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Optimization of resonant capacitance values for high-efficiency uninterruptible wireless power transfer system using CST software

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ABSTRACT

This paper introduces an innovative methodology for optimizing resonant capacitance values (Cp and Cs) to enhance the efficiency of uninterruptible wireless power transfer (UWPT) systems, utilizing advanced computer simulation technology (CST) software. Precise tuning of resonant capacitance is critical for achieving optimal frequency matching, which directly influences system performance. The study focuses on three coil configuration strategies: standard coil configuration, coil integrated with ferrite, and coil enclosed within a casing and ferrite. These configurations were analyzed to identify the optimal capacitance values, resulting in significant efficiency improvements. Through comprehensive CST simulations, the capacitance values of Cp1, Cp2, and Cs were optimized to 140.8 nF, 105.6 nF, and 145.5 nF, respectively, achieving a remarkable power transfer efficiency of 99.61% in the casing and ferrite configuration. The proposed optimization methodology consistently achieved efficiencies exceeding 90% between the transmitter and receiver coils. Beyond simulation results, this research highlights the potential for real-world applications and underscores the importance of precise parameter optimization in advancing high-efficiency wireless power transfer systems. Future studies will aim to validate the findings experimentally and explore broader applications of the proposed system.

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1. INTRODUCTION

Wireless power transfer (WPT) is a transformative technology that offers significant advantages, including flexibility, convenience, safety, and potential for full automation. By enabling the transmission of electrical energy without physical connectors, WPT has become a focal point of research and development, with applications spanning electric vehicle battery chargers, mobile devices, LED TVs, and lighting systems [1]-[4]. This ability to transfer power wirelessly addresses critical energy supply challenges while promoting miniaturization and cost-effectiveness, key factors for widespread adoption [5]-[8].

WPT technologies are implemented through various methods, such as lasers, radio waves, photoelectric techniques, microwaves, capacitive coupling, and inductive coupling. Among these, inductive coupling stands out for delivering power with high efficiency over short distances [9]. Resonant inductive wireless charging, in particular, has gained traction due to its superior efficiency and low maintenance requirements compared to other methods [10]. A notable breakthrough in this field occurred in 2007, when

Kurs *et al.* [11] introduced coupled magnetic resonance, enabling efficient power transfer via magnetic coupling resonance.

The literature provides extensive insights into WPT system designs, including a comparative analysis of converter topologies that evaluates their characteristics, benefits, and limitations [10]. For inductive power transfer (IPT) systems, radiated electromagnetic interference (EMI) has been studied comprehensively, revealing critical factors contributing to efficiency losses and mechanisms driving EMI generation [12]. Despite significant advancements, WPT systems still face challenges, particularly in achieving high power transfer efficiency, as losses due to wireless transmission techniques remain a concern [13], [14].

In the context of electric vehicles (EVs), WPT is seen as a sustainable alternative to fossil-fuel-powered systems. To improve the efficiency and range of WPT systems, research has explored resonant frequency tuning and the use of resonant coils to align transmitter and receiver operating frequencies for optimal energy transfer [15], [16]. Additionally, metamaterials and frequency-reconfigurable designs have been employed to enhance WPT efficiency dynamically, enabling better performance across varying distances and operating conditions [17]. Furthermore, nonlinear resistance matching networks have been proposed to mitigate efficiency losses during wide load variations, contributing to overall system performance improvements [15]. The concept of uninterruptible wireless power transfer (UWPT) has emerged as a subset of uninterruptible wireless power supply (UWPS) systems, focusing on achieving reliable and efficient wireless energy transfer. Earlier research demonstrated that UWPT systems could achieve efficiencies exceeding 90%, but these studies were limited to simulation environments without experimental validation [18]-[21].

In recent years, the use of advanced simulation tools has played a pivotal role in optimizing WPT systems. Computer simulation technology (CST) software, renowned for its electromagnetic simulation capabilities, has become indispensable in modelling and analyzing complex WPT scenarios. CST employs cutting-edge numerical techniques, such as the finite element method (FEM) and the finite integration technique (FIT), to solve Maxwell's equations with precision, facilitating the design and optimization of electromagnetic devices across various industries [22]-[25].

