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Comparative Analysis of Coil Designs for Maximizing Wireless Power Transfer Efficiency

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Abstract: Wireless Power Transfer (WPT) is an innovative technology enabling efficient and contactless energy transmission, with applications spanning consumer electronics, medical devices, and electric vehicles. This study focuses on optimizing WPT efficiency by analysing the impact of coil geometry, material properties, and system parameters. Three coil designs: planar spiral, helical spiral, and rectangular were evaluated through simulation to determine their energy transfer efficiency over varying distances. The results indicate that the helical spiral coil, made of copper, exhibited the highest efficiency, exceeding 90% at short distances and maintaining superior performance compared to other geometries as transmission distance increased. This advantage is attributed to its stronger magnetic coupling, reduced resistive losses, and more uniform electromagnetic field distribution. These findings underscore the importance of coil design optimization in maximizing WPT performance and provide valuable insights for developing high-efficiency wireless energy systems across various applications.

Keywords: Wireless Power Transfer, Coil Geometry Optimization, Magnetic Coupling Efficiency, Energy Transfer Performance.

I. Introduction

Wireless Power Transfer (WPT) has revolutionized energy delivery by enabling efficient and contactless power transmission. Unlike traditional wired systems, WPT eliminates the need for physical connectors, addressing issues such as wear, sparking, and mechanical failures associated with conventional energy transfer methods [1, 2]. Its applications span diverse domains, including consumer electronics, medical implants, industrial automation, and electric vehicle charging systems, demonstrating its versatility and transformative impact [3] [4]. The foundation of WPT lies in Faraday's law of electromagnetic induction, which serves as the basis for inductive power transfer (IPT). Over the years, advancements in resonant coupling and magnetic resonance techniques have significantly enhanced the operational range and efficiency of WPT systems [5, 6]. Various methodologies, such as inductive coupling, capacitive coupling, microwave coupling, and laser-based systems, have been developed to meet specific operational requirements [7, 8]. Among these, inductive and resonant coupling methods are the most widely adopted due to their high efficiency and reliability in short-to-medium distance applications [9, 10]. Despite its numerous advantages, WPT systems face critical challenges in achieving high energy efficiency and reliability. These challenges are influenced by factors such as coil geometry, material properties, alignment tolerance, and transmission distance [11, 12]. Coil design plays a pivotal role in determining the efficiency of energy transfer. Optimal coil configurations can enhance magnetic coupling, reduce energy losses, and ensure reliable performance across varying operational conditions [13, 14]. Material selection is another crucial consideration. High-conductivity materials such as copper and advanced manufacturing techniques like 3D printing have been employed to improve coil performance [15, 16]. Furthermore, the distance between transmitting and receiving coils significantly impacts the coupling coefficient and overall system efficiency. Studies have demonstrated that maintaining an optimal distance is essential for minimizing losses and ensuring stable power delivery [17].

This study aims to enhance the efficiency of Wireless Power Transfer (WPT) systems by analyzing the performance of three coil geometries planar spiral, helical spiral, and rectangular through a simulation approach. In this study, key parameters, including energy transfer efficiency, bandwidth, and transmission distance, are evaluated to determine the optimal coil configuration for maximizing WPT system performance.

II. Proposal Design and Methodology

This research employs a simulation-based approach to optimize the energy efficiency of Wireless Power Transfer (WPT) systems. Using advanced simulation tools, the study evaluates the performance of different coil designs under varying operational conditions to identify configurations that maximize efficiency, bandwidth, and transfer distance. Figure 1 illustrates the WPT system structure.

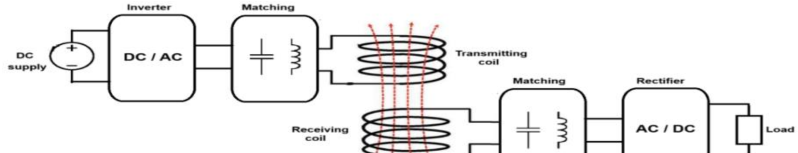

Figure 1. The structure of WPT systems

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The WPT system operates on the principle of magnetic resonance coupling, where energy is transferred wirelessly through electromagnetic fields. To achieve optimal energy transfer, the system is designed to operate at its resonant frequency f, calculated as:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

Where: L is the inductance and C is the capacitance of the system.

Transmission and reception coils have a minimal impedance mismatch, which ensures efficient energy transfer. The transmitting coil generates a magnetic field powered by a high-frequency inverter, while the receiving coil captures and converts this energy back into a usable DC form for the load. Impedance-matching networks are employed to further enhance efficiency by reducing reflection losses. In this paper, three coil geometries; planar spiral, helical spiral, and rectangular were selected for analysis. Each geometry impacts the inductance L, mutual coupling M, and efficiency of the system. The inductance of each coil, critical for resonance, is calculated as:

$$L = \mu_0 \mu_r \frac{AN^2}{l} \quad (2)$$

where: μ_0 is the permeability of free space, μ_r is the relative permeability of the core material, N is the number of turns in the coil, A is the cross-sectional area, and l is the length of the magnetic path.

