Biosys Journal Biotechnology & Bioengineering

PRIME OPEN ACCESS

Volume 1, Issue 1

Research Article

Date of Submission: 04 April, 2025
Date of Acceptance: 06 June, 2025
Date of Publication: 11 June, 2025

Comprehensive Analysis of Coil Designs for Wireless Power Transfer

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Citation: Adatiya, V., Rajput, K. (2025). Comprehensive Analysis of Coil Designs for Wireless Power Transfer. *Biosys J Biotechnol Bioeng, 1*(1), 01-07.

Abstract
With this it is analyzed how wireless power transfer based on magnetic resonance coupling can provide energy transfer over mid sized distances with a high transfer efficiency in this study. The power transfer through a 10 cm gap in an experimental setup with two magnetically coupled resonant coils was demonstrated. The parameters of coil are optimized to improve transfer efficiency, theoretical modeling, and resonant frequency analysis; practical implementation details are given. Comparison with previous work [1,2] on the use of magnetic resonance techniques for wireless energy delivery in low power applications confirms the suitability of doing this, and interesting results in the development of a radio frequency delivery/induction network are lead to.

Keywords Wireless Power Transfer (WPT)
Inductive Coupling, Resonant Circuit, Coil Design, Mutual Inductance, Energy Transfer Efficiency.

Introduction

Due to their increased attention for the potential of revolutionizing energy delivery in different sectors such as electric vehicles, consumer electronics, biomedical implants, Wireless Power Transfer (WPT) systems are gaining yet more attention.

Magnetic Resonant Coupling (MRC) has proved to be the most user friendly among the various WPT techniques and is preferred as MRC can transmit efficiently over a mid-range distance. Nevertheless, the development of resonators is still in progress and a systematic and comparative analysis of coil geometries is not well explored.

In this paper, the different coil configurations such as spiral, circular, and square are presented for a comparative and novel analysis of magnetic field distribution, efficiency, and coupling coefficient. By both theoretical modeling and electromagnetic simulation, this paper quantitatively evaluates how these coil designs affect the WPT system performance. This work is significant in that it reduces coil parameter space while maximizing power transfer efficiency while minimizing material usage and volume — the most crucial for actual deployments including wireless charging pads, EV dynamic charging and compact medical devices. This work closes the gap in the systematic evaluation of WPT coil design and offers design guidelines to directly guide the design of an efficient and scalable WPT system.

Wireless Power Transfer (WPT) has emerged as a transformative technology with significant implications across diverse domains, including biomedical implants, consumer electronics, and electric vehicle (EV) charging. The ability to transfer power efficiently without physical connectors not only offers convenience but also enhances system durability, safety, and design flexibility. Among the various techniques in WPT, inductive coupling has garnered particular attention due to its practicality and relatively straightforward implementation for short-range applications.

Despite significant advancements, coil design remains a critical bottleneck in optimizing the efficiency, stability, and range of inductive power transfer systems.

Most existing research has focused either on theoretical models or on specific application-driven constraints, leaving a notable gap in comparative analyses across multiple coil geometries under unified simulation conditions. Moreover, many studies fail to explicitly consider the influence of coil parameters—such as spacing, number of turns, and geometry—on power transmission efficiency and electromagnetic interference.

This paper aims to address these gaps by performing a systematic simulation-based analysis of three commonly used coil types: circular, square, and hexagonal. The novelty of our work lies in the side-by-side evaluation of these coil geometries using consistent parameters and conditions, providing a clearer understanding of their respective performance in practical WPT systems. We also consider real-world constraints such as coil alignment, quality factor, and magnetic field distribution to make our analysis application-relevant.

Our findings are expected to assist designers in selecting optimal coil configurations for specific WPT scenarios, enabling improved system performance while minimizing cost and electromagnetic leakage

Literature Review

Wireless Power Transfer (WPT) systems, particularly those based on magnetic resonance and inductive coupling, have gained increasing research interest over the past two decades. Many studies have focused on improving the transmission efficiency, extending the range, and optimizing the design of coils and compensation networks.

A significant body of work explores the role of coil geometry in determining the efficiency and magnetic field characteristics of WPT systems. For instance, Imura et al. investigated loosely coupled magnetic resonance systems and proposed techniques to enhance efficiency over mid-range distances. Similarly, Sample et al. focused on dynamic tuning mechanisms that maintain power transfer even with misalignment.

