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Original Article

Enhanced Wireless Power Transfer Using LCCL–LC Compensation for Electric Vehicle Charging

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ABSTRACT

The rapid adoption of electric vehicles (EVs) has become an essential step toward reducing greenhouse gas emissions and minimizing dependence on fossil fuels. In this context, the development of efficient and user-friendly charging systems is crucial for supporting the growing EV infrastructure. This paper presents the design and analysis of an LCCL–LC compensated wireless power transfer (WPT) system for EV charging applications. The proposed system employs a resonant inductive coupling technique to improve power transfer efficiency and maintain stable operation under varying load conditions that represent different battery states of charge and capacities. The performance of the system is evaluated by analysing output voltage stability, resonance behaviour, and power transfer efficiency across different load resistances and coupling coefficients. Simulation results demonstrate that the proposed LCCL–LC topology achieves efficient power transfer ranging from 50% to 94% as the coupling coefficient varies from 0 to 0.9 at a load resistance of 3 Ω. In addition, the system maintains stable output voltage under load resistance variations between 1 Ω and 4.5 Ω, indicating strong tolerance to changing operating conditions. The proposed compensation topology also enhances resonance stability and reduces performance degradation caused by coil misalignment and load fluctuations. The findings confirm that the LCCL–LC compensated WPT system provides a reliable and efficient solution for wireless EV charging applications. The proposed approach contributes to the advancement of flexible, high-performance, and sustainable EV charging infrastructure, supporting the wider adoption of electric transportation technologies.

Keywords: electric vehicle, wireless power transmission, LCCL to LC topology, inductive link..

INTRODUCTION

Magnetic Resonant Coupling Wireless Power Transfer (WPT) technology has become an advanced method for charging electric vehicles (EVs) without requiring direct electrical contact. In this technology, electrical energy is transferred from a power source to the vehicle through magnetic resonance between two coils. One coil act as the transmitter connected to the power supply, while the other acts as the receiver integrated into the EV system. This contactless charging approach improves convenience and provides greater flexibility in EV charging applications.

Wireless charging systems offer several advantages compared to conventional plug-in charging methods. They eliminate the need for physical connectors, making the charging process simpler and more user-friendly. In addition, the absence of exposed conductive parts reduces the possibility of electric shock and minimizes mechanical wear caused by repeated connection and disconnection of charging cables. Another important advantage is the capability of supporting both stationary and dynamic charging, allowing vehicles to charge even while moving. These benefits make WPT technology an attractive solution for future EV charging infrastructure.

Despite these advantages, several technical challenges still limit the widespread adoption of wireless charging systems. Maintaining high power transfer efficiency, reducing sensitivity to coil misalignment, increasing transmission distance, minimizing system cost, and achieving proper standardization remain important research issues. Among these challenges, the design of the compensation network plays a major role in determining the overall performance of the WPT system. Compensation circuits are essential for

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maintaining resonance conditions, improving power transfer capability, and reducing the Volt–Ampere (VA) stress on power electronic components.

Various compensation topologies have been developed for EV wireless charging applications. The commonly used basic compensation structures include Series–Series (SS), Series–Parallel (SP), Parallel–Series (PS), and Parallel–Parallel (PP) topologies. In these configurations, the terms series and parallel represent the connection type used on the primary and secondary sides of the system. Although these topologies are widely used because of their simplicity, they often suffer from drawbacks such as sensitivity to parameter variations, reduced efficiency under changing operating conditions, and control instability.

To improve system performance, researchers have introduced higher-order compensation topologies such as LCL and LCC configurations. The LCL topology is widely used in applications requiring harmonic filtering and stable power transfer, including EV charging systems and grid-connected converters. However, the inclusion of additional inductors and capacitors increases circuit complexity, system size, and implementation cost. Moreover, careful design and tuning are necessary to avoid resonance instability and maintain reliable operation.

