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Research Article

Comparative Analysis of Square and Spiral Coils for Efficient Inductive Wireless Power Transfer

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Abstract – This paper presents the simulation and comparative analysis of different coil geometries used in wireless power transfer systems, focusing on square and spiral coil configurations. Using the Ansys Maxwell 3D simulation environment, key electromagnetic parameters such as self-inductance, mutual inductance, and coupling coefficients were calculated to evaluate the performance of each design. For the square coil, the simulation results demonstrated a consistent self-inductance and a varying coupling coefficient depending on the distance between the coils. As the separation distance increased, the mutual inductance and coupling coefficient values decreased, confirming the distance-sensitive nature of inductive coupling. The spiral coil, formed by side-by-side winding of copper tubing, showed the highest efficiency in magnetic field distribution and inductive characteristics. Visual representations revealed that the magnetic field intensity was most concentrated near the inner diameter of the spiral coil due to the denser turn count and reduced inter-turn spacing. These findings suggest that geometric parameters significantly influence coil efficiency and coupling behavior in inductive wireless power systems. The study offers practical insights into coil design optimization for improved power transfer efficiency and system reliability in real-world applications.

Keywords – Wireless Energy Transfer, Inductive Coupling, Wireless Power Transfer, Ansys Maxwell 3D Simulation, Square Coil, Spiral Coil.

I. INTRODUCTION

Wireless energy transfer is the transfer of electrical energy without any physical conductor [1]. This method of energy transfer has been an area of study for many years, with research focusing on ensuring the efficient transmission of energy through wireless means. Inductive coupling, first developed by Tesla, has been instrumental in applying wireless energy in various fields, including electronics, healthcare, and industry. This technology has dramatically enhanced convenience in our daily lives through high-frequency and semiconductor technology. The use of wireless energy transfer has reduced the complexities associated with physical connections, providing various advantages to the end user. The charging of modern technological devices, such as phones [2], electric toothbrushes, and electric vehicles [3], [4], is now possible through wireless energy transfer.

Inductive coupling is a short-distance wireless energy transmission method more cost-effective and efficient than long-distance wireless energy transmission systems. As a result, it has a wide range of applications. It is commonly used in wet environments, such as electric toothbrushes and shavers, due to its reduced risk of shock and improved ease of use. It is also utilized in medical implants, including pacemakers and insulin pumps, and in charging pads for mobile devices and electric vehicles. This method typically involves the transfer of power between two non-contacting inductor coils, with designs focusing on the electromagnetic field between the coils.

Efficiency in the power transmission method using inductive coupling can be improved by increasing the operating bandwidth of the inductive coil. This is achieved by adding resonance capacitors to the driver coil, with the resonant frequencies adjusted to the most appropriate frequency range by modifying the capacitor values. Optimum values are set to ensure a constant output signal at the peak reached, with the resonant capacitor essential in obtaining a stable power transfer coefficient and eliminating frequency division.

Wireless power transfer (WPT) using inductive coupling can pose challenges in meeting output power and efficiency requirements for some applications due to the small coupling coefficient between the transmit and receiver coils. Additionally, the transmission efficiency based on inductive coupling decreases as the coupling factor decreases. In WPT using inductive coupling, four different topologies exist based on the state of the coils in the circuit: series-serial, series-parallel, parallel-serial, and parallel-parallel. Each has advantages and disadvantages, with the efficiency of parallel-parallel and series-parallel topologies higher at low frequencies and the serial-to-serial topology more efficient than others at high frequencies. The serial-to-serial topology is the most widely used method, both theoretically and practically, especially at low powers.

This paper aims to investigate various WPT methods, followed by the design and analysis of the system using Maxwell 3D Design simulation program. Based on the analysis results, the circuit will be constructed, and data will be collected and recorded for further evaluation.

II. MATERIALS AND METHOD

Wireless power transmission with the inductive coupling technique encompasses four distinct topologies determined by the coil arrangement inside the circuit: series-series, series-parallel, parallel-series, and parallel-parallel. Every topology has distinct benefits and drawbacks. The parallel-parallel and series-parallel configurations exhibit greater efficiency at low frequencies, whereas at high frequencies, the series-series configuration demonstrates much superior efficiency compared to the alternatives. The series-series topology is the most prevalent approach conceptually and practically in low-power applications [3].

