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Design and Analysis LCCL–LC Compensation for Electric Vehicle Systems

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ABSTRACT

The shift towards cars electric vehicle (EVs) plays a role in the global effort to combat climate change by reducing dependence on fossil fuels. An important part of this shift involves creating user EV charging systems. This study looks into how a connected coil design in a wireless power transfer system can help overcome challenges in EV charging when dealing with varying loads. We examine how well the system performs under load resistances that mimic states of charge and battery capacities in EVs. By assessing the stability of output voltage and efficiency of power transfer across these loads we focus on maintaining resonance within the system. Our findings show that the LCCL to LC WPT system maintains efficiency in power transfer 50–94% when coupling coefficient change (0–0.9) at load resistance 3 Ω and stable output voltage when facing changes in load resistance 1–4.5 Ω. This suggests that the system is resilient against load variations, which's crucial for real world EV charging situations. This research supports the potential of WPT systems as an efficient solution to meet the evolving demands of EV infrastructure leading towards increased adoption of EVs and a sustainable future for transportation.

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

INTRODUCTION

Magnetic resonant coupling wireless power transfer (WPT) technology enables EVs to charge by transferring electrical energy from a power source to the vehicle without the need for physical connections [1, 2]. This innovative approach harnesses magnetic resonance principles to establish a field between two coils, one linked to the power source (transmitter) and the other to the vehicle (receiver) facilitating energy transfer [3, 4]. The advantages of this method include charging without requiring plugging enhancing user friendliness [5, 6], it is easier and more user friendly [7], reduces the chance of shock [8], eliminating exposed conductors decreases wear and tear on connectors that are used often [9], and allows for charging in different scenarios like dynamic charging while vehicles are moving [10–12]. However, with all of these benefits there are also many challenges still under research like efficiency, standardization, range and alignment and cost [13, 14]. In WPT systems having a compensation circuit is crucial. It helps optimize power transfer efficiency and reduce the Volt-Ampere (VA) rating of the power electronics supply [15]. Typically, four common mono resonant compensation setups. SS, SP, PS and PP are commonly utilized [16, 17]. In each of these setup's S signifies series and P denotes parallel with the term linked to the side and the second term associated with the secondary coil. However, these configurations come with drawbacks like sensitivity to parameter changes and challenges in maintaining control stability [17]. Many researchers have also developed high-order compensation topologies but still the compensation topologies are the most crucial part that affects system performance [18]. Several topologies are used, each with its advantages depending on EV charging the best topology can depend on factors like efficiency, power requirements, transfer distance, and cost [19, 20]. However, some of the most prominent and effective topologies include in Table 1.

When it comes to WPT for EV charging, the choice of resonant circuit topology plays a crucial role in efficiency [21], cost, and ease of implementation. In the context of EVs, the choice of compensation topology is critical for optimizing the performance and efficiency of power electronic systems [22–25]. The LCL configuration is commonly applied in situations that demand filtering like connecting energy sources to the power grid and setting up EV charging stations. The main drawback of the LCL setup lies in its complexity [26]. Therefore, careful design is crucial to prevent resonance problems and maintain stability. Introducing components like another inductor and capacitor can raise both the expenses and dimensions of the system while the necessity for control might add complexity to the overall system layout [27].

LCC configurations are popular, in converters designed for efficiency commonly found in applications such as wireless charging systems for electric vehicles. However, the drawback of LCC configurations lies in their sensitivity to changes in load. Improper adjustment may result in operation loss of efficiency and potential strain on components ultimately decreasing the reliability of the system. Additionally, mastering the control of behaviour can pose a challenge due to its complexity [28]. Moving from LCL to LC might be an option in setups where top notch filtering performance's not a priority with the goal of streamlining the setup and cutting down on expenses. One downside of shifting to an LC configuration is the decrease in filtering capacity, which could result in noise and harmonics suppression performance. This can make the system more susceptible to disruptions have an impact on power quality [29].