Similarly, LCC compensation topologies are preferred in high-efficiency wireless charging systems because of their improved resonance characteristics and better power transfer capability. However, LCC networks are highly sensitive to load variations, and improper tuning may result in efficiency reduction, increased component stress, and unstable operation. In addition, the control strategy of LCC systems is comparatively complex, making practical implementation more challenging. On the other hand, LC compensation networks provide a simpler and lower-cost alternative. Transitioning from LCL or LCC structures to LC compensation can reduce circuit complexity and minimize component count. However, LC topologies may experience lower filtering performance, increased harmonic distortion, and reduced efficiency under varying load conditions. Therefore, selecting an appropriate compensation topology involves balancing efficiency, complexity, cost, and operational stability. With the rapid growth of electric vehicle adoption, the demand for efficient and reliable wireless charging systems is continuously increasing. Conventional charging methods often suffer from power losses, reduced efficiency, and long charging durations. To address these limitations, this paper investigates the design and analysis of an LCCL–LC compensated wireless power transfer system for EV charging applications. The proposed topology combines the advantages of LCCL and LC compensation methods to improve power transfer efficiency, maintain resonance stability, and provide reliable performance under varying load and coupling conditions. The system performance is analysed under different operating scenarios to evaluate its suitability for practical EV wireless charging applications.

II. PROPOSED METHOD

The topology operates based on magnetic resonant inductive coupling, which allows electrical power to be transmitted across an air gap without any physical electrical connection between the transmitter and receiver.

On the primary side, the AC input voltage source V_{in}supplies energy to the resonant compensation network formed by inductor $L_1$and capacitors $C_1$and C_2. These elements create the LCCL resonant circuit, which regulates the input current and maintains resonance at the desired operating frequency. The resonant network helps reduce reactive power losses and improves overall transmission efficiency.

The transfer of energy from the transmitter to the receiver takes place through the coupled inductors $L_2$and L_3, which function as a loosely coupled transformer. The strength of the magnetic coupling between these coils directly affects the amount of transferred power and the efficiency of the system. On the secondary side, capacitor $C_3$is connected in series with inductor $L_3$to form the LC compensation network. This secondary resonant circuit ensures proper resonance matching with the primary side, thereby maximizing wireless power transfer performance.

The EV battery charging section is represented by the load resistance R_{load}, while resistor $R_2$is included to improve circuit stability and suppress unwanted fluctuations during operation. The resonant frequency of the primary LCCL compensation circuit is expressed as:

$$f_{r1} = \frac{1}{2\pi\sqrt{(L_1 + L_2)C_1}}$$

Similarly, the resonant frequency of the secondary LC compensation circuit is given by:

$$f_{r2} = \frac{1}{2\pi\sqrt{L_3 C_3}}$$

The quality factors of the resonant inductors are calculated using:

$$Q_{L1} = \frac{\omega L_1}{R_1}, Q_{L2} = \frac{\omega L_2}{R_2}, Q_{L3} = \frac{\omega L_3}{R_{load}}$$

where $\omega = 2\pi f$, and $R_1$and R_2denote the resistive losses associated with the primary and secondary coils.

The mutual inductance between the coupled coils is determined by:

$$M = K_{23}\sqrt{L_2 L_3}$$

where K_{23}represents the coupling coefficient between the transmitter and receiver coils.

The efficiency of the proposed WPT system is evaluated using the following expression:

$$\eta = \frac{k_{23}^2 Q_2 Q_3}{(1 + k_{23}^2 Q_2 Q_3)(Q_2 + Q_3)} \times \frac{R_{load}}{R_{load} + R_2}$$

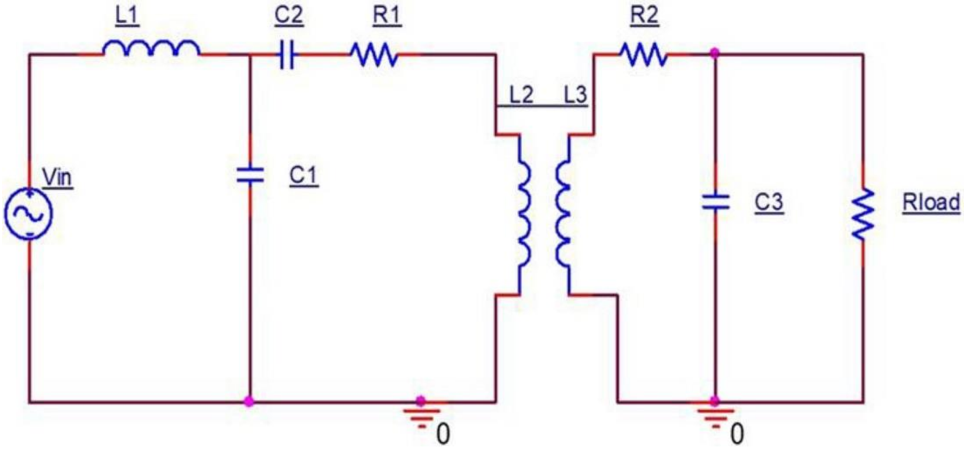

Fig:1 The LCCL to LCL topology

This equation considers the influence of the coupling coefficient, resonant quality factors, and resistive losses on overall power transfer efficiency. Under resonance conditions, the inductive and capacitive reactance cancel each other, resulting in a purely resistive impedance that enhances power transfer capability.