From a geometric perspective, Li et al. compared circular and rectangular coils and demonstrated that geometry has a substantial impact on coupling efficiency and magnetic field uniformity. Kim et al. introduced spiral coil designs to enhance the Q-factor and reduce power loss. On the other hand, Singh and Ghosh analyzed the performance of hexagonal coils in EV charging and observed favourable efficiency gains due to the tighter field confinement. Despite these advances, a clear gap exists in the comparative evaluation of multiple coil geometries under identical simulation parameters. Most prior works focus on a single geometry or real-world prototypes without offering baseline simulations across different coil types. Furthermore, studies often lack discussion on how geometric design affects electromagnetic interference, alignment tolerance, and manufacturability.

This paper addresses these limitations by providing a comparative simulation-based study of circular, square, and hexagonal coils under a unified set of conditions. Unlike prior research that isolates one geometry, our approach highlights the trade-offs and advantages of each type, offering valuable design insights for engineers developing WPT systems for EVs, wearables, and consumer electronics.

Fundamentals of Coil Design

The efficiency of a WPT system is largely influenced by the inductance, mutual inductance, and quality factor of the coil design. The inductance of a coil is given by:

$$L = (N^2 \mu A) / l$$

where:

- L = Inductance (H)
- N = Number of turns
- μ = Permeability of the core material
- A = Cross-sectional area of the coil (m^2)
- l = Length of the coil (m)

Mutual inductance, a critical factor in determining energy transfer efficiency, is expressed as:

$M = k \sqrt{(L_1 L_2)}$ where:

- M = Mutual inductance (H)
- k = Coupling coefficient
- L_1, L_2 = Self-inductance of primary and secondary coils

Different Coil Geometries

Different coil geometries play a crucial role in optimizing wireless power transfer efficiency. The four main types of coils used in WPT systems are circular, rectangular, helical, and planar spiral coils. Each has its own characteristics, advantages, and drawbacks.

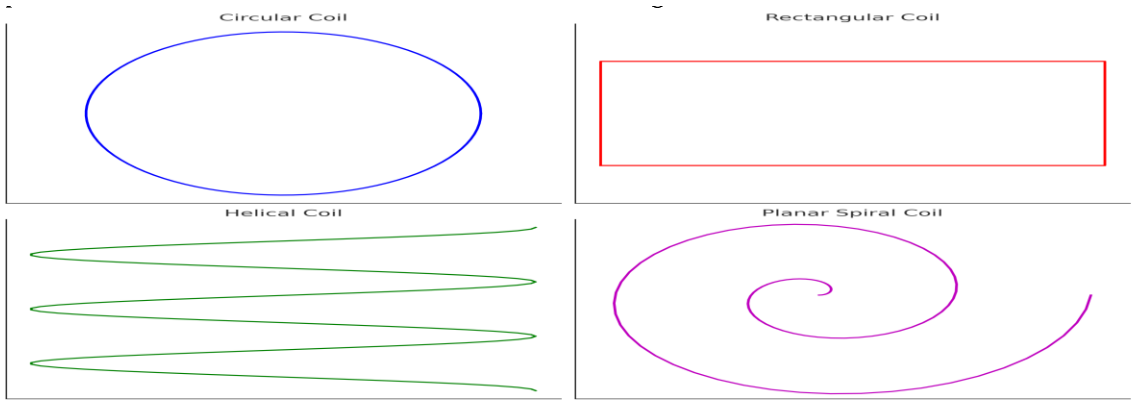

Figure 1: Coil Geometries

Circular Coils

Circular coils are the most common in WPT applications due to their symmetrical magnetic field distribution and high coupling efficiency at short distances. The inductance of a circular coil is given by:

$L = (\mu 0\ N^2\ R^2) / (2(R + h))$ where:

- R = Coil radius
- h = Coil height

They are widely used in Qi wireless charging systems for smartphones and wearable devices. However, they suffer from misalignment sensitivity, reducing efficiency when the receiver is not properly aligned.

Rectangular Coils

Rectangular coils are preferred for applications where large surface areas need coverage, such as EV charging pads. Their inductance is calculated using:

- $L = (\mu 0\ N^2\ w\ l) / (3(w + l))$ where:
- w = Coil width
- l = Coil length

These coils provide better tolerance for lateral misalignment but generate a non-uniform magnetic field, requiring compensation circuits for efficiency improvements.

Helical Coils

Helical coils provide long-range power transfer and are often used in biomedical implants and RFID applications. Their inductance is given by:

$L = (\mu 0\ N^2\ A) / l$ where:

- A = Cross-sectional area

Helical coils exhibit low eddy current losses and stable magnetic fields but are complex to manufacture due to their 3D structure.

