

Research Article

Comparative analysis of magnetic coupler geometries for inductive EV charging

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ABSTRACT

Background: Wireless power transfer is becoming increasingly popular in electric vehicle (EV) charging systems. Without any mechanical contact, wireless power transfer can provide energy transmission from the power source to the load in application scenarios like "park and charge" and "move and charge."

Methods: This study investigates the effects of various inductive power transfer (IPT) coupler geometries on performance. It considers four possible coupler topologies: circular, rectangular, double-D (DD), and double-D quadrature receiver (DD-Q). We compare these different coupler topologies, and the results indicate that DD and DD-Q have the best performance. However, this article aims to use coils that offer a good balance of performance and cost. For this reason, we designed rectangular and circular coils using ANSYS Maxwell to test their performance since they require fewer materials to construct and are therefore the most economical options.

Results: The simulation results illustrate that the performance of the rectangular coil is superior to that of the circular coil.

Conclusion: Finally, after selecting the coil with the best performance, it can be installed on the ground of the road to power the battery of the electric vehicle.

Keywords: Electric vehicles, Coils, Inductive power transfer, Mutual inductance.

Introduction

Global interest in creating environmentally friendly and efficient transportation systems is expanding quickly. Electric vehicles (EVs) are gaining popularity due to the anticipated significant reduction in carbon footprint (1).

Modern studies currently focus on EV charging methods, specifically wireless charging via resonant inductive power transfer. This method uses Ampere and Faraday's laws of induction to enable an alternating magnetic field in a primary coil, (transmitter), to induce an electromotive force (EMF) in a secondary coil (receiver) without the need for conductive chargers. The two coils are not directly connected electrically. An electric vehicle can be charged wirelessly while it is stationary or moving, depending on the vehicle's overall battery capacity (2). Recent researchers are seeking to develop extremely effective EV wireless charging systems that can optimize of power transfer efficiency.

The magnetic coupler is made up of the primary and secondary coils. The primary coils in the Dynamic Wireless Power Transfer (DWPT) system for EVs should be well designed and optimized to produce high power output, better efficiency, and low EMF. This increases the dynamic performance of the magnetic couplers in the system.

The literature reports numerous coupler topologies of inductive power transfer (IPT) used in EV charging (3, 4). Depending on the coil winding shape, There are two types of lumped IPT charge pads (5): planar or single-sided flux couplers; and solenoid or double-sided flux couplers (6). Using the fundamental flux path as a basis, two families can be identified: Circular and rectangular design shapes (7) are examples of non-polarized couplers, meanwhile, double D (DD) (8) and double D-Quadrature (DDQ) are an example of multi-coil polarized couplers, Figure 1.

Methods

The used method in this study is based on the dynamic wireless charging system. It consists in a power source linked to a power converter that supplies the transmitter coil. This creates a magnetic field that helps to convert magnetic energy into electrical energy that powers the receiver coil (9). This coil is connected to another power converter to power the batteries as shown in Figure 2.

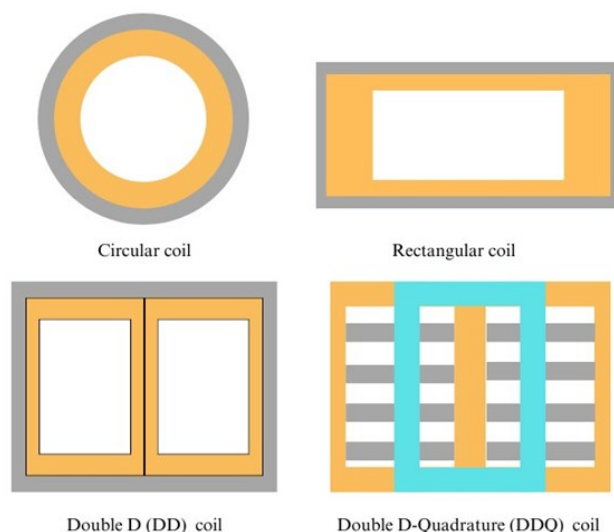


Figure 1. Design of different coil shapes.