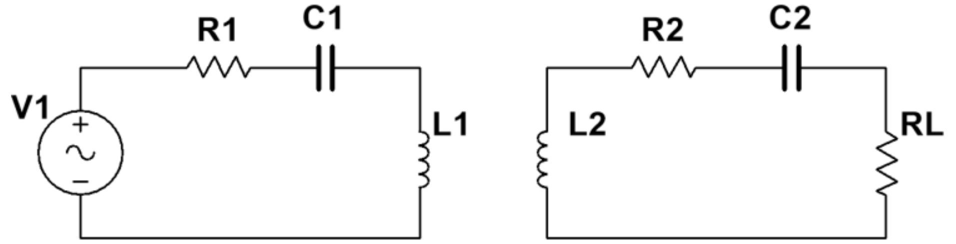


Fig. 1 Series-series inductive coupling circuit diagram

Research was done to analyze inductively coupled wireless power transfer systems, focusing on the computation of self-inductance, mutual inductance, and the coupling coefficient. The self-inductance may be determined via Wheeler's formula:

$$L = 31.33\,\mu_o \left(\frac{N^2 r^2}{8r + 11w}\right) \tag{1}$$

Where, N signifies the number of turns, r indicates the average radius, and w represents the width of the coil. μ_o The Biot–Savart Law and Stokes' Theorem may determine the mutual inductance and coupling coefficient. The coupling coefficient (k) is determined as follows:

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{2}$$

where, M denotes the mutual inductance. The coupling coefficient is inversely related to axial misalignment and the distance separating the coils. As axial misalignment escalates, the coupling coefficient diminishes swiftly, decreasing efficiency [5].

A. *Coil Simulations*

The present research involved simulating various coil shapes using the Ansys Electronics simulation program, specifically Maxwell 3D, and comparing the results to determine the optimal coil shape. In particular, the study examined the inductance values (L), mutual inductance between two coils (M), coupling coefficient (k), magnetic fields (B), and their respective changes as a function of distance for two different coil types: square and spiral [6-10].

B. *Square Coil*

The design of the square coil can be implemented in Maxwell 3D by defining a set of key parameters as outlined below in Table 1. Figure 2 explains the design of receiver and transmitter square coils and their view from the -Z axis.

Table 1. Key parameters of the square coil

Parameter	Description	Value	Remarks
Xpos	Displacement along the x-axis from the origin	0	Starting point of the square coil
Ypos	Displacement along the y-axis from the origin	0	Matches the X position
Dist	Distance between adjacent windings	3.41 mm	Based on total diameter of 30 cm and wire diameter of 1 cm
Turns	Number of full coils turns	44	88 wires total, 44 per side
Width	Width of square copper conductor	0.71 mm	Derived from equivalence with circular cross-section
Thickness	Thickness of the square wire	0.71 mm	Equal to width due to square profile

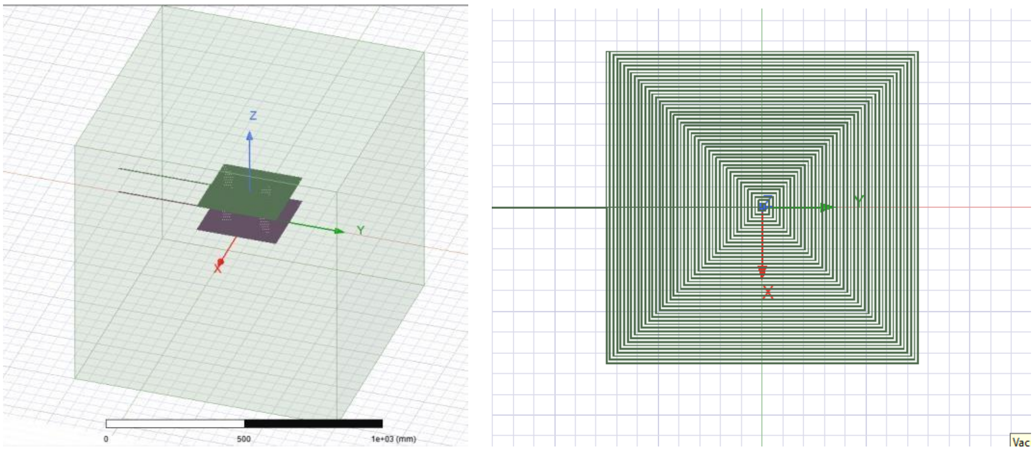
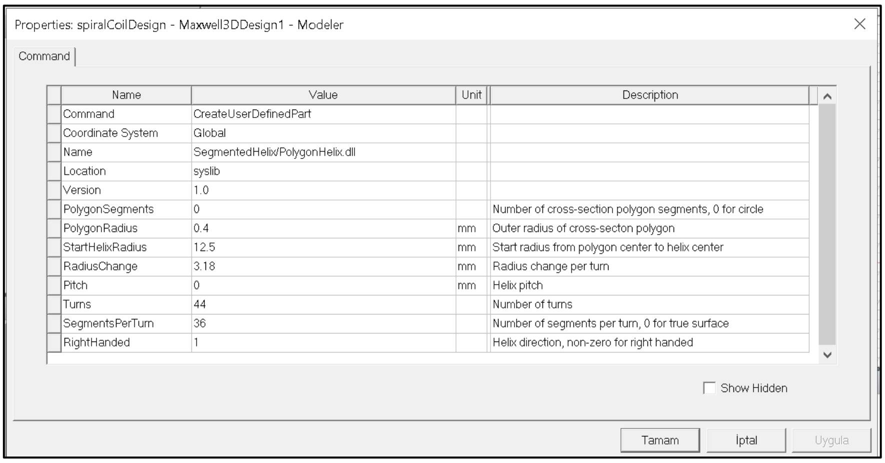