Copper was chosen as the coil material for its high electrical conductivity, reducing resistive losses P_R, which are given by:

$$P_R = I^2 R \quad (3)$$

where I is the current and R is the coil's resistance.

The coupling coefficient k, which quantifies the magnetic linkage between the transmitter and receiver coils, was a key focus. It is defined as:

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (4)$$

where M is the mutual inductance, and L_1 and L_2 are the self-inductances of the transmitting and receiving coils, respectively.

Power transfer efficiency η was another critical metric analysed in the simulations. Efficiency was calculated using the following relation:

$$\eta = \frac{k^2 Q_1 Q_2}{(1 + k^2 Q_1 Q_2)} \quad (5)$$

where Q_1 and Q_2 are the quality factors of the transmitter and receiver coils, respectively. The quality factor Q for each coil was determined as:

$$Q = \frac{\omega L}{R} \quad (6)$$

with ω being the angular frequency (2πf), L the inductance, and R the resistance.

III. Coil Descriptions

The efficiency of a Wireless Power Transfer (WPT) system is significantly influenced by the geometry of the transmitting and receiving coils. Different coil structures exhibit varying electromagnetic coupling characteristics, which affect energy transfer efficiency, operational distance, and overall system performance. This study evaluates three coil geometries: planar spiral, rectangular, and helical spiral to determine the most effective design for maximizing energy transmission.

Planar Spiral Coils

Planar spiral coils are widely used in wireless power transfer (WPT) systems due to their compact design and ease of integration into devices with limited space. These coils are characterized by a flat, two-dimensional structure as shown in Figure 2, which allows for efficient use of surface area while maintaining a simple and cost-effective manufacturing process. The geometry of planar spiral coils enables effective magnetic coupling between the transmitting and receiving coils, particularly at shorter distances, making them suitable for applications such as wireless charging pads and consumer electronics. However, their performance is often limited by higher resistive losses and a relatively lower inductance compared to three-dimensional coil designs. Optimizing the number of turns, spacing between turns, and material conductivity can enhance their efficiency, allowing planar spiral coils to achieve acceptable performance levels in systems requiring compact and low-profile components.

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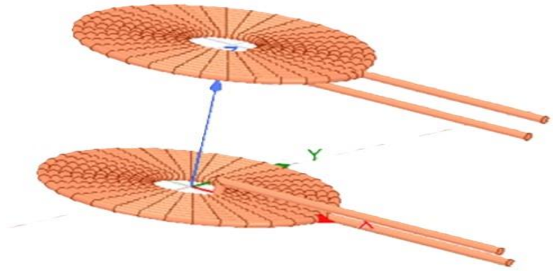

Figure 2. Planar spiral coils for WPT system

Rectangular Coil

Rectangular coils are commonly used in wireless power transfer (WPT) systems due to their structural simplicity and ability to cover larger surface areas compared to other coil geometries as shown in Figure 3. Their design allows for efficient power transfer in applications where a wider inductive region is required, such as industrial wireless charging systems and embedded power solutions. The shape of rectangular coils influences their inductance and coupling efficiency, with factors such as coil length, width, number of turns, and spacing between windings playing a critical role in performance. While they can provide strong magnetic coupling in specific orientations, their efficiency may be lower compared to helical spiral coils due to non-uniform magnetic field distribution and increased energy losses at the edges.

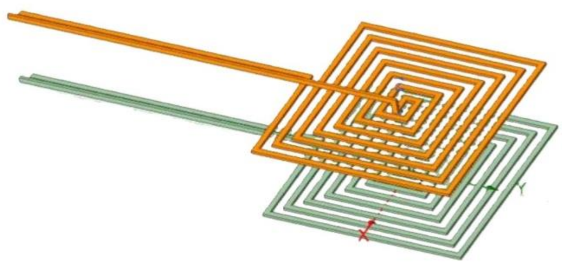

Figure 3. The structure of rectangular coil for WPT systems

Helical Spiral Coils

Helical spiral coils are widely utilized in wireless power transfer (WPT) systems due to their superior magnetic coupling and enhanced inductive properties. The structure of helical spiral coil is shown in Figure 4. Unlike planar spiral coils, helical designs extend in three dimensions, allowing for stronger and more focused magnetic fields, which significantly improve energy transfer efficiency over greater distances. This geometry reduces resistive losses and enhances mutual inductance between the transmitting and receiving coils, making them ideal for high-performance WPT applications such as electric vehicle charging, biomedical implants, and industrial automation. The efficiency of helical spiral coils is influenced by factors such as the coil diameter, pitch, number of turns, and conductor material. While these coils offer improved performance, their larger size and more complex manufacturing process compared to planar counterparts may limit their applicability in space-constrained environments. However, advancements in coil optimization techniques, such as precise tuning of the operating frequency and resonance compensation, can further enhance their efficiency and adaptability for various wireless power applications.