Planar Spiral Coils

Planar spiral coils are widely used in compact wireless charging systems. Their inductance is approximated as

- $L = (\mu 0\ N^2\ d) / (2(3.5 + 2 \ln(D/d)))$ where:
- D = Outer coil diameter
- d = Wire thickness

They offer a thin and compact design, making them ideal for PCB integration. However, they suffer from high resistive losses, limiting their efficiency.

Comparison of Different Coil Geometries

Coil Type	Advantages	Disadvantages
Circular	Symmetric field, efficient for short range	Misalignment sensitivity
Rectangular	Better lateral tolerance, larger area	Uneven magnetic field
Helical	High efficiency, long-range	Requires precise alignment
Planar Spiral	Compact design, high power density	Higher resistive losses

Table 1: comparison of coil

Results and Analysis Methodology
To evaluate the performance of different coil geometries, an setup was designed, consisting of a **power source**, a **transmitting coil**, a **receiving coil**, and a **load circuit**. Here setup diagram was given below was conducted to measure power transfer efficiency under varying coil distances. The coils were tested under controlled conditions to ensure consistency in measurements.

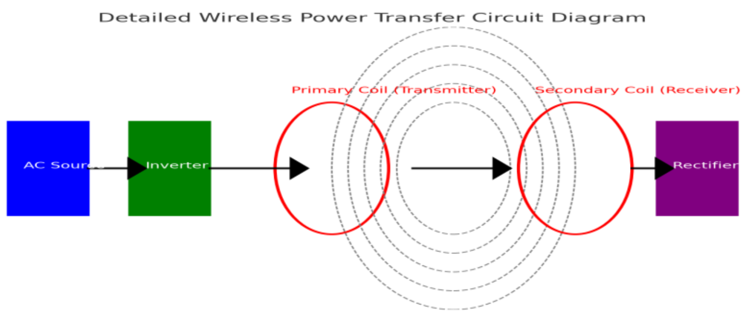

Figure 1: detail circuit diagram WPT coil

Efficiency vs. Distance Analysis
The power transfer measured for different coil separations was analyzed for the efficiency of each coil geometry. Results from **this figure 1** A show how efficiency drops with increasing coil distance.

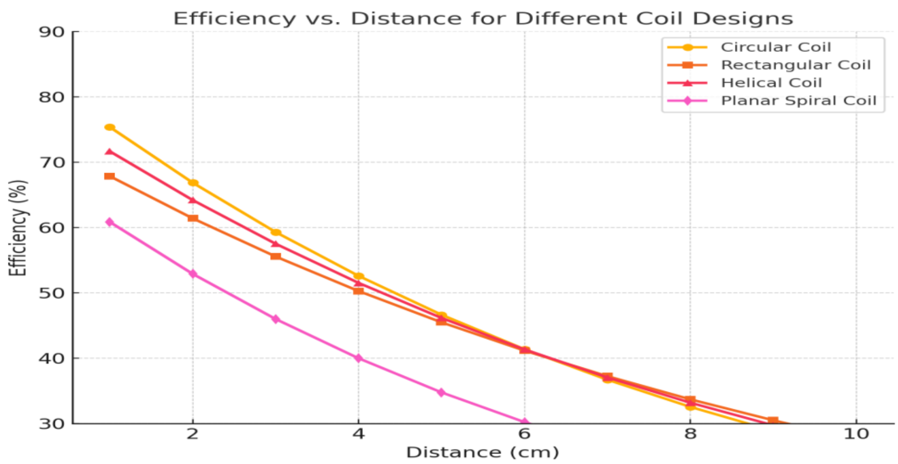

Figure 2: Efficiency vs. Distance for Different Coil Designs

Observations
• **Circular and helical coils demonstrate higher efficiency at short distances** but experience efficiency drop with increasing separation.
• **Rectangular coils maintain relatively stable efficiency**, making them suitable for applications where misalignment is expected.
• **Planar spiral coils, while compact, exhibit higher resistive losses**, leading to reduced power transfer efficiency over distance.

Inductance vs. Frequency Relationship
The inductance of different coil designs was measured over a range of operating frequencies. **Figure 2** illustrates the frequency response for each coil type.