The proposed system is designed to operate with an input voltage of 400 V and a resonant frequency of 85 kHz to satisfy EV charging requirements. The values of inductors $L_1, L_2, L_3$and capacitors C_1, C_2, and $C_3$are selected through iterative simulations and optimization procedures to achieve maximum efficiency and stable resonant operation.

To validate the proposed design, the system performance is analysed under different operating conditions, including variations in coupling coefficient and load resistance. These variations represent practical EV charging situations such as coil misalignment, air-gap changes, and battery state-of-charge fluctuations. The evaluation focuses on resonance stability, output voltage regulation, and power transfer efficiency to confirm the suitability of the proposed LCCL–LC compensation topology for practical wireless EV charging applications.

Topology	**Configuration**	**Advantages**	**Disadvantages**	**Best used for**
Series-Series (SS)	Both sides with series resonant circuits	Simple, high efficiency, effective in closely coupled systems	Less effective over larger distances or misalignments	Applications with fixed, close distance between coils
Series-Parallel (SP)	Transmitter in series, receiver in parallel	Good power transfer over varying distances, forgiving of misalignments	More complex than SS	Situations with variable distances or alignments
Parallel-Series (PS)	Transmitter in parallel, receiver in series	Stable voltage across varying power levels	Complexity in tuning	Applications with variable loads on the receiver
Parallel-Parallel (PP)	Both sides with parallel resonant circuits	Suitable for high power levels, stable with fixed coupling coefficient	Less common, can be inefficient if not closely coupled	High power applications with stable coupling coefficient

Table 1. The different types of compensation topologies

RESULT AND DISCUSSION

WPT systems show promise, in providing Wireless Power Transfer (WPT) systems have gained significant attention as an efficient and convenient charging solution for electric vehicles (EVs). Among the various WPT techniques, inductive resonant coupling is widely preferred because of its high-power transfer capability, operational safety, and suitability for EV charging applications.

The performance of these systems mainly depends on the LC resonant circuit, where accurate tuning of the resonance frequency is essential for achieving maximum efficiency and stable operation.

This study investigates the behaviour of the proposed LCCL–LC compensated WPT system under different coupling conditions to analyse the effect of coupling coefficient variations on resonance frequency and power transfer efficiency. The obtained simulation results provide valuable insight into the operating characteristics of the system and its suitability for practical EV charging applications under varying environmental and load conditions.

The simulation results indicate that the resonance frequency changes according to the coupling conditions between the transmitter and receiver coils. Distinct resonance peaks are observed at different coupling coefficients, representing the operating points where the system achieves maximum power transfer efficiency.

These resonance peaks occur when the transmitter and receiver coils are properly aligned, allowing effective magnetic coupling and improved energy transfer.

Specifications	**Value**
Input voltage, *Vin*	400 V
Resonance frequency, f_0	85 KHz
Self-inductance of the coil1, L_1	900 nH
Self-inductance of the coil2, L_2	1.15 µH
Self-inductance of the coil3, L_3	90 µH
Compensation capacitor, C_1	3.90 µF
Compensation capacitor, C_2	3.05 µF
Compensation capacitor, C_3	38.95 nF
Resistance, R_1	0.417 Ω
Resistance, R_2	0.55 Ω
Load resistance, *Rload*	3 Ω