This paper presents a novel approach to optimizing the resonant capacitance values of the parallel capacitor (Cp) and series capacitor (Cs) in the transmitter (Tx) and receiver (Rx) coils to achieve high-efficiency UWPT systems. Using CST software, this study systematically varies switching frequencies and capacitance values to identify optimal configurations that maximize power transfer efficiency. The findings reveal that careful tuning of Cp and Cs values enables the proposed UWPT system to achieve power transfer efficiencies exceeding 90%, with certain configurations surpassing 99%. These results underscore the critical role of precise parameter optimization in advancing WPT technologies, paving the way for practical and highly efficient UWPT solutions.

2. COMPUTER SIMULATION MODEL OF UWPT SYSTEM USING CST

The proposed UWPS system integrates both uninterruptible power supply (UPS) and UWPT components, as illustrated in Figure 1, to achieve high-efficiency and reliable power transfer. The system is designed around five primary functional blocks: the power supply, transmitting circuit, receiving circuit, magnetic coil, and load. The process begins with a 48 V DC power supply, which is converted into high-frequency AC via a full-bridge inverter. This high-frequency AC voltage is delivered to the transmitter coil, where it induces an alternating voltage in the receiver coil through magnetic field coupling. The induced AC power is then rectified into DC using a high-frequency full-bridge diode rectifier and supplied to the connected load or devices.

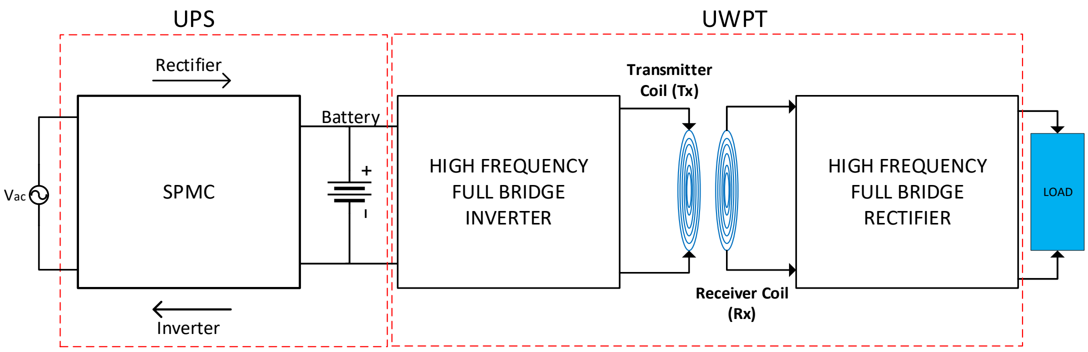

Figure 1. The proposed uninterruptible wireless power supply (UWPS) block diagram

The schematic diagram of the proposed UWPT system, as simulated in CST software, is shown in Figure 2. This diagram highlights a section of the transmitter circuit, which employs a resonant inductive coupling design. The resonant circuit, consisting of inductors and capacitors, is critical for achieving efficient power transfer by tuning the system to its optimal operating frequency. CST software is leveraged to model and simulate the circuit's behavior, enabling the prediction of performance metrics such as power transfer efficiency, S-parameters, Q-factor, and the optimal capacitance values.

To ensure the accuracy and reliability of the simulation, the key parameters used in the CST Studio configuration are summarized in Table 1. These parameters include the number of coils turns (22), operating frequency (44 kHz), inductance (24 µH), coil dimensions, and spacing. For this study, the distance between the transmitter and receiver coils is set at 20 mm. These parameters represent a subset of the overall design considerations, which must also account for the type of WPT technology (e.g., inductive or capacitive coupling), targeted power level, desired system efficiency, and safety standards.

The core focus of this research is on optimizing the resonant capacitance values, specifically the parallel capacitor (Cp) and series capacitor (Cs), to achieve high-frequency operation and maximize power transfer efficiency. Using CST software, a detailed parametric study was conducted by systematically varying Cp and Cs values. This approach allowed for the identification of optimal capacitance settings that align the system's resonant frequency with its operating frequency, thereby minimizing power losses and enhancing efficiency.

