—positive half DC, zero, and negative half DC—across the transformer's primary winding. This is achieved by controlling the switching pairs in a 180° phase-shifted pattern. The entire structure is optimized to ensure high power transfer capability while maintaining isolation and voltage scaling through a high-frequency transformer.

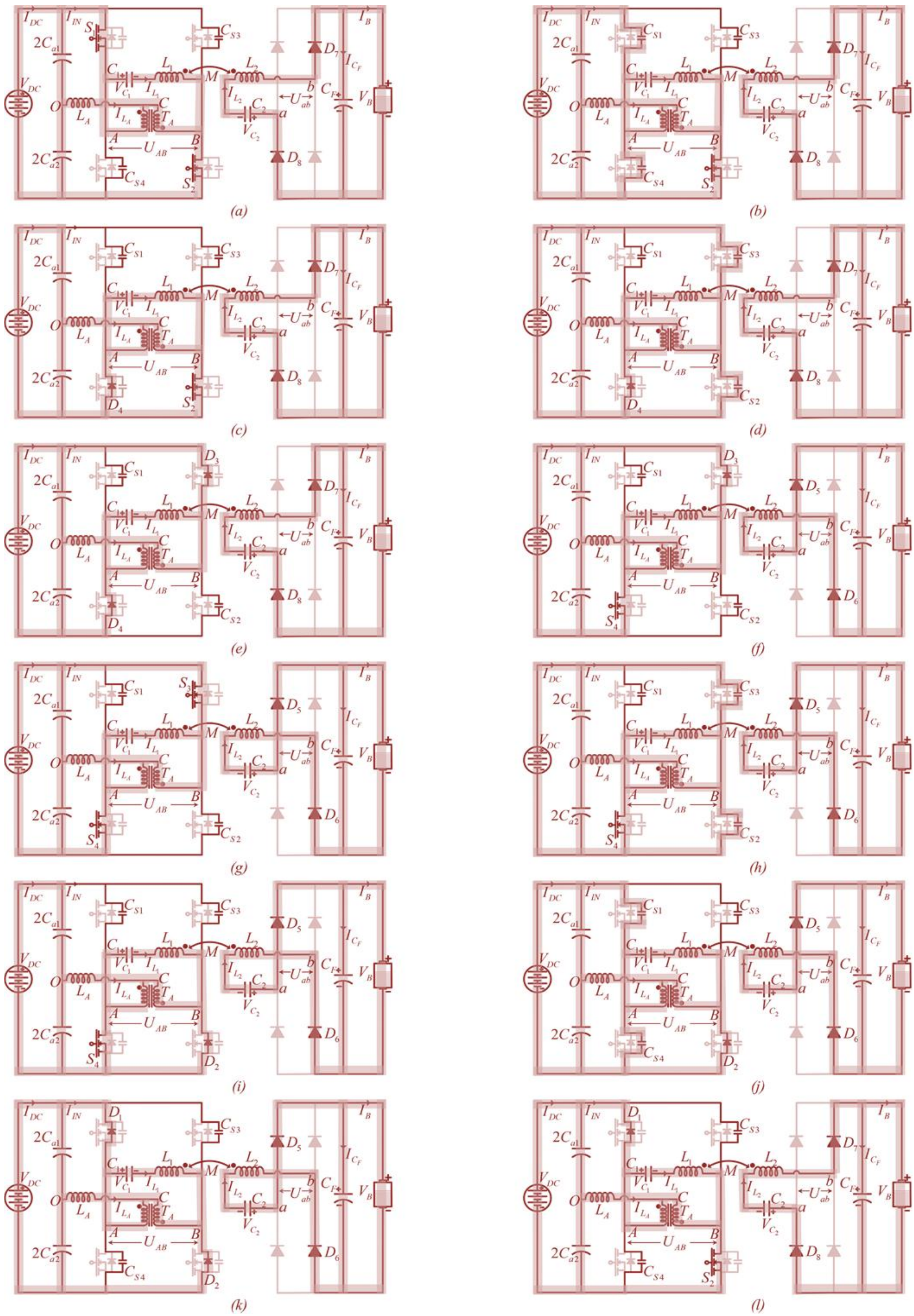

Fig.1. Operating modes of proposed battery charger topology

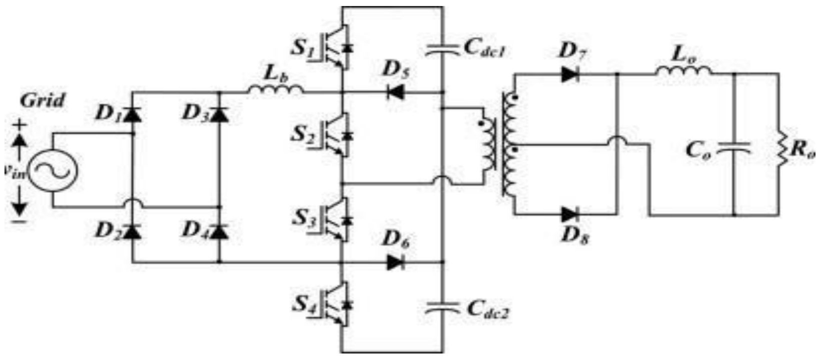

Fig. 2. Diode bridge and a boost inductor with standard three-level converter