Fig 2. Design of receiver and transmitter square coils and their view from the -Z axis

C. *Spiral Coil*

To design a spiral coil, like the process used for the helical coil, the only primary difference from the helical coil lies in the *pitch* value, which is set to 0 for the spiral coil. The parameters used for the spiral coil design are given in Figure 3.



Properties: spiralCoilDesign - Maxwell3DDesign1 - Modeler

Command

Name	Value	Unit	Description
Command	CreateUserDefinedPart		
Coordinate System	Global		
Name	SegmentedHelix/PolygonHelix.dll		
Location	syslib		
Version	1.0		
PolygonSegments	0		Number of cross-section polygon segments, 0 for circle
PolygonRadius	0.4	mm	Outer radius of cross-secton polygon
StartHelixRadius	12.5	mm	Start radius from polygon center to helix center
RadiusChange	3.18	mm	Radius change per turn
Pitch	0	mm	Helix pitch
Turns	44		Number of turns
SegmentsPerTurn	36		Number of segments per turn, 0 for true surface
RightHanded	1		Helix direction, non-zero for right handed

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Fig 3. Parameters used for spiral coil design

Figure 4 shows the design of receiver and transmitter spiral coils and their view from the -Z axis.

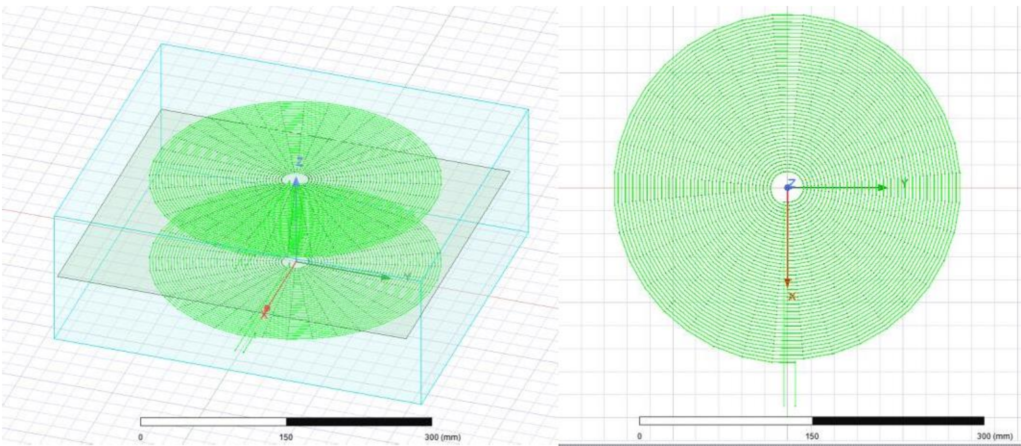

Fig 4. Design of receiver and transmitter spiral coils and their view from the -Z axis

III. RESULTS & DISCUSSION

An inverter circuit was used in the transmitter circuit to convert the provided DC voltage into AC, facilitating power transmission between the coils [11-20]. The circuit featured IRF640 MOSFETs with their source terminals interconnected [21-28]. This layout reduces power loss in the transmitter circuit, elevates both current and voltage levels, and improves the system's overall efficiency [29-35]. Additionally, since the current is necessary to augment the magnetic field inside the circuit, one coil was connected in series to each of the two positive terminals of the power supply [36-47]. Figure 5 illustrates the oscilloscope used to exhibit the output signal of the transmitter coil.