Moving from LCC to LC is usually done to make the system simpler and cheaper for tasks. However, this shift comes with a trade-off. While LC may be more straightforward it lacks the efficiency advantages of LCC like its ability to operate efficiently. With an LC setup managing power peaks may not be as effective potentially resulting in energy loss and decreased system performance when dealing with fluctuating loads [30].

With the increasing adoption of electric vehicles, the demand for efficient and high-performance charging solutions is rising. Traditional charging methods often suffer from high losses and inefficiencies, which can result in longer charging times and increased energy consumption. In this paper, we investigate the application of transitioning from using the LCCL (inductor – capacitor – capacitor – inductor) topology to the LC (inductor – capacitor) configuration in EV charging systems. This change plays a role in improving the power transfer process with the goal of maximizing both the effectiveness and dependability of EV battery charging.

METHODOLOGY

The diagram in Figure 1 showcases a converter design consisting of passive components and a power source for effective wireless charging in EVs. The design employs a resonant inductive

Table 1. The different types of compensation topologies

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

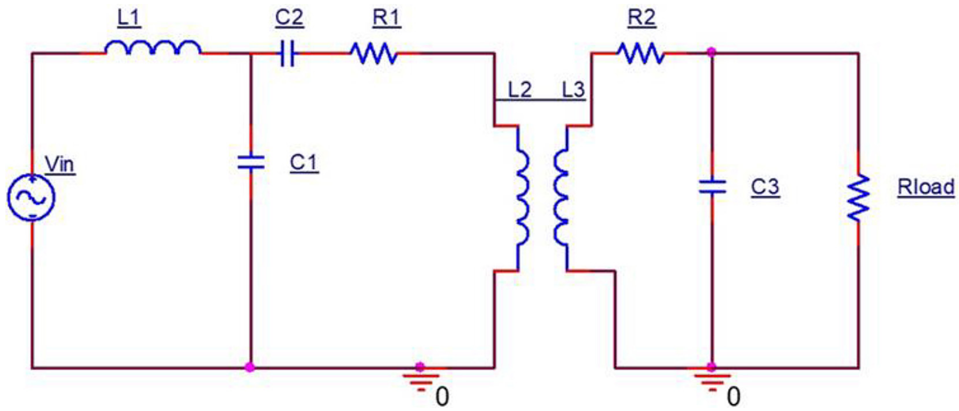

Figure 1. The LCCL to LCL topology

coupling approach, which is advantageous due to its ability to transfer power over a gap with high efficiency. The input stage consists of an AC voltage source V_{in}, which feeds into an L_1-C_1 resonant tank circuit. Inductor L_1, in conjunction with capacitors C_1 and C_2, form a series-parallel resonant circuit that filters and amplifies the AC input according to the resonant frequency determined by their values.

The energy is then transferred through a magnetically coupled L_2-L_3 inductor pair, functioning as a loosely coupled transformer, optimizing the power transfer efficiency to the secondary side. Resonant capacitor C_3, in series with the secondary inductor L_3, establishes the resonant condition necessary to match the frequency of the primary side, thereby maximizing the power transfer. On the load side, load resistor R_{load} represents the electric vehicle's battery charging circuit. The circuit is completed with a damping resistor R_2, which serves to stabilize the circuit against fluctuations and provide a pathway for startup and excess energy dissipation. Both LCCL and LC networks are types of resonant circuits used in WPT systems. The resonant frequency for LCCL side (primary side) can be find from Equation 1.

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

And the resonant Frequency for LC Side (secondary side) can be found from Equation 2.

$$f_{r2} = \frac{1}{2\pi\sqrt{L_3C_3}} \tag{2}$$

These formulas are foundational for understanding how LCCL and LC networks resonate at a frequency that facilitates efficient power transfer, the quality factors can be found from equations 3–5 [31].

$$Q_{L1} = \frac{\omega L_1}{R_1} \tag{3}$$

$$Q_{L2} = \frac{\omega L_2}{R_2} \tag{4}$$

$$Q_{L3} = \frac{\omega L_3}{R_{load}} \tag{5}$$

Here, $\omega = 2\pi f$, where f is the operating frequency, R_1 and R_2 are the resistive losses in the inductors on the primary and secondary sides, respectively.