The boost inductor plays a crucial role in controlling the shape of the input current waveform. By operating in Discontinuous Conduction Mode (DCM), the inductor ensures that the current drawn from the supply resembles a sinusoidal waveform, thereby improving the input power factor.

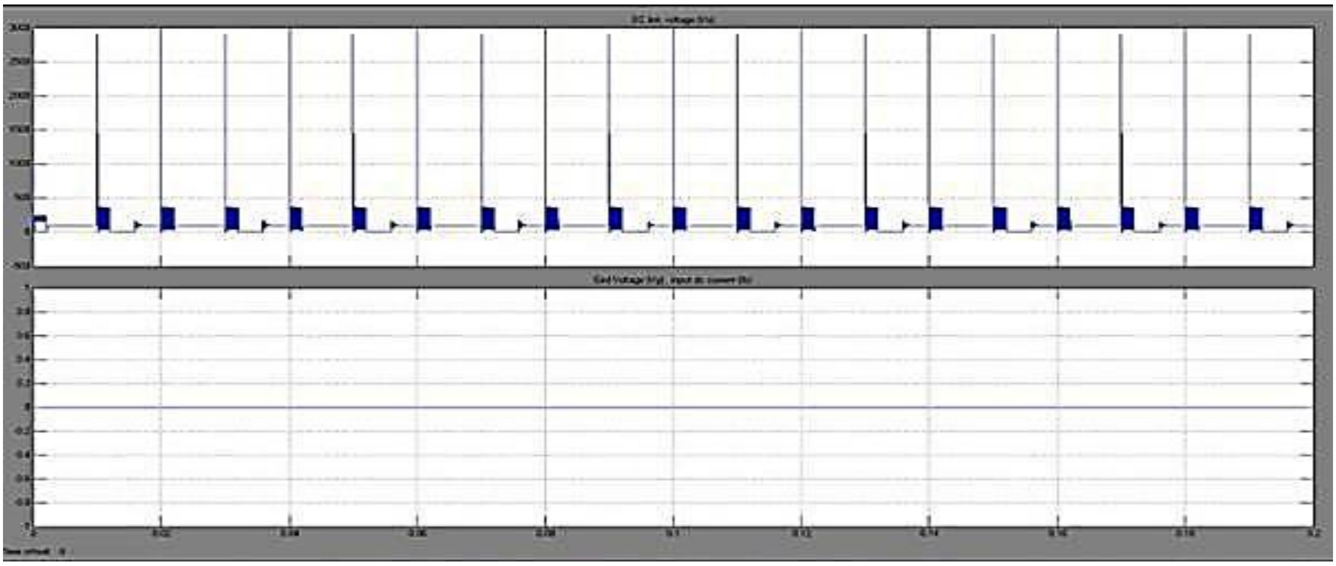

Fig. 3. WPT current and voltage

During the switch ON period, energy is stored in the boost inductor and is later released when the switches turn OFF. The current rise in the inductor during the charging period can be described by