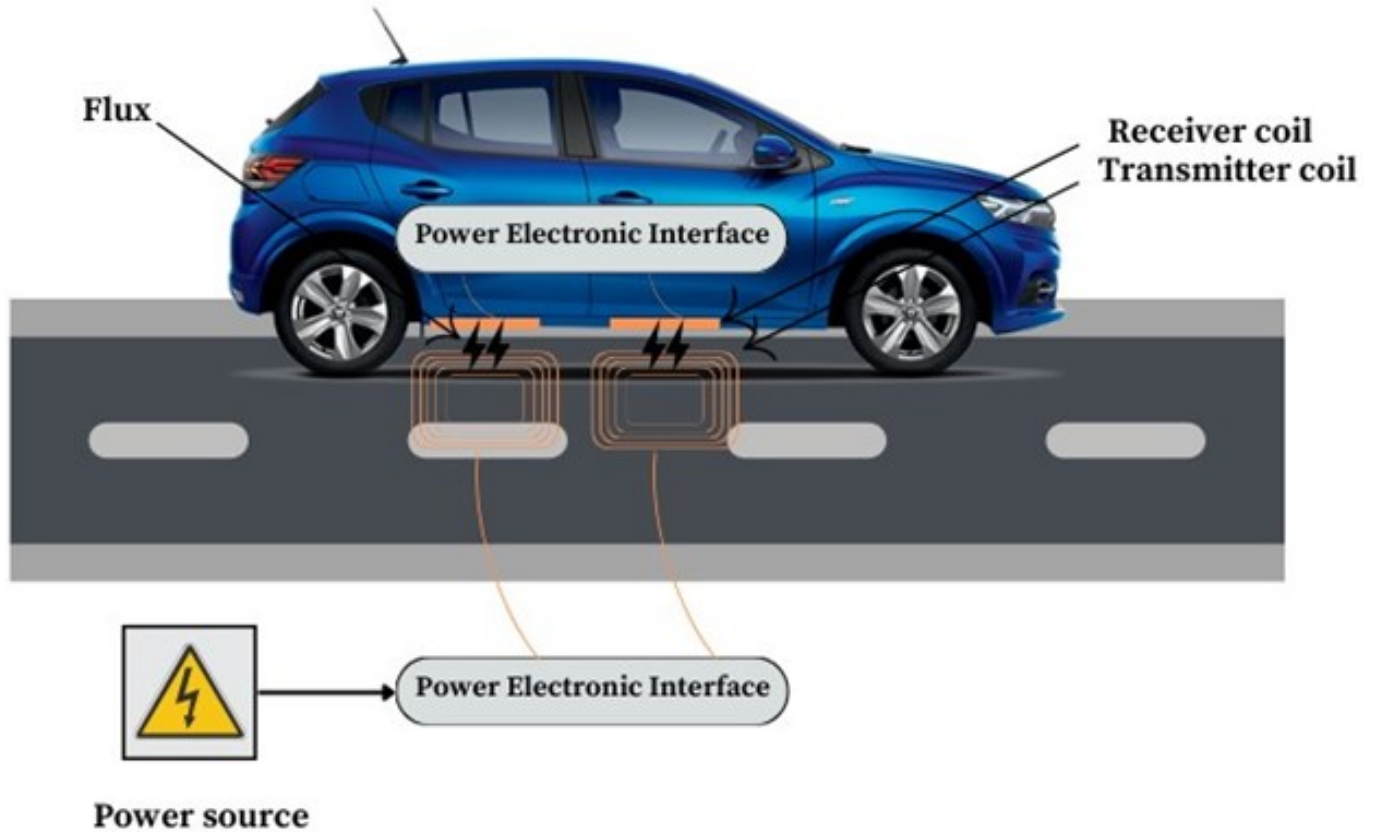


Figure 2. DWPT charging system

Wireless charging can be more convenient for drivers because it eliminates the need to plug and unplug a cable. Additionally, it can be integrated into roads, allowing vehicles to charge while driving, which could extend their range; it helps eliminate range anxiety, as it makes charging and recharging easier. It can also be integrated with renewable energy sources, contributing to a more sustainable future in transportation. However, key issues with this technique are the interaction time between transmitter and receiver coils, what makes difficult ensuring smooth and stable charging performance.

To solve these problems, it is necessary to use resonance circuits that ensure efficient power transfer considering the high reactive power. To make sure that the charger operates at a specific voltage with the current required by the battery, it is necessary to adjust the load-side output parameters. Mainly, four resonant circuit topologies could be used in an inductive energy transfer system: series-series (SS), series-parallel (SP), parallel-parallel (PP), and parallel-series (PS) assembly (8). The specifications for WPT topologies can be summarized in Table 1. Resonant topologies offer several advantages, they are listed in Table 2 (10).

Table 1. Basic specifications for WPT system topologies.

Topology	Model	Primary Capacitor	Primary Quality Factor	Secondary Quality Factor
SS		$C_p = \frac{1}{\omega_0^2 L_p}$	$Q_p = \frac{R L_p}{\omega_0 M^2}$	$Q_s = \frac{\omega_0 L_s}{R}$
SP		$C_p = \frac{1}{\omega_0^2 (L_p - \frac{M^2}{L_s})}$	$Q_p = \frac{\omega_0 L_p L_s^2}{M^2 R}$	$Q_s = \frac{R}{\omega_0 L_s}$
PP		$C_p = \frac{1}{\left(\frac{\omega_0^2 M^2}{R}\right) + \omega_0^2 L_p^2}$	$Q_p = \frac{R L_p}{\omega_0 M^2}$	$Q_s = \frac{\omega_0 L_s}{R}$
PS		$C_p = \frac{(L_p - \frac{M^2}{L_s})}{\left(\frac{M^2 R}{L_s^2}\right) + \omega_0^2 (L_p - \frac{M^2}{L_s})^2}$	$Q_p = \frac{\omega_0 L_p L_s^2}{M^2 R}$	$Q_s = \frac{R}{\omega_0 L_s}$

Table 2. Advantages of different resonant topologies.