The power transfer is related to the mutual inductance M between the primary and the secondary coils being $M = K_{23}\sqrt{L_2L_3}$. However, a commonly used basic formula for efficiency (η) in resonant inductive coupling systems, which takes into account the mutual inductance and the quality factor of the coils is given by:

$$\eta = \frac{k_{23}^2 Q_2 Q_3}{(1+k_{23}^2 Q_2 Q_3)(Q_2+Q_3)} \times \frac{R_{load}}{R_{load}+R_2} \tag{6}$$

where: k – the coupling coefficient between the inductors. Q_2 and Q_3 – the quality factors of the primary and secondary resonant circuits, respectively. R_2 – represents losses in the secondary side including the secondary coil's resistance.

This formula assumes that both coils are in resonance and that the load is purely resistive. The term R losses should include all losses in the system, such as resistive losses in the coils, losses in the tuning capacitors, and any other parasitic losses. The purpose of these networks is to achieve impedance matching between the power source and the load, maximizing the power transfer efficiency. In an LC circuit, impedance (Z) at resonance is ideally purely resistive, and the reactive components (inductive and capacitive) cancel each other out. The choice between LCCL and LC affects the EV charging system's performance in terms of efficiency, power capacity, charging speed, and operational range. These aspects are often quantified through parameters like coupling coefficient (*k*), quality factor (*Q*), and voltage gain. The circuit parameters designed are presented in Table 2.

In our implementation, the circuit operates with an input voltage of 400 V at a frequency of 85 kHz, tailored to meet the specific power requirements of the target EV. The design methodology encompasses iterative simulation paired with empirical testing to fine-tune the values of inductors L_1, L_2, L_3 and capacitors C_1, C_2, C_3 to pinpoint the optimal resonant conditions that maximize power transfer efficiency. In real world applications setting up the system requires alignment of the (L_1, C_1, C_2) and secondary (L_2, L_3, C_3) coils to be in resonance with the EV's onboard charging coil. The systems performance is thoroughly evaluated across scenarios to guarantee reliability considering variations in coil spacing and changes and in the vehicle's battery load. This thorough process ensures that the system can effectively transmit power efficiently in real world operating conditions.

RESULT AND DISCUSSION

WPT systems show promise, in providing convenient charging solutions for (EVs). Among the WPT technologies available inductive power transfer through coupling is considered a top choice due to its advantageous power and safety features. The core of systems is centered around the LC circuit, where finely adjusting the resonance frequency's vital for achieving top notch performance. This study focuses on examining an LC coupled WPT system to understand how changes in coupling coefficients affect both the resonance frequency and efficiency of power transfer. The results of this research are significant, for addressing the obstacle of establishing an EV charging network that can accommodate environmental settings and vehicle types. The outcomes obtained by conducting simulations, on the LCCL to LC resonance circuit provide information on the mechanism of power transmission. In particular the resonance frequency exhibits peaks that align with coupling scenarios. These peaks indicate the points of efficiency in the system, where the transmitter and receiver are perfectly matched to optimize power transfer to its potential.

Table 2. Illustration of the parameter value of the circuit

Specifications	Value
Input voltage, V_{in}	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, R_{load}	3 Ω

The data suggests a link between the coupling coefficient and the resonance frequency as illustrated in Figure 2. When the coupling coefficient decreases due to physical distance between the coils or misalignments there is a distinct change in the resonance frequency. This change emphasizes how sensitive the system is to arrangements emphasizing the need to properly align the transmitter and receiver coils for power transfer. Moreover, the voltage amplitude across the circuit when it resonates gives an indication of the power that can be transmitted with varying coupling settings. The peak voltage level indicates the power transfer, which happens at a resonance frequency. This peak is notably sharper and more pronounced than those corresponding to weaker couplings, indicating a higher quality factor (Q factor) of the circuit and consequently reduced energy losses.