Table 2. Illustration of the parameter value of the circuit

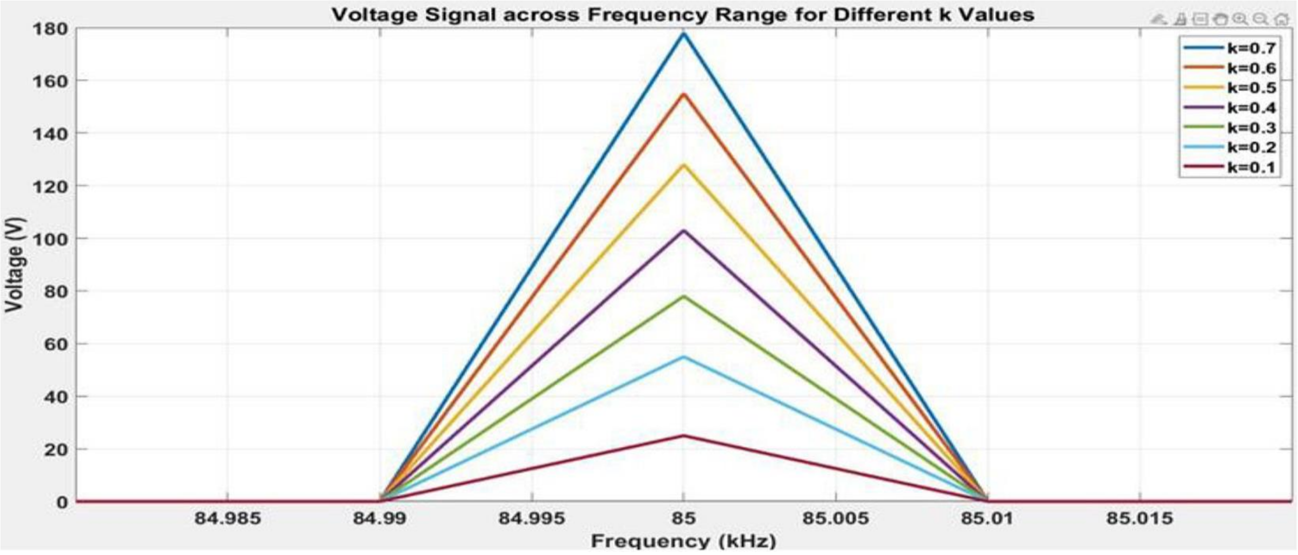

Figure 2. The resonance frequency between the transmitter and receiver coils with variable coupling