The CST simulation framework not only facilitates precise modeling of the electromagnetic interactions between the transmitter and receiver coils but also provides insights into the effects of varying design parameters. This level of detail ensures that the proposed UWPT system achieves its targeted efficiency benchmarks while offering a scalable design for real-world applications. By enabling a systematic exploration of the design space, CST software serves as a robust tool for advancing the development of high-performance WPT systems.

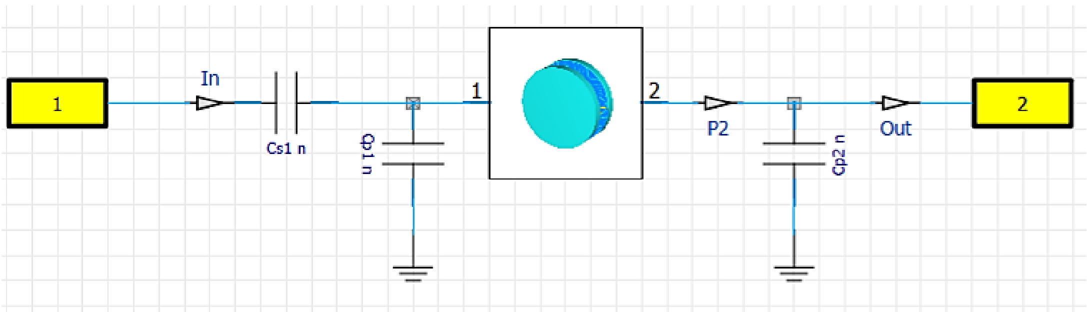

Figure 2. The UWPT schematic diagram simulated using CST software

Table 1. Parameter of UWPT for simulation using CST software

Parameter	Value
Number of turn	22 turn
Frequency	44 Khz
Inductance	24 µF
Wire diameter	0.15 mm, 1.5 mm
Wire radius	0.35 mm
Size inner radius	1.42 cm
Size outer radius	5.15 cm
Casing material	polycarbonate
Distance between both coil	20 mm
H-ferrite	10
Ferrite	50

3. SIMULATION MODEL OF UWPT SYSTEM USING COIL CONFIGURATION

In this research, the configuration of the transmitter coil (Tx) and receiver coil (Rx) in the WPT system is modeled and simulated using CST software, as shown in Figure 3. The Tx and Rx coils operate at a frequency of 44 kHz without incorporating ferrite or casing materials. This setup provides a baseline for evaluating the system's performance under standard conditions.

The figure depicts two parallel planar coils, with the receiver coil (Rx) positioned above the transmitter coil (Tx). The magnetic field distribution is illustrated as blue concentric patterns surrounding the coils, representing field intensity. The alignment along a common axis and the distance between the coils are critical parameters for achieving efficient power transfer. The Tx coil generates an alternating magnetic field when powered, inducing an alternating current in the Rx coil via electromagnetic induction. This configuration is optimized to enhance resonance and maximize power transfer efficiency, providing a clear visualization of the magnetic interaction between the coils and laying the foundation for performance optimization.

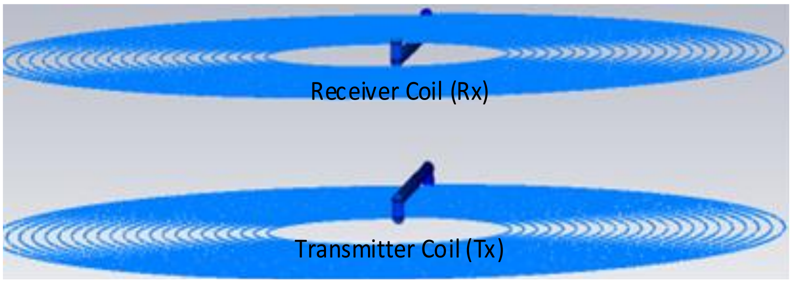

Figure 3. The coil configuration of the Tx and Rx in the WPT system using CST

3.1. Magnetic field distribution in Tx, Rx, and combined configurations

Figures 4-6 provide detailed visualizations of the magnetic field distributions for the Tx, Rx, and the combined coil configuration, respectively, as simulated using CST software. These figures are instrumental in analyzing the magnetic coupling and identifying regions of strong interaction and potential leakage.