The Figure 3 displays multiple voltage waveforms, each denoted by a different colour and symbol corresponding to various coupling coefficients between the inductive coils. These coefficients which are indicative of the magnetic linkage between the coils play a crucial role in the overall efficiency and feasibility of the wireless power system. From the waveforms, it is evident that the magnitude of the output voltage varies with the coupling coefficient. Higher coupling coefficients likely indicative of closer proximity or better alignment between the coils result in higher voltage amplitudes. This is in line with theoretical expectations as stronger coupling leads to more efficient magnetic flux linkage and increased induced voltage in the secondary coil. Another key observation is the phase relationship between the voltage waveforms at different coupling coefficients. All waveforms seem to follow the same general pattern but display phase shifts relative to one another. The phase shift between

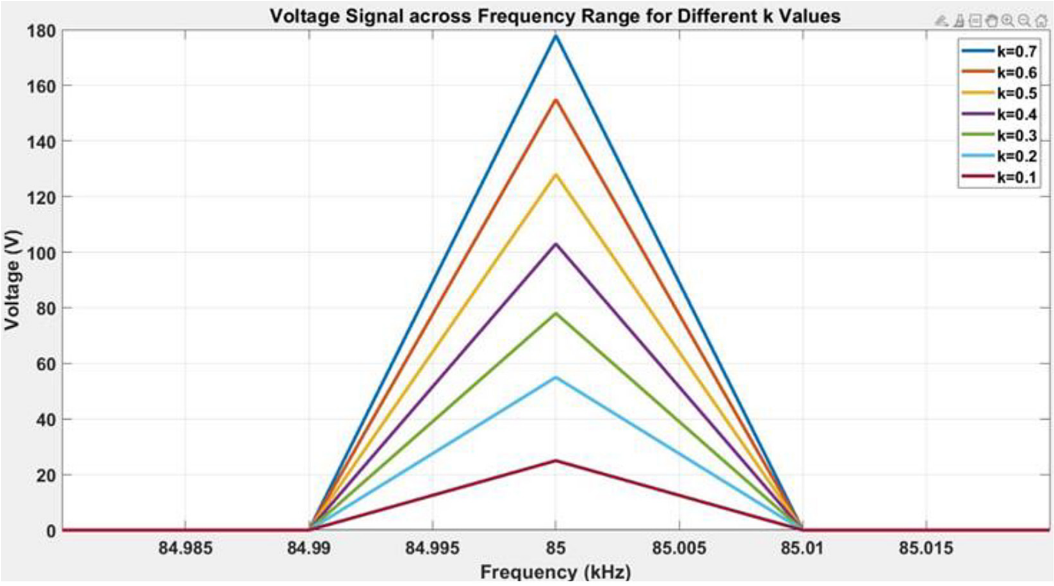

Figure 2. The resonance frequency between the transmitter and receiver coils with variable coupling coefficient