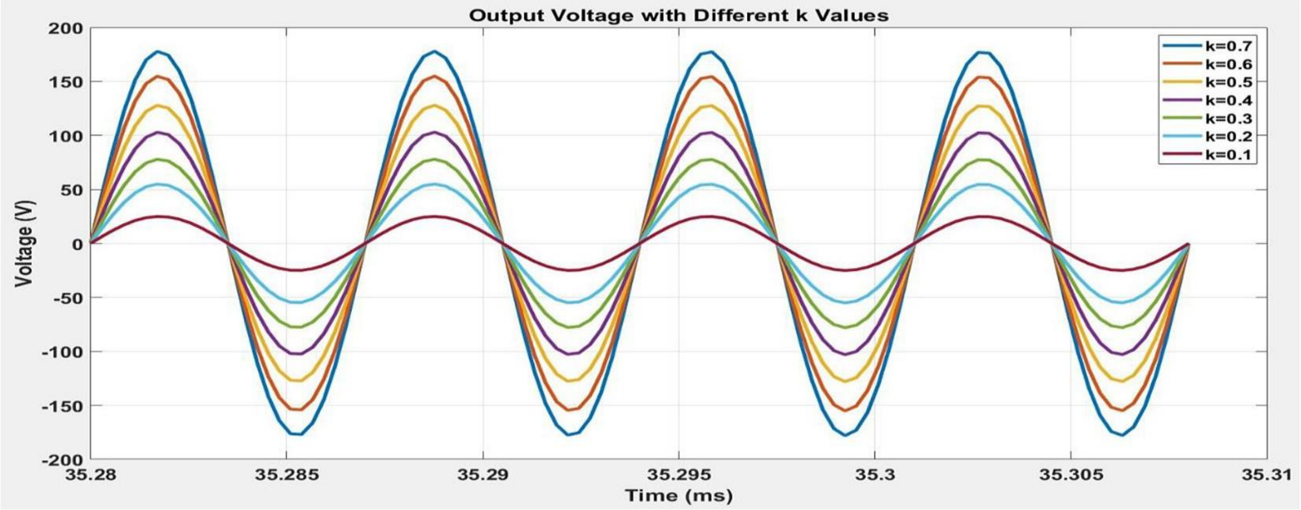

Figure 3. The multiple voltage waveforms with various coupling coefficients

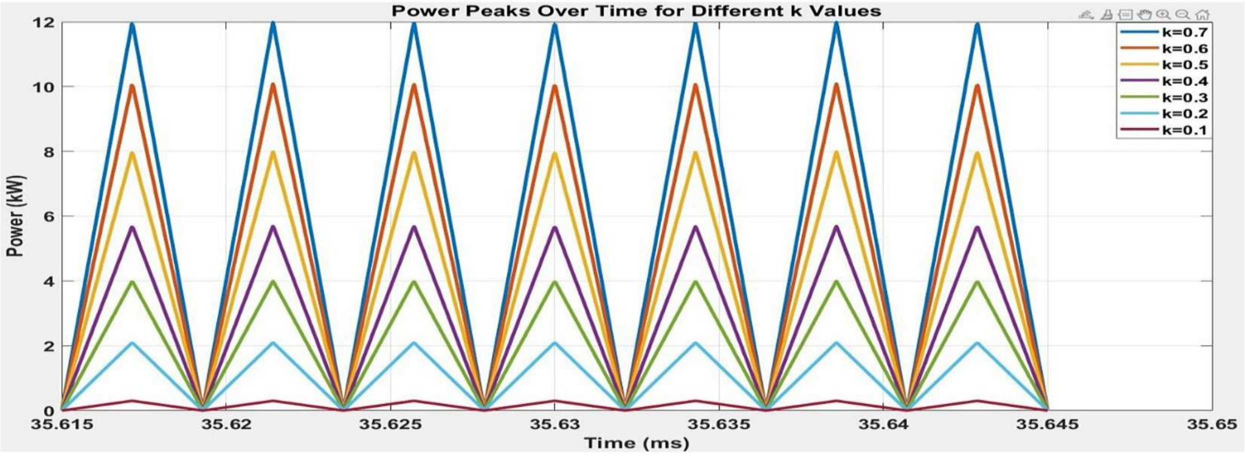

Figure 4. The output power corresponding to a high coupling coefficient

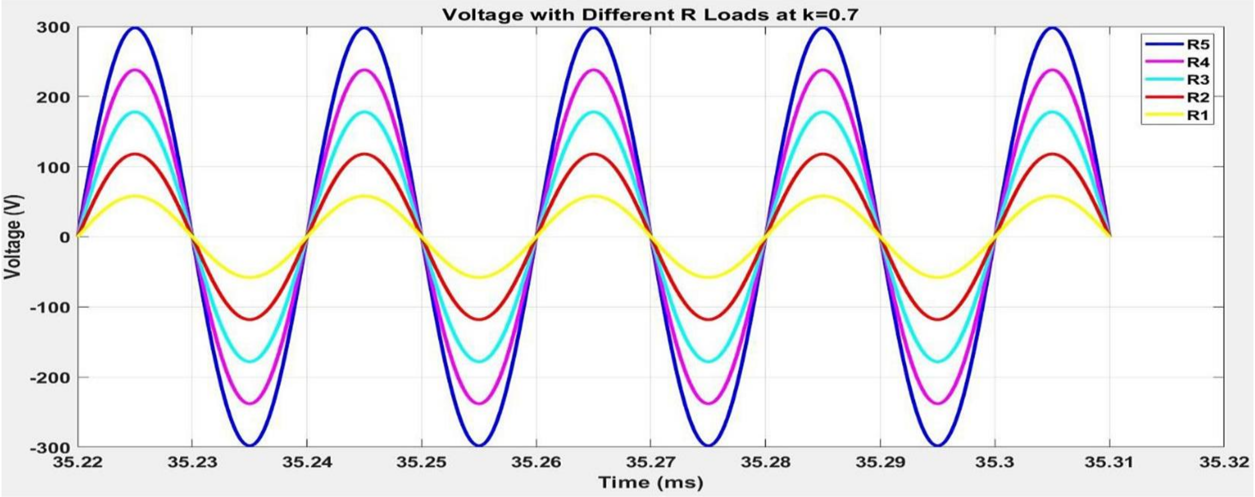

Figure 5. The output voltage with variable resistance load

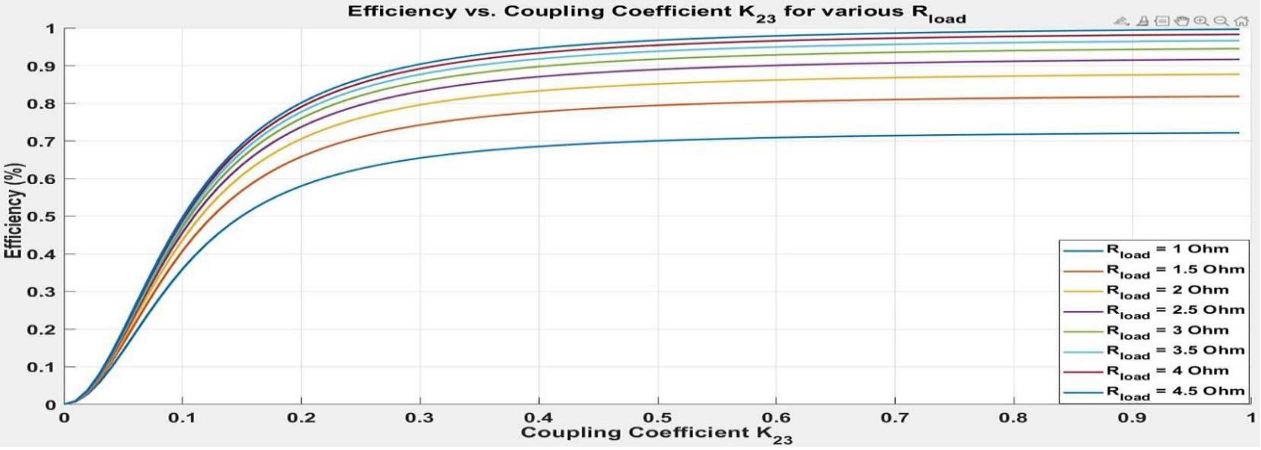

Figure 6. The relationship between efficiency and the coupling coefficient *K*23 for various load resistances *R_{load}*

Figure 2 illustrates the relationship between the coupling coefficient and the resonance frequency of the proposed system. As the coupling coefficient decreases due to increased coil separation or misalignment, noticeable shifts occur in the resonance frequency. This behavior demonstrates the sensitivity of the system to coil positioning and highlights the importance of maintaining proper alignment between the transmitter and receiver coils for efficient wireless power transfer.

The voltage amplitude across the resonant circuit also varies with the coupling coefficient. At resonance, the voltage reaches its maximum value, indicating effective power transfer between the primary and secondary sides. Higher coupling coefficients produce sharper and more pronounced resonance peaks, which correspond to higher quality factor (Q-factor) characteristics and lower energy losses within the circuit. In contrast, weaker coupling conditions result in reduced voltage amplitude and lower transfer efficiency.

Figure 3 presents the output voltage waveforms corresponding to different coupling coefficients between the inductive coils. The results clearly show that the output voltage magnitude increases with an increase in coupling coefficient. Strong magnetic coupling, achieved through closer coil alignment, improves magnetic flux linkage and increases the induced voltage in the secondary coil. This observation agrees with the theoretical characteristics of resonant inductive power transfer systems.

In addition to voltage magnitude variation, phase differences are also observed between the voltage waveforms under different coupling conditions. Although the waveforms maintain a sinusoidal nature, slight phase shifts occur as the coupling coefficient changes. The phase relationship between the primary and secondary voltages plays an important role in determining the real power delivered to the load and directly affects the overall efficiency of the WPT system.

The coupling coefficient also influences the tolerance of the system to coil misalignment and positional variations. A WPT system capable of maintaining stable output voltage over a wide range of coupling coefficients is more suitable for practical EV charging applications, where perfect alignment between the charging coils cannot always be achieved. The simulation results demonstrate that the proposed LCCL–LC topology maintains acceptable performance even under varying coupling conditions.