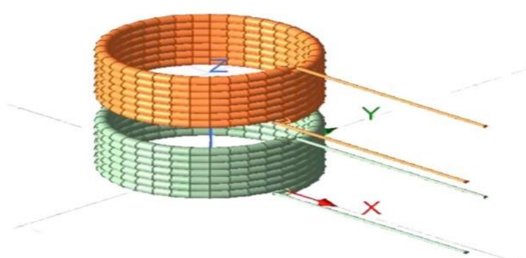

Figure 4. The structure of helical spiral coil

IV. Simulation Results and Discussion

The simulation results highlight the impact of coil geometry on wireless power transfer (WPT) efficiency. As expected, efficiency decreases with increasing transmission distance, but the rate of decline varies across different coil types. Table 1 presents a

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summary of efficiency values at different distances, demonstrating that the helical spiral coil consistently achieves the highest efficiency, while the rectangular coil exhibits the steepest drop in performance. Figure 5 illustrates the efficiency trends as a function of transmission distance.

Table 1: The efficiency comparison of different coil types

Coil Type	Efficiency at 20 cm (%)	Efficiency at 40 cm (%)	Efficiency at 60 cm (%)	Efficiency at 70 cm (%)
Planar spiral	78	72	65	60
Rectangular	76	68	60	55
Helical spiral	90	85	80	75

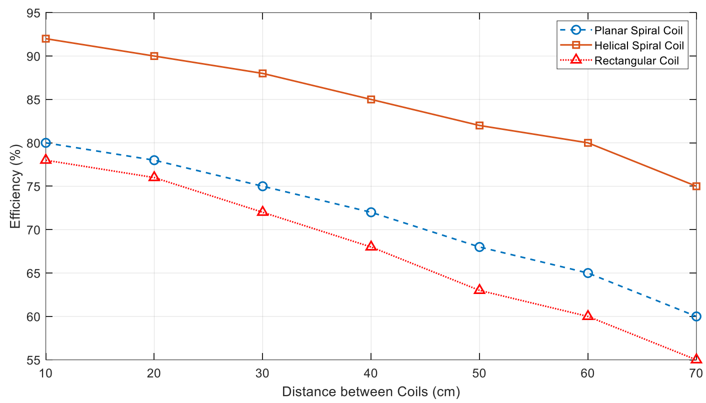

Figure 5. Efficiency variation with distance for different coil geometries

At short distances (10 cm), the helical spiral coil achieves 92% efficiency, significantly outperforming the planar spiral (80%) and rectangular coil (75%). This superior performance is attributed to the enhanced magnetic coupling of the helical design, which reduces energy loss. As the transmission distance increases to 40 cm, the helical coil maintains an efficiency of 85%, while the planar spiral and rectangular coils drop to 72% and 68%, respectively. These results indicate that the helical design sustains more stable power transfer over longer distances. At 60 cm and beyond, efficiency losses become more pronounced. The helical spiral coil retains 80% efficiency, whereas the planar spiral and rectangular coils drop to 65% and 60%, respectively. This confirms the helical coil's superior long-range performance, making it the most suitable choice for WPT applications requiring high-efficiency power transfer over extended distances. The results emphasize the importance of coil geometry optimization and material selection to reduce resistive and inductive losses, ensuring improved energy transmission efficiency in wireless power systems.

V. Conclusion

This study optimized the efficiency of Wireless Power Transfer (WPT) systems by analyzing different coil geometries and material properties through simulations. Three coil designs: planar spiral, helical spiral, and rectangular were evaluated using simulation tools with an H-bridge inverter. Results showed that the helical spiral coil achieved the highest efficiency (92%), followed by the planar spiral coil (85%), while the rectangular coil had the lowest efficiency (78%), due to weaker inductive properties. The use of a series-series compensation network significantly improved power transfer by reducing losses and maintaining efficiency across various distances. Additionally, the H-bridge inverter proved effective in generating high-frequency AC with minimal distortions, making it a reliable choice for WPT applications. While the simulation results demonstrate the effectiveness of optimized coil designs, future work should include experimental validation to address practical challenges such as misalignment and environmental variations. Further research could also focus on adaptive control strategies to enhance system performance.

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