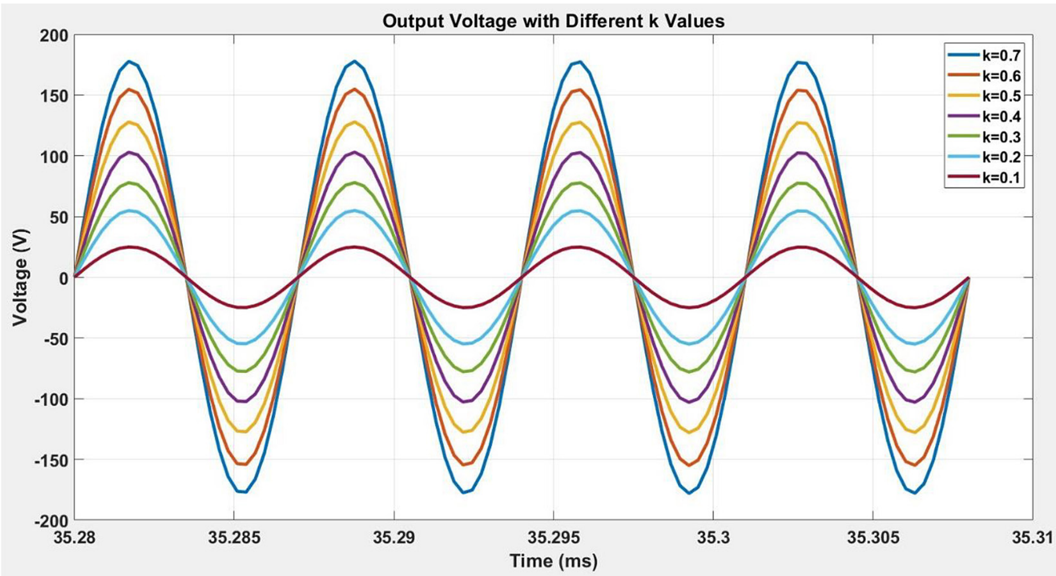

Figure 3. The multiple voltage waveforms with various coupling coefficients

the voltage across the primary and secondary sides of the transformer is a significant parameter in wireless power systems as it affects the real power transferred to the load. The coupling coefficient not only influences the amplitude of the output voltage but also the system's tolerance to misalignment and positional variance. A coupling system that maintains a relatively stable output voltage over a range of k values offers more practical applicability, as perfect alignment is challenging to achieve consistently in real-world EV charging scenarios. It is evident that the coupling coefficient has a significant impact on the output power as shown in Figure 3, there is a clear peak in the output power corresponding to a high coupling coefficient likely representing a short distance between the coils as shown in Figure 4. This peak indicates that the system is most efficient when the coils are close together as would be expected due to stronger magnetic field interactions. As the coupling coefficient decreases, we observe a substantial drop in the output power. This suggests that as the distance between the coils increases, the efficiency of power transfer decreases dramatically. The sharpness and height of the resonant peaks for higher k values

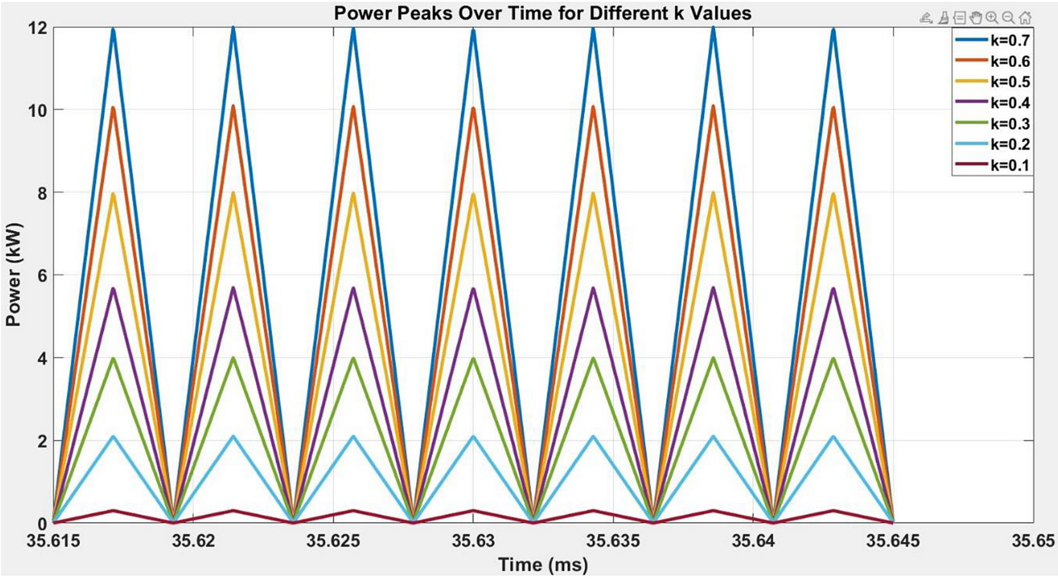

Figure 4. The output power corresponding to a high coupling coefficient

indicate that the system is capable of transferring power within a limited range which the vehicle must be positioned for optimal charging.