Figure 4 shows the relationship between output power and coupling coefficient. The results indicate that the output power reaches its maximum value at higher coupling coefficients, which correspond to shorter distances and stronger magnetic interaction between the coils. As the coupling coefficient decreases, the output power reduces significantly due to weaker magnetic coupling. The sharp resonance peaks observed at high coupling conditions indicate that efficient power transfer can be achieved within a limited operating range where proper coil alignment is maintained. The effect of load variation on system performance is also investigated. In practical EV charging systems, the battery load is not constant because the internal battery resistance changes during the charging process. The simulation results show that the proposed WPT system can accommodate these load variations without significant degradation in efficiency or power delivery performance. This characteristic is essential for maintaining reliable charging operation under different battery conditions. The voltage waveforms corresponding to different load resistances are presented in Figure 5. The results indicate that the output voltage amplitude changes with variations in load resistance due to differences in impedance matching between the WPT system and the load. Each load resistance value produces a distinct resonant response within the system. However, despite these variations, the output waveforms remain predominantly sinusoidal, confirming stable resonant operation. Slight waveform distortions observed under certain operating conditions indicate the presence of harmonics and minor deviations from ideal resonance. Nevertheless, the proposed system demonstrates good tolerance against load resistance variations, which is an important requirement for practical EV charging systems. The ability to maintain stable operation under changing battery conditions improves charging reliability and overall system performance. Figure 6 illustrates the relationship between efficiency and coupling coefficient K_{23} for different load resistance values ranging from 1 Ω to 4.5 Ω. The results show that the system efficiency increases with increasing coupling coefficient for all load conditions. Stronger coupling improves magnetic energy transfer between the coils, thereby increasing overall efficiency. It is also observed that the difference between efficiency curves for different load resistances decreases at higher coupling coefficients. This indicates that the influence of load resistance becomes less significant when strong magnetic coupling is achieved. Furthermore, the highest efficiency is obtained at an intermediate load resistance rather than the minimum resistance value, indicating the existence of an optimal impedance matching condition for maximum power transfer efficiency. The proposed LCCL–LC compensation topology offers several advantages compared to conventional LC compensation structures. While traditional LC compensation is simple and cost-effective, the LCCL configuration improves filtering performance, resonance stability, and overall power transfer efficiency. The inclusion of additional inductive and capacitive components enables better control of the frequency response, resulting in sharper resonance characteristics and reduced passband fluctuations. Another advantage of the proposed topology is its ability to achieve high quality factor performance without requiring large inductance values, thereby reducing the physical size and cost of the system. The LCCL–LC structure effectively balances efficiency, performance, and practical implementation requirements, making it highly suitable for modern EV wireless charging applications. Table 3 compares the proposed topology with other compensation techniques reported in previous studies. The proposed LCCL–LC topology achieves an output power of 8 kW with an efficiency of 94% at an operating frequency of 85 kHz. These results demonstrate that the proposed system provides superior performance, stable operation, and high-power transfer capability compared to other existing compensation topologies used in EV wireless charging systems.

References	Compensation topology	Frequency (KHz)	Output power (KW)	Efficiency (%)
[32]	SS	85	3.7	90.02
[33]	LCL	85	3	95
[34]	LCCL-S	85	3.3	94.35
[35]	LCC- LCC	81.25	3	96.3
[36]	LCL-CLC	81.4	0.144	92.43
Proposed	LCCL-LC	85	8	94

Table 3: Comparison of WPT for charging EVs with different topologies

CONCLUSION

The proposed LCCL–LC resonant Wireless Power Transfer (WPT) system for electric vehicle (EV) charging demonstrated effective performance under varying load resistance conditions while maintaining efficient power transfer characteristics. The results confirm that the proposed compensation topology provides stable operation and reliable energy transmission even when the load conditions change according to different EV battery charging states. The ability of the system to adapt to varying load resistances highlights its suitability for practical EV charging applications. The proposed WPT system maintained stable output voltage and acceptable efficiency levels under different operating conditions, indicating strong tolerance against load fluctuations and coupling variations. This capability is important for real-world EV charging environments where battery conditions and coil alignment continuously vary during operation. The analysis also showed that the proposed topology can achieve efficient wireless energy transfer without requiring direct electrical contact or precise coil positioning. Such flexibility improves user convenience, enhances operational safety, and reduces the limitations associated with conventional wired charging systems. In addition, the LCCL–LC compensation structure improves resonance stability and power transfer performance while reducing energy losses within the system. The findings of this work demonstrate the potential of the proposed LCCL–LC compensated WPT system as a reliable and high-performance solution for future EV charging infrastructure. The improved efficiency, stable operation, and adaptability of the system make it suitable for supporting the increasing demand for wireless EV charging technologies. As electric vehicle adoption continues to increase globally, the development of efficient and intelligent wireless charging systems becomes increasingly important. The proposed approach contributes toward the advancement of sustainable transportation technology by enabling convenient, efficient, and user-friendly EV charging solutions. Therefore, this research represents an important step toward the realization of advanced wireless charging infrastructure for next-generation electric vehicles.

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