$$\Delta I_{Lb} = \frac{V_{in} \cdot D \cdot T_s}{L_b}$$

Where Vin is the instantaneous input voltage, D is the duty cycle, Ts is the switching period, and Lb is the boost inductor. This controlled energy transfer mechanism minimizes total harmonic distortion (THD) and allows for natural power factor correction, as confirmed in the current waveform in Fig. 3.

The transformer in the circuit provides galvanic isolation and enables voltage level adjustment between the input and output sides. The output voltage depends on the switching duty cycle and the turns ratio of the transformer. The relationship is expressed as:

$$D_2 = \frac{N \cdot V_0}{V_{dc}}$$

Where V_o denotes the regulated output voltage, V_{dc} refers to the voltage present across the DC link capacitors, and N represents the transformer's turns ratio. This relation is instrumental in determining appropriate transformer dimensions and in maintaining output stability across diverse operating scenarios.

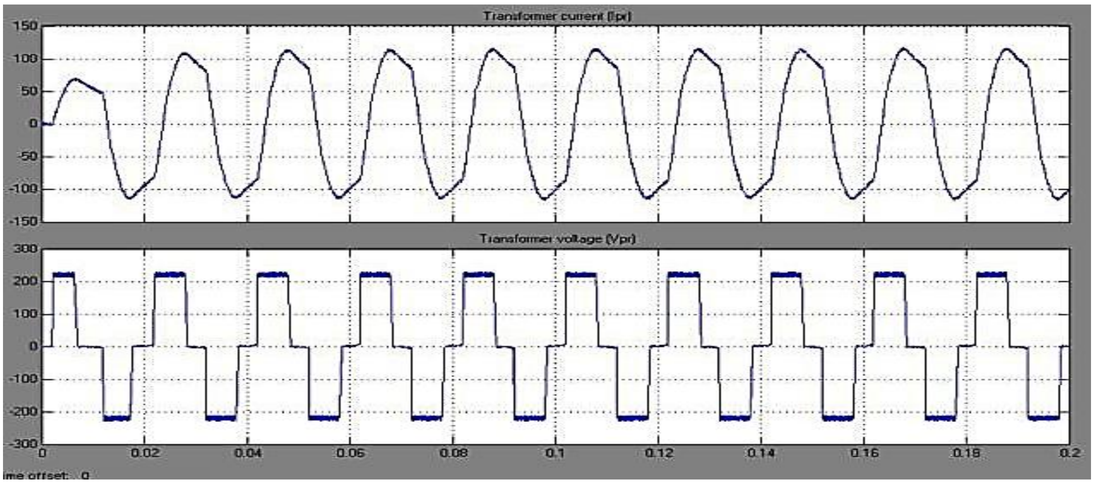

Fig. 4.Transformer current and Transformer voltage

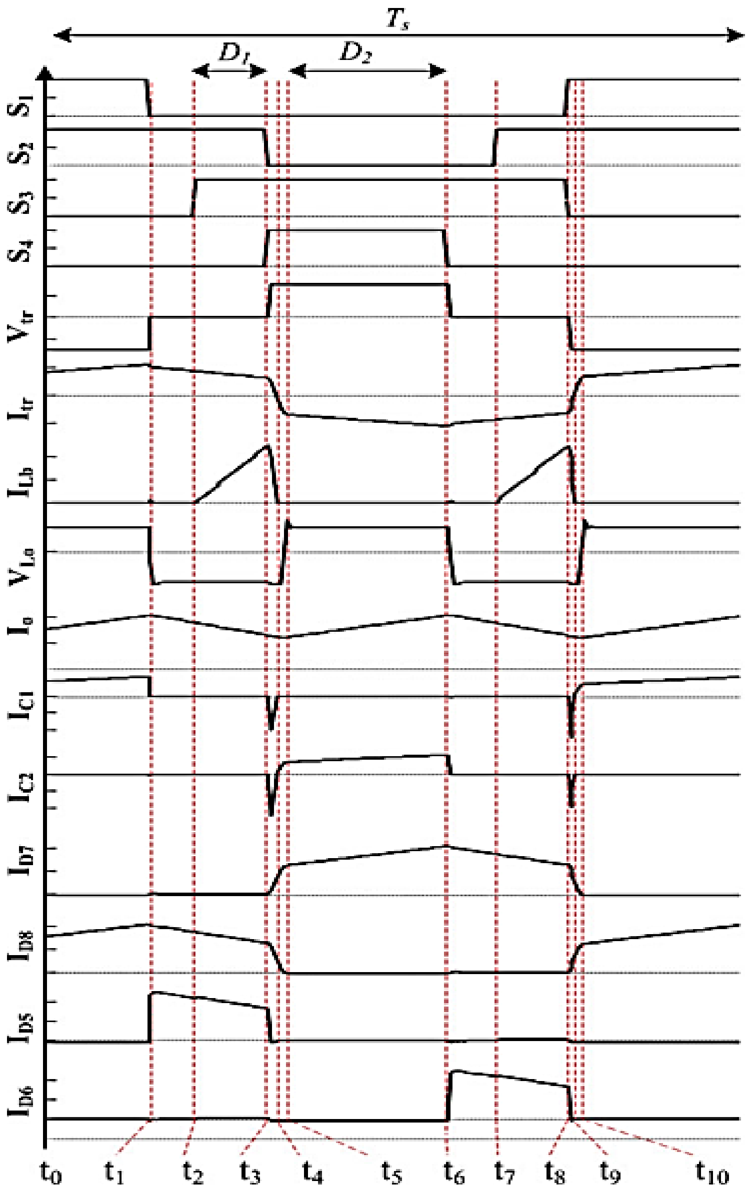

Fig. 5. Switching scheme of the given converter

To improve switching performance, the converter is configured to function under soft-switching conditions. Zero Voltage Switching (ZVS) is realized on the primary-side switches (S1 to S4) by enabling resonance between the leakage inductance of the transformer and the parasitic capacitance during dead-time, ensuring the switch voltage is near zero upon activation. The approximate ZVS condition is expressed as:

$$I_{res} > \frac{C_{oss} \cdot V_{sw}}{t_{dead}}$$

Where Ires is the resonant current, Coss is the switch output capacitance, Vsw is the switch voltage and tdead is the time gap between switch transitions. On the secondary side, ZCS is enabled for the diodes (D5 to D8) as the current through them naturally falls to zero before they are turned off. This eliminates reverse recovery losses and reduces the stress on the diodes. Fig. 4 illustrates the transformer voltage and current waveforms, highlighting the achievement of ZVS and ZCS conditions.

The effectiveness of the proposed system is validated through simulation, and the power conversion efficiency is calculated using:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Where Pout=Vo ·Io is the power delivered to the load and Pin=Vin· I in is the power drawn from the source. The simulation results, illustrated in Fig. 9 and Fig. 10, confirm that the converter operates with minimal voltage and current ripple and maintains an overall efficiency of approximately 91.26%. This efficiency is achieved while preserving soft-switching operation and meeting the output voltage requirements for both resistive and battery-type loads.