In analysing these waveforms, it's important to consider their implications for real-world EV charging. The load in an EV charging system is not static; as the battery charges, its internal resistance changes. The presented data suggests that the WPT system is capable of handling these variations without significant losses in efficiency or power delivery. Moreover, the charging process's efficiency and speed are determined by how well the system can adapt to these changing loads. A WPT system that can sustain efficient power transfer over a wide range of load resistances is preferable, as it would ensure that the EV can be charged quickly and reliably regardless of the initial state of charge or battery health. The amplitude of the voltage across the loads appears to be affected by the resistance values. There is a noticeable variation in peak voltage levels which could be attributed to the impedance matching between the WPT system and the load. The resonant conditions of the circuit are dependent on the load, and each resistance value creates a unique response in the system's behaviour.

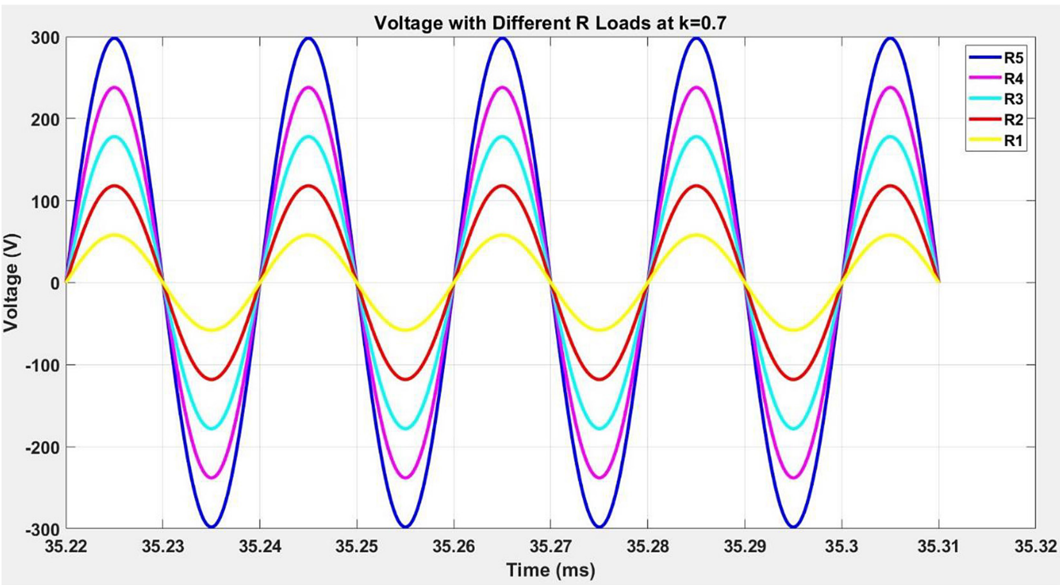

Figure 5. The output voltage with variable resistance load

Despite the change in load, the waveforms maintain a sinusoidal shape which is characteristic of resonant circuits. However, the presence of multiple harmonics could be inferred from the slight distortion in the waveforms, suggesting a deviation from ideal resonance. The system exhibits a degree of tolerance to changes in load resistance as shown in Figure 5. This is an important characteristic for EV charging applications, as the charger must accommodate different battery conditions and still deliver the necessary power for charging.

The Figure 6 depicts the relationship between efficiency and the coupling coefficient K_{23} for various load resistances R_{load}. The efficiency is presented as a percentage on the y-axis, and the coupling coefficient K_{23} is on the x-axis, ranging from 0 to 1. Each curve represents a different load resistance with values ranging from 1 Ohm to 4.5 Ohms. From the Figure 5, we can observe the coupling coefficient K_{23} increases as well as efficiency for all values of R_{load}. This suggests that better coupling between the components involved leads to more efficient energy transfer. The separation between the efficiency curves for different R_{load} values decreases as K_{23} gets larger. This suggests that at very high coupling coefficients, the impact of load resistance on efficiency becomes less significant. At the highest coupling coefficient shown (close to 1), the highest efficiency is not with the lowest resistance (1 Ohm) but somewhere in between, suggesting that there is an optimal load resistance for maximum efficiency that is not the lowest possible resistance. This is a common characteristic of resonant circuits where impedance matching is key to maximum energy transfer.