3.1.1. Magnetic field distribution at the transmitter coil (Tx)

Figure 4 illustrates the magnetic field distribution at the Tx coil. A cross-sectional view reveals the field intensity surrounding the Tx. The color scale highlights varying levels of intensity, with red indicating regions of higher magnetic field strength and blue representing lower intensities. The strongest field is concentrated in the immediate vicinity of the Tx coil, as shown by the red area, which diminishes with increasing distance, transitioning through green, yellow, and blue hues. This visualization emphasizes the field propagation characteristics and provides insights into how energy radiates from the Tx coil.

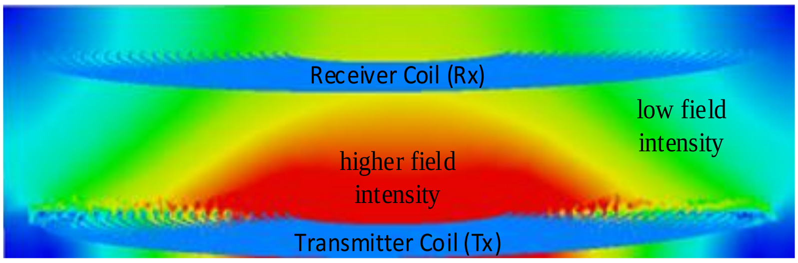

Figure 4. The coil configuration of the Tx and Rx in the WPT system using CST

3.1.2. Magnetic field distribution at the receiver coil (Rx)

Figure 5 presents the magnetic field distribution at the Rx coil. Similar to the Tx visualization, the color-coded intensity highlights the strength of the magnetic field interacting with the Rx coil. Positioned within the Tx's field influence, the Rx coil exhibits strong coupling where the magnetic field intensity is high. This interaction facilitates efficient energy transfer through electromagnetic induction. The transition of colors from red (high intensity) to blue (low intensity) indicates a gradual reduction in field strength with increasing distance from the Tx coil. Analyzing this figure is crucial for understanding the efficiency of energy transfer and identifying regions where coupling can be improved.

3.1.3. Combined magnetic field distribution of Tx and Rx

Figure 6 displays the combined magnetic field distribution of the Tx and Rx coils, offering a holistic view of the magnetic interaction within the WPT system. This figure highlights areas of strong coupling (depicted by red regions) and magnetic field leakage (shown by the transition from red to blue at the edges of the coils). The spatial visualization of the field intensity between the Tx and Rx coils underscores regions of optimal coupling and areas where field leakage could lead to energy losses. By identifying these leakage regions, the system design can be refined to minimize inefficiencies and enhance power transfer performance.

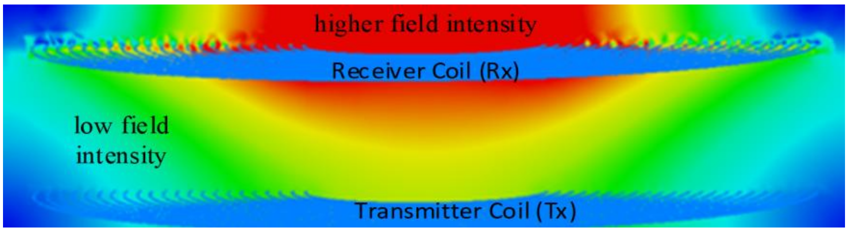

Figure 5. Magnetic field at receiver coil (Rx)