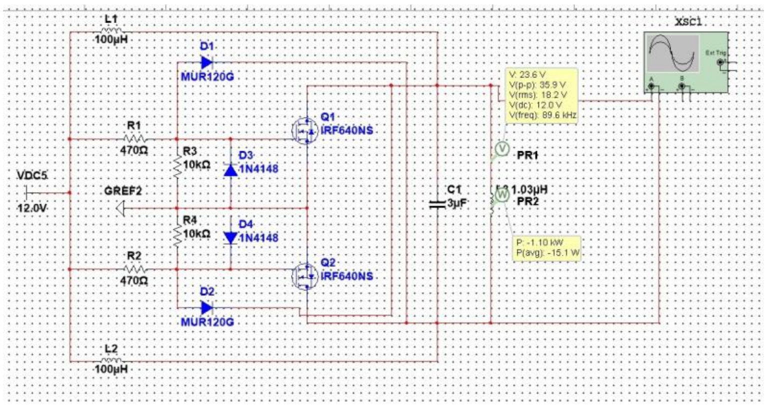

Fig 5. Transmitter circuit diagram

The circuit simulation shown in Figure 6 illustrates the components and design of the receiver part of the WPT circuit. The element designated L1 signifies the reception coil. A capacitor linked in parallel to the receiver coil is included in the circuit to improve the power transfer efficiency of the coil. A full-wave diode rectifier is included after the capacitor to convert the alternating current signals obtained from the transmitter coil into direct current. Subsequently, a capacitor and a resistor are connected in parallel after the full-wave rectifier to enhance the signals and diminish the generation of noise signals.

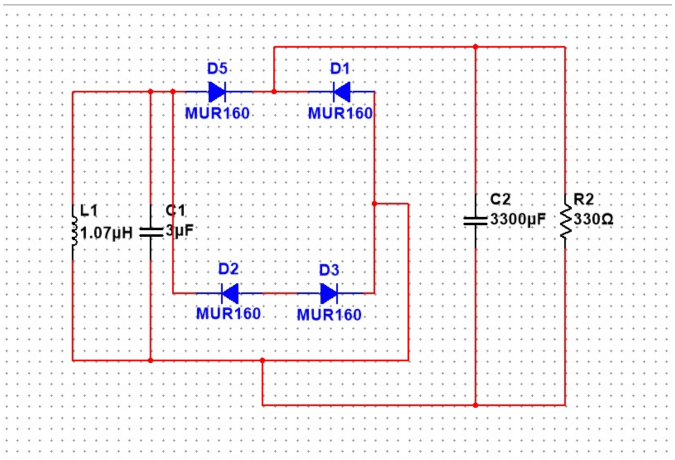

Fig 6. Receiver circuit diagram

A. *Square Coil*

As a result of the simulations conducted for the coil with a square design, the self-inductance and mutual inductance values were obtained. Table 2 provides the inductance values of the square coil with respect to distance. Table 3 shows the variation of the coupling coefficient of the square coil with respect to distance. Figure 7 depicts the coupling coefficient graph of the square coil.

Table 2. Inductance values of the square coil with respect to distance

Dist [mm]	Matrix1.L(Rx_in,Rx_in) [uH]	Matrix1.L(Tx_in,Rx_in) [nH]	Matrix1.L(Rx_in,Tx_in) [nH]	Matrix1.L(Tx_in,Tx_in) [uH]
50	253,480	109,968	109,968	252,907
100	253,905	565,751	565,751	253,03
150	253,905	313,597	313,597	253,018

Table 3. Variation of the coupling coefficient of the square coil with respect to distance

Dist [mm]	Matrix1.CplCoef (Rx_i,Rx_in)	Matrix1.CplCoef (Tx_in,Rx_in)	Matrix1.CplCoef (Rx_in,Tx_in)	Matrix1.CplCoef (Tx_in,Tx_in)
50	1	0,353512	0,353512	1
100	1	0,194471	0,194471	1
150	1	0,046385	0,046385	1
200	1	0,030148	0,030148	1

B. *Spiral Coil*

Another coil simulation performed using the Ansys Maxwell program is the spiral coil, which is formed by winding copper tubing side by side. The spiral coil exhibits the highest efficiency regarding the magnetic field it generates and its inductance values. Efficiency can be increased up to a certain point by increasing the number of turns and the coil diameter as given in Figure 8, which show the spiral coil design from different angles.