The LCCL design marks a progression from the LC setup providing improved performance and adaptability. Although the conventional LC layout is popular for its simplicity and effectiveness in filtering tasks the LCCL arrangement enhances these features with filter properties and increased efficiency. By incorporating an inductor and capacitor, in the LCCL design it enables precise management of the filters frequency response resulting in sharper cutoffs and minimized passband fluctuations. The LCCL configuration is particularly beneficial for tasks that demand frequency differentiation and top-notch signal processing. Additionally, this circuit can attain Q factors without the need for inductors with high inductance values leading to a decrease in both size and cost. Essentially the LCCL setup presents a method for filtering closing the divide between performance requirements and real-world limitations in contemporary electronic designs. The Table 3 provides a concise comparison of various compensation topologies. The proposed LCCL-LC topology is the best choice due to its superior output power of 8 KW, high efficiency of 94%, and consistent operating frequency. It offers a balanced and versatile solution for high-power applications, making it the most advantageous among the compared topologies.

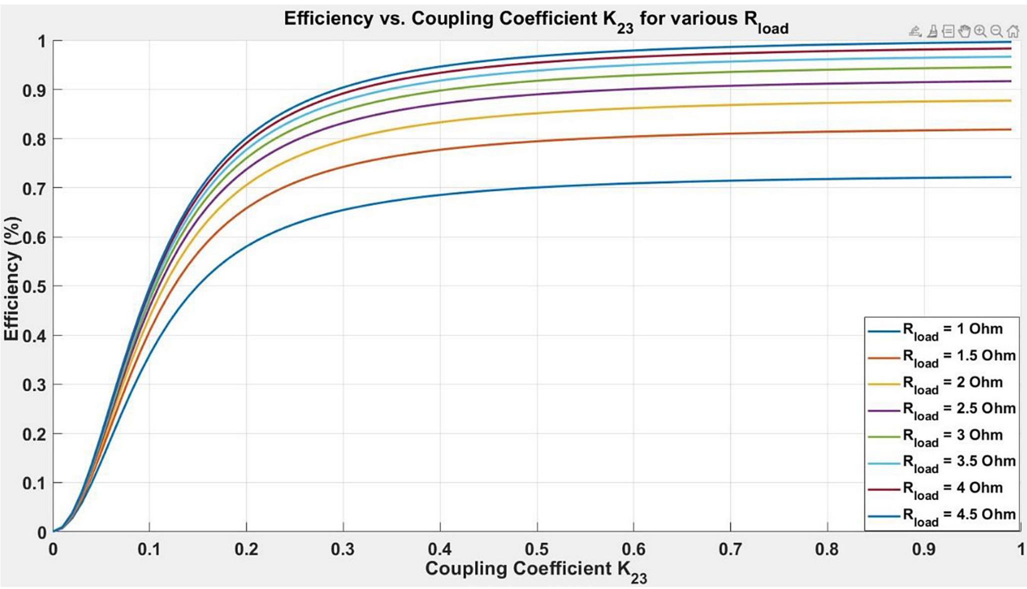

Figure 6. The relationship between efficiency and the coupling coefficient K_{23} for various load resistances R_{load}

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

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

CONCLUSIONS

In summary our study, on the LCCL to LC resonant WPT system for charging EVs has shown a strong ability to handle different load resistances effectively all while ensuring efficient power transfer. The systems flexibility in adjusting to varying loads mimicking EV battery conditions highlights its promise as an answer to existing issues in EV charging setups. Based on our findings it appears that the system can effectively transmit power when there are changes in load resistance. This capability is vital as it allows for charging options that cater to electric vehicles all without requiring direct contact or exact alignment. The impact of this study reaches beyond technical feasibility offering a path towards more convenient and user-friendly EV charging methods that could encourage broader adoption of EV technology. The implications of these findings are significant and holding the promise of contributing to a sustainable transportation ecosystem. As the demand for EVs continues to grow, the need for innovative charging solutions like the one presented in this study becomes increasingly important signalling a leap forward in our journey towards a cleaner and greener future.

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