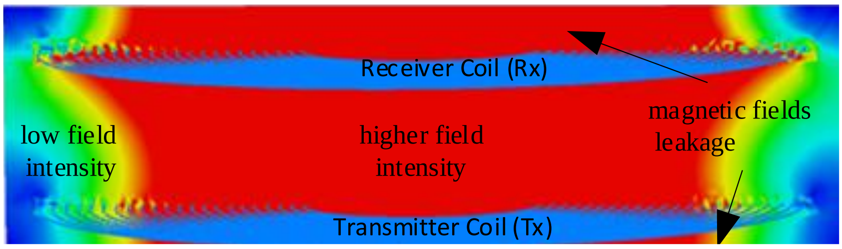

Figure 6. Combination magnetic field at pair of transmitters (Tx) and receiver (Rx) at WPT system using coil without ferrite or casing

3.2. Coupling strength and optimization of magnetic fields

The coupling strength between the Tx and Rx coils is a critical determinant of energy transfer efficiency in the WPT system. Magnetic field leakage, which occurs when the field extends outside the intended coupling region, contributes to energy losses and reduces overall system performance. Figures 4-6 underscore the importance of addressing these leakage areas to optimize coupling strength and improve efficiency.

Through CST simulations, this research identifies optimal resonant capacitance values for the parallel capacitor (Cp) and series capacitor (Cs). By systematically varying these values, the study seeks to minimize magnetic field leakage while maximizing power transfer efficiency. The iterative parametric study enables the identification of capacitance settings that align the system's resonant frequency with the operating frequency, ensuring strong coupling, and reduced energy losses.

The insights gained from the magnetic field distribution visualizations and parametric optimization establish a robust foundation for designing efficient WPT systems. The proposed approach contributes to a deeper understanding of magnetic field interactions in UWPT systems, paving the way for enhanced performance in real-world applications.

4. RESULTS AND DISCUSSION

This section presents the simulation results obtained using CST software to optimize the WPT system's performance by tuning the resonant capacitance values (Cp and Cs). Figures 7-10 and Table 2 provide a comprehensive analysis of the improvements in S-parameters, magnetic field energy transfer efficiency, and overall system performance before and after tuning.

4.1. S-parameter analysis

Figure 7 illustrates the S-parameter results before tuning for the Tx and Rx coil pair without ferrite or casing. The S21 parameter (blue curve) represents the forward transmission coefficient, indicating the power transferred from the Tx to the Rx coil, while the S22 parameter (red curve) represents the input reflection coefficient, indicating the power reflected back to the Tx coil. Before tuning, the S21 value is relatively low, indicating suboptimal power transfer, and the S22 value is high, signifying significant reflection losses. These results highlight the inefficiency of the system due to poor resonance and impedance mismatch.

Figure 8 presents the S-parameter results after tuning, again without ferrite or casing. After optimizing the capacitance values, the S21 value improves significantly, approaching 0 dB, which reflects excellent power transfer efficiency. Simultaneously, the S22 value decreases markedly, indicating enhanced impedance matching and reduced reflection losses. The tuning process adjusts the resonant frequency to 38.1 kHz, aligning the system components and enhancing overall performance.

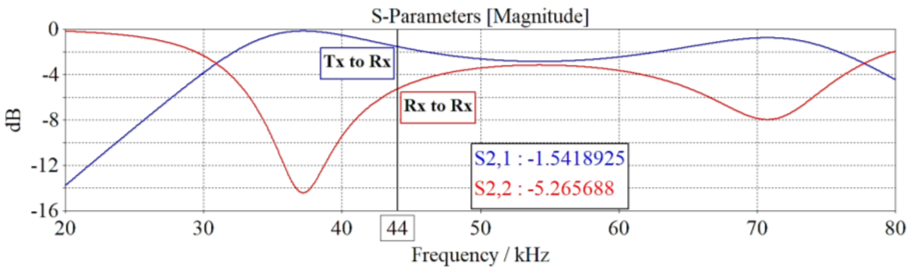

Figure 7. S-parameter results before tune without ferrite or casing for pair of transmitters (Tx) and receiver (Rx) at WPT