V. SIMULATION RESULTS

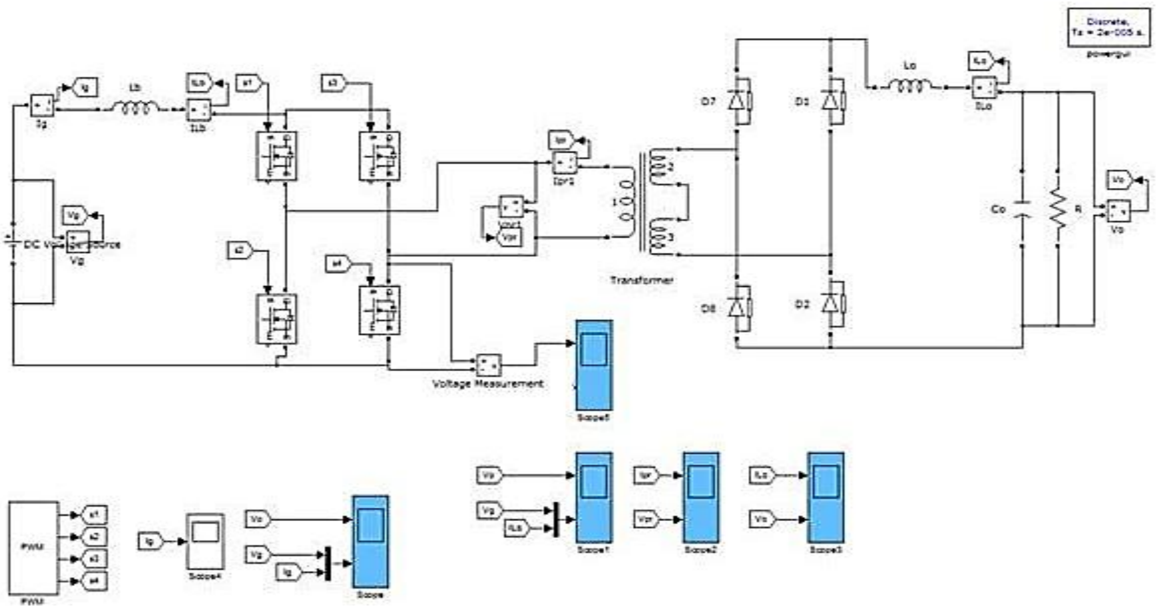

Fig. 6. Simulation circuit (reference topology)