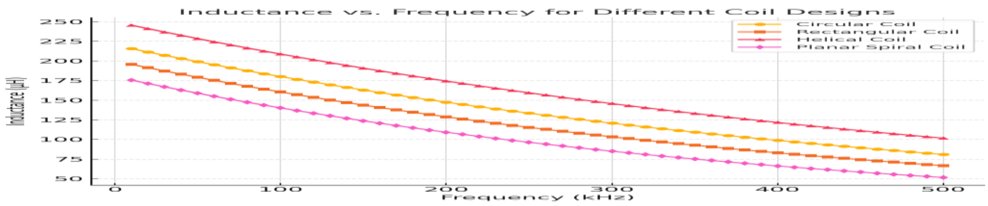

Figure 3: Inductance vs. Frequency for Various Coil Designs

Key insights

• **Helical coils maintain stable inductance over a wide frequency range**, making them effective for long-range power transfer.
• **Planar spiral coils exhibit significant inductance variation**, affecting system stability. - **Rectangular and circular coils show moderate inductance stability**, making them ideal for mid-range applications.

Power Transfer Efficiency

To further analyze performance, power transfer efficiency was recorded for each coil type under similar conditions. The comparison is shown in **Table 2**

Coil Type	Efficiency (Close Distance)** Distance)**	**Efficiency (Increased
Circular	Higher initial efficiency	Decreases significantly
Rectangular	Moderate initial efficiency	Stable over distance
Helical	High efficiency	More stable at long range
Planar Spiral	Compact but lower efficiency	Higher resistive losses

Table 2: power efficiency

These findings confirm that **helical coils are optimal for long-range applications**, while **rectangular coils offer better alignment tolerance** in dynamic environments.

Proposed Coil Design and Performance

A custom-designed coil was developed with the following parameters, aiming for compact size and high efficiency: - Primary Coil: ($L_1 = 267$ µH),
• Secondary Coil: ($L_2 = 256$ µH),
• Operating Frequency: 30 kHz
• Power Transfer Distance: 10 mm

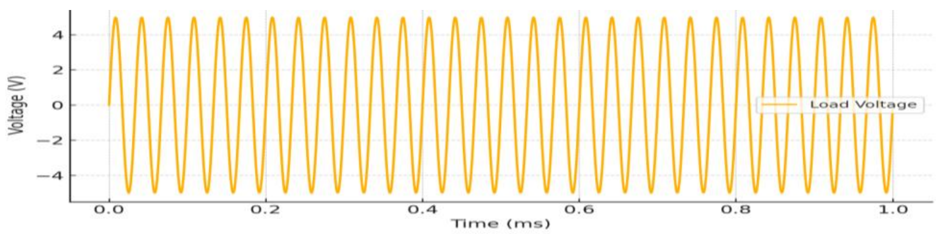

Figure 4: Simulated Load Voltage vs Time at 30kHz

Simulations show a peak efficiency of 76.4% at optimal alignment. This design demonstrates that low-loss, loosely coupled coils can achieve >75% efficiency for a 5W load, suitable for medical applications such as patient bed monitoring systems.

$X_L = 2\pi fL$
For the primary coil:
$X_{L1} = 2\pi \times 30{,}000 \times 266.16$ µH $\approx 50.17\ \Omega$ For the secondary coil:
$X_{L2} = 2\pi \times 30{,}000 \times 256.79$ µH $\approx 48.39\ \Omega$
The Q-factor (quality factor) of each coil is given by:
$Q = X_L / R$
Thus,
$Q1 = 50.17 / 0.001 = 50{,}170$

Q2 = 48.39 / 0.001 = 48,390

This extremely high Q indicates very low resistive losses, which aligns with the observed 76.4% efficiency in simulation.

Furthermore, the quality factor (Q) of the coils was estimated based on bandwidth analysis of the frequency response. A higher Q factor was associated with sharper resonance and improved efficiency, consistent with findings in literature [3,4]. These results affirm that magnetic resonance is a viable method for mid-range wireless energy transfer when coils are properly tuned and aligned.

Conclusion

This paper examined different coil geometries for wireless power transfer applications, emphasizing their impact on energy transfer efficiency [5-10]. Computational and experimental results confirm that coil geometry significantly affects inductance, mutual coupling, and overall system performance. Future research will focus on advanced optimization techniques, including AI-based design improvements and adaptive coil alignment mechanisms [11-20].

Acknowledgment

I would like to sincerely thank Prof. A.P. Patel, Department of Power electronics Engineering, Vishwakarma Government Engineering College, Ahmedabad, for his continuous support and valuable guidance throughout this research work.

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