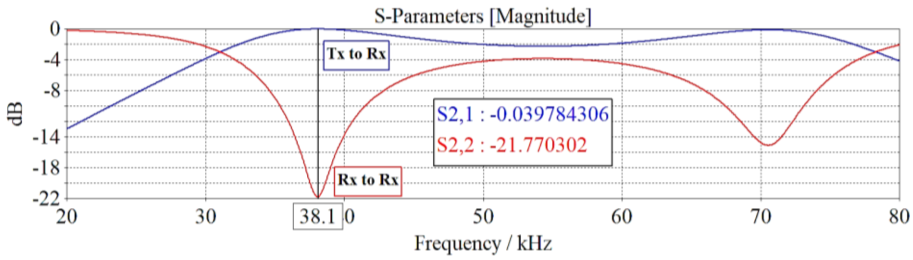

Figure 8. S-parameter results after tune without ferrite or casing for pair of transmitters (Tx) and receiver (Rx) at WPT

4.2. Magnetic field energy transfer efficiency

Figure 9 shows the magnetic field energy transfer efficiency from the Tx to the Rx coil before tuning as a function of frequency. The maximum efficiency observed is approximately 70.10% at around 44 kHz. This suboptimal efficiency indicates substantial power losses due to the initial capacitance values and poor impedance matching in the system.

Figure 10 illustrates the efficiency results after tuning. The optimized capacitance values realign the resonant frequency to 38.1 kHz, resulting in a dramatic efficiency increase to 99.09%. This significant improvement demonstrates the effectiveness of tuning in achieving better resonance and impedance matching. The sharp contrast between Figures 9 and 10 underscores the critical role of precise capacitance optimization in minimizing energy losses and maximizing power transfer efficiency.

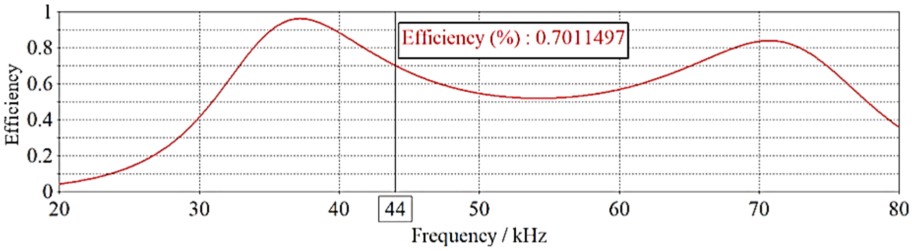

Figure 9. Efficiency result of magnetic field energy transfer from transmitter (Tx) and receiver (Rx) before tune

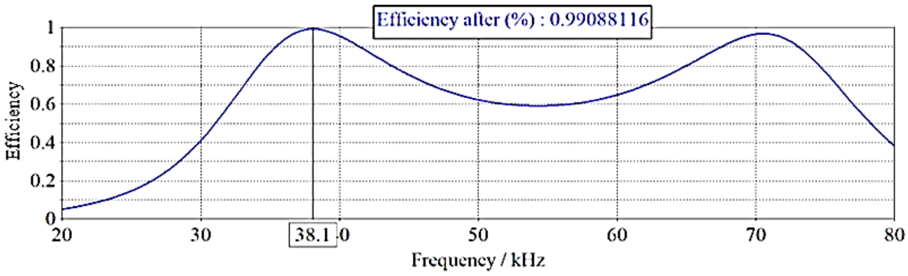

Figure 10. Efficiency results magnetic field energy transfer from transmitter (Tx) and receiver (Rx) after tune

4.3. Comparative analysis of system parameters

Table 2 provides a detailed comparison of the key system parameters, including capacitance values (Cs1, Cp1, Cp2), resonant frequency, and efficiency (η), both before and after the tuning process. Before tuning, the system exhibited suboptimal performance with capacitance values of Cs1 = 168 nF, Cp1 = 145 nF, and Cp2 = 224 nF. These initial settings corresponded to a resonant frequency of 44 kHz, yielding a relatively low efficiency of 70.10%. This inefficiency was primarily attributed to poor impedance matching and inadequate resonance alignment between the transmitter (Tx) and receiver (Rx) coils, resulting in significant energy losses.