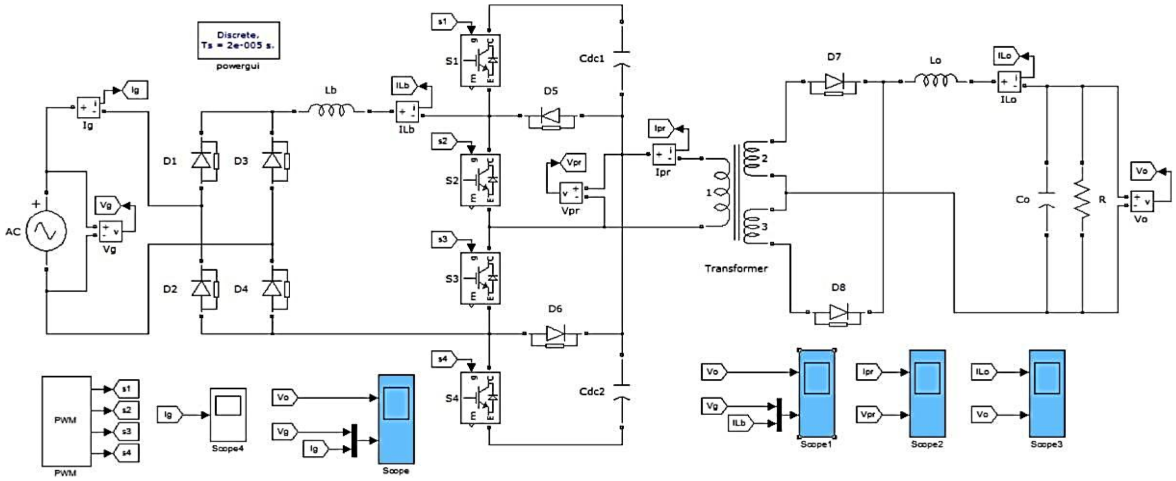

Fig. 7. Proposed circuit

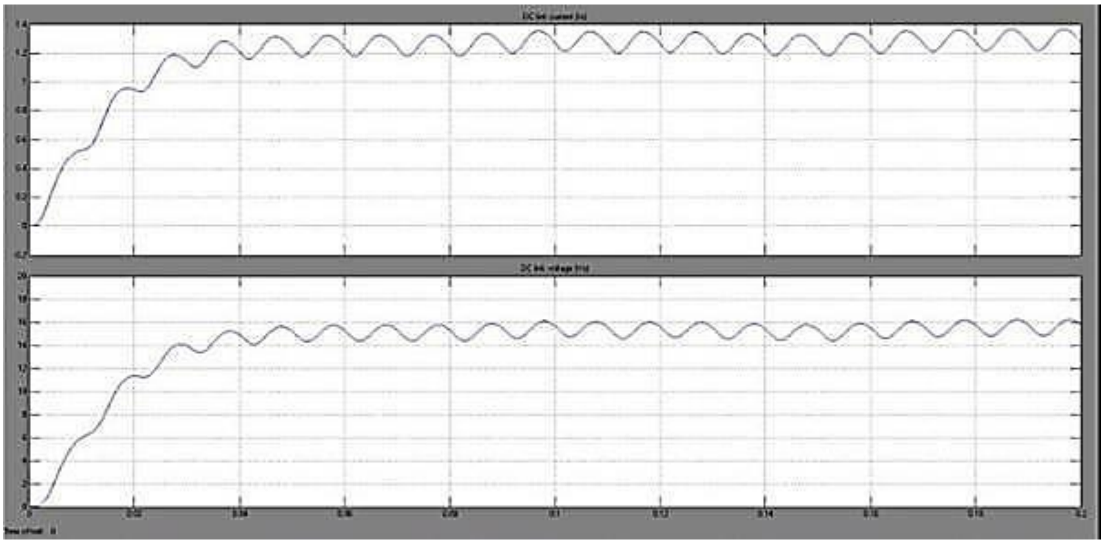

Fig. 8. Output voltage and current with the ripple

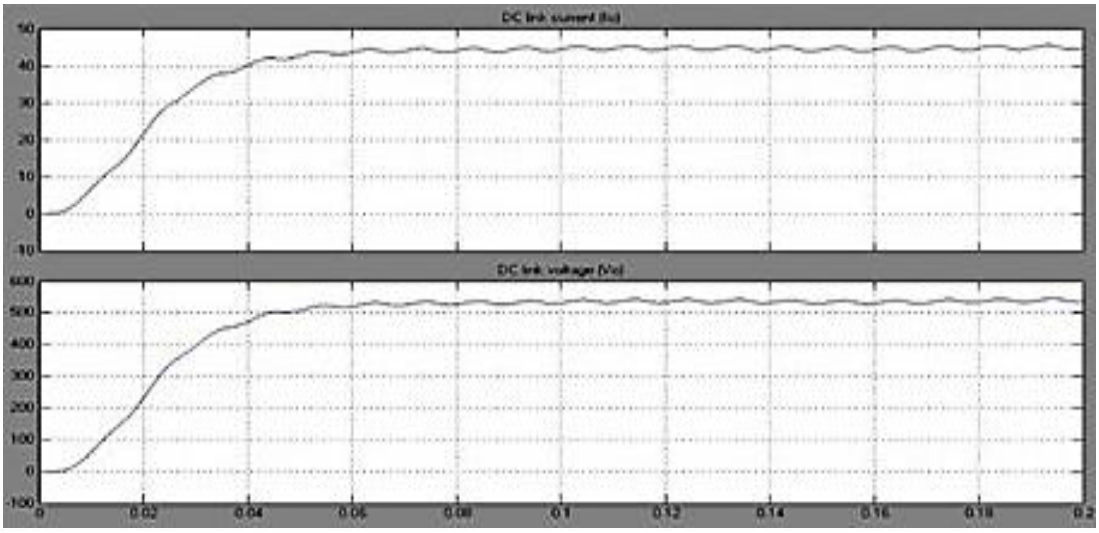

Fig. 9. Achieved DC link voltage and Grid voltage with decreased ripple

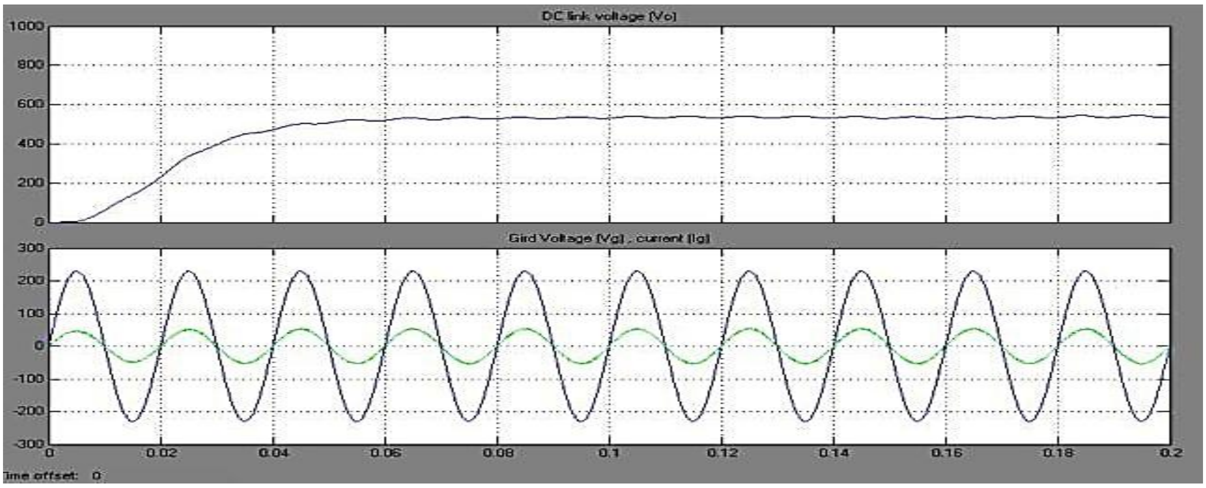

Fig. 10.DC link current and Voltage with the decreased ripple

VI. CONCLUSION

This study introduces a refined wireless power transfer topology specifically designed for charging electric vehicle (EV) batteries. The configuration employs a voltage-driven series compensation method, paired with a precisely engineered tuning strategy that enhances the operational efficiency of a full-bridge DC–DC converter. These improvements enable the converter to handle a wide range of input voltage fluctuations effectively, ensuring consistent and reliable power delivery under various loading conditions. A significant advantage of this topology is its ability to operate without the use of high-speed digital processors or advanced control units, simplifying the overall system design and lowering manufacturing costs. To maintain soft-switching capabilities—namely, achieving both zero-voltage switching (ZVS) and zero-current switching (ZCS)—without adding complexity, the proposed method leverages comprehensive analytical modelling and theoretical simulations. These efforts ensure optimal control over the switching sequences, reducing switching losses and enhancing overall energy efficiency. Additionally, the system utilizes smaller DC link and output filter capacitors, which contributes to minimizing voltage and current oscillations on both the input and output sides. This design approach not only improves electrical performance but also supports a more compact and economical hardware layout.

By addressing both switching efficiency and ripple reduction, this method ensures optimal functionality without the need for high-end components or controllers. As a result, the topology delivers superior performance while maintaining affordability and simplicity, making it an attractive solution for wireless EV charging applications that demand reliability, efficiency, and low system overhead. Its capability to maintain soft switching over a wide operating range reinforces its practicality in modern energy transfer systems.

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