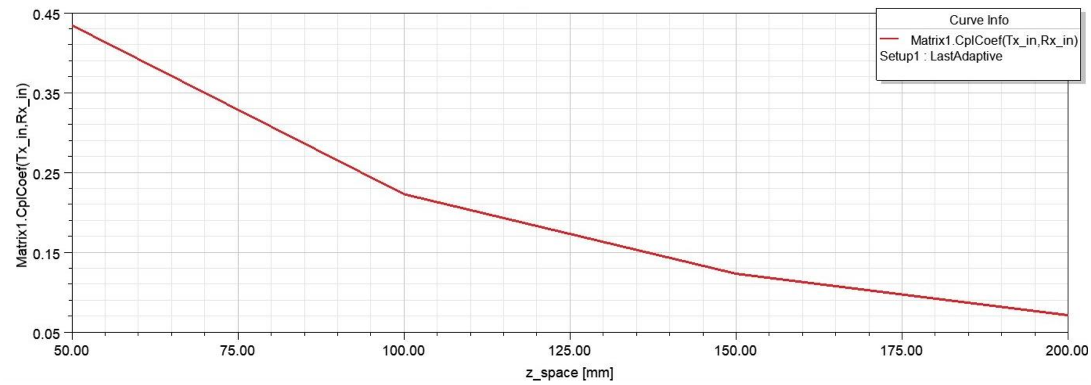

Fig 7. Coupling coefficient graph of the square coil

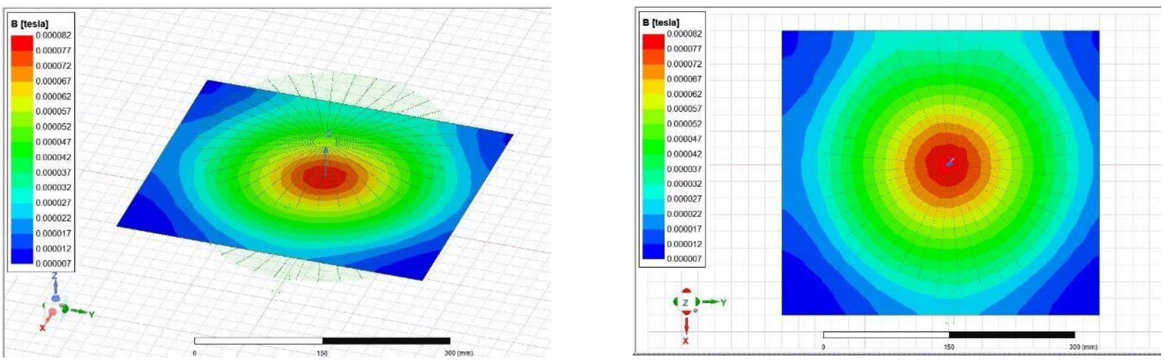

Fig 8. The magnetic field intensity of the spiral coil as displayed on the plate

The magnetic field intensity per unit area of the copper wire-wound spiral coil is represented on the plate using a color scale. The intensity of the magnetic field decreases from the inner diameter of the spiral coil toward its outer diameter. This phenomenon occurs because the number of turns at the inner diameter is greater than at the outer diameter, and the spacing between the turns increases toward the outer diameter.

IV. CONCLUSION

The simulation-based investigation of square and spiral coil designs has provided valuable insights into the inductive wireless power transfer mechanism. The square coil demonstrated stable self-inductance values but a noticeable decline in mutual inductance and coupling coefficient with increasing separation distance. These characteristics highlight the inherent limitations of square coils in maintaining high efficiency over extended distances. Conversely, the spiral coil exhibited superior magnetic field intensity and inductance performance, especially at the inner turns, where winding density is higher. The field distribution analysis confirmed that magnetic field concentration and turn geometry affect the system's efficiency. Notably, the spiral coil's design enables enhanced coupling by minimizing air gaps and maximizing the effective interaction area, making it a strong candidate for practical WPT implementations. However, both designs emphasize the importance of precise geometric configuration and spatial alignment in achieving optimal energy transfer. Future studies should explore additional parameters such as frequency variation, thermal effects, and material properties to enhance system performance.

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