After tuning, following the optimization process, the capacitance values were fine-tuned to Cs1 = 220 nF, Cp1 = 162.8 nF, and Cp2 = 200 nF. These adjustments shifted the resonant frequency to 38.1 kHz, achieving a dramatic efficiency improvement to 99.09%. This significant enhancement reflects the critical role of capacitance tuning in achieving precise resonance and minimizing reflection losses, enabling near-perfect energy transfer between the Tx and Rx coils.

The optimization process demonstrates a substantial leap in system performance, transitioning from a moderate efficiency level to near-ideal energy transfer. These results underscore the pivotal importance of aligning resonant frequency with operating conditions to mitigate inefficiencies, improve power coupling, and maximize overall system performance. This comparative analysis highlights the transformative impact of precise capacitance tuning, providing a strong foundation for future advancements in high-efficiency wireless power transfer systems.

Table 2. Optimal efficiency, frequency, and capacitive result using CST

Capacitive	Before tune	After tune
Cs1	168nF	220nF
Cp1	145nF	162.8nF
Cp2	224nF	200nF
Frequency	44Khz	38.1Khz
η	70.10%	99.09%

4.4. Discussion

The simulation results demonstrate the profound impact of capacitance optimization on the performance of WPT systems. The improved S-parameters and magnetic field energy transfer efficiency after tuning confirm that precise parameter adjustments can significantly enhance power transfer capabilities. Achieving an efficiency of 99.09% underscores the potential of resonant inductive coupling for high-efficiency wireless energy transfer.

These findings emphasize the necessity of detailed parametric studies to identify optimal system configurations. By systematically varying capacitance values, this study highlights the importance of aligning the system's resonant frequency with its operating frequency to minimize energy losses and improve coupling. Future work should include experimental validation of these results to confirm their applicability in real-world scenarios and extend the study to include variations in load conditions, coil configurations, and environmental factors.

5. CONCLUSION

This study successfully demonstrates the optimization of resonant capacitance values for achieving high-efficiency UWPT systems using CST software. By systematically varying the capacitance values of the parallel capacitor (Cp) and series capacitor (Cs), the power transfer efficiency improved significantly from

70.10% before tuning to an impressive 99.09% after tuning. The optimal capacitance values identified were Cs1 = 220 nF, Cp1 = 162.8 nF, and Cp2 = 200 nF, which aligned the resonant frequency to 38.1 kHz, ensuring optimal system performance. The detailed analysis of S-parameters and magnetic field energy transfer efficiency provided critical insights into the design and optimization of resonant capacitance values. The observed improvement in the S21 parameter (forward transmission coefficient) and the reduction in the S22 parameter (input reflection coefficient) after tuning confirm more efficient power transfer and enhanced impedance matching. These enhancements are essential for achieving high-efficiency UWPT systems, as reflected in the significant increase in power transfer efficiency. This research underscores the effectiveness of using CST software for simulating and optimizing WPT systems. The ability to accurately model and analyze the system's electromagnetic behavior enabled the identification of optimal capacitance values, maximizing power transfer efficiency while providing valuable insights into magnetic field interactions and the factors influencing system performance.

Future research should focus on experimental validation of the proposed optimization method to verify the simulation results in practical applications. Additionally, the impact of various factors, such as different coil geometries, materials, and environmental conditions, on WPT efficiency warrants further investigation. The integration of ferrite materials and casing into the system design offers promising avenues for reducing magnetic field leakage and further enhancing system performance.

The optimized UWPT system has potential applications in diverse domains, including electric vehicle charging, consumer electronics, and medical devices. By achieving high-efficiency wireless power transfer, the proposed method contributes to the development of more reliable and energy-efficient wireless power solutions. These findings address the growing demand for advanced WPT technologies and demonstrate the practical viability of UWPT systems in real-world applications. This study makes a significant contribution to the field of WPT by providing a robust methodology for optimizing resonant capacitance values. The results pave the way for more efficient and effective UWPT systems, ultimately advancing the development of high-performance wireless power transfer technologies and fostering innovations in energy delivery systems.

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