Topology	Advantages
SS	Achieves excellent efficiency, frequently above 90%. For WPT systems, this is essential to reduce energy loss during power transfer. Among popular resonant topologies for WPT, the SS design is seen to be the most straightforward. This means there may be fewer components needed and easier implementation. There is no dependence of the resonant frequency on the coupling coefficient between the coils. Because efficiency is not as negatively impacted by misalignment in WPT as it is in other topologies, this is important.
SP	Can achieve slightly higher efficiency, particularly at higher power levels, due to reduced voltage stress on components in the secondary circuit. Compared to SS, it is less sensitive to exact component matching, which simplifies design and might save production costs. Tolerates slight deviations in the resonant frequency due to misalignment or variations in coil distance without a significant efficiency drop.
PP	Because of its low switching losses, it achieves excellent efficiency, much like SS. Offers galvanic isolation between the input and output, which in some applications may be necessary for safety. Provides a greater operating range than SS around the resonant frequency.
PS	Like SS and PP, achieves excellent efficiency due to minimal switching losses. Like PP, offers a wider operating range around the resonant frequency compared to SS

The basic and essential part of the inductive power transfer (IPT) system is the magnetic coupler. The transmitter, receiver, and shield forms the magnetic coupler. Flux distribution is controlled by switching between the transmitter and receiver coils, which use shielding and the air as a power medium. Coupling pads are used in most static wireless power transfer systems.

Fig. 1 proposes an architecture with planar pads. The key features of a wireless power transfer system are misalignment tolerance in all directions, and reduced pad volume and weight. The structure's core, coil, and shield are all designed and constructed with these qualities in mind.

Planner pads are classified as Non-Polarized Pads (NPPs) or Polarized Pads (PPs) according to the coupled flux component. Non-polarized coils are single coils that transfer electricity and have vertical flux components connected to the receiver coil. Let us examine a circle pad (CP) and a rectangle pad (RP), for example: Power is transferred by the receiver coil and the vertical and horizontal flux components that are produced by polarized pads. For instance, double-D (DD) and double-D quadrature (DDQ), as indicated in Table 3 enhance the power flow between the source and the load by adding intermediary coils (11).

Table 3. Comparison between the different coil structures of the inductive pad.

Single sided				Double-
Pad structure	RP	CP	DD	DDQ
Magnetic	One-sided	One-sided	One-sided	Double-
Shielding impact	Moderate	Weak	High	High
Flux leakage	Medium	High	Extremely low	Extremely low
Distance	Low	Low	Medium	High
System Complex	Simple	Simple	Simple	Complex
Charging zone	Small	Small	Medium	Large
Misalignmen t	Moderate	Poor	Moderate	High
Commonly used us	Transmitter and receiver	Transmitter	Transmitter	Receiver
Air gap	Non-polarized	Non-polarized	Non-interoperabl e with NPPs	Receiver
#Coils	1	1	2	3

According to Table 3, we notice that the two coils DD and DDQ have the best performance compared to other types of coils, but this article aims to use coils that have good performance and cost, from the design of the coils in Figure 1, it is observed that the rectangular and circular coils are the cheapest using less materials to construct them. For this reason, the rectangular and circular coils were chosen to simulate on Ansys Maxwell to compare the performances of the

two coils.

Modeling of WPT system

The WPT system can be presented in Figure 3.

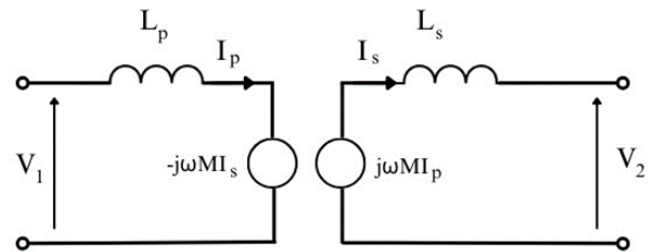


Figure 3. A simplified design of the WPT system.

The input and output voltages of the WPT system are denoted V_1 and V_2 . In this model, the primary and secondary currents I_1 and I_2 , mutual inductance M , and angular frequency " ω " are used to represent the voltages across the primary and secondary windings in these equations (1) and (2) (12, 13):

$$V_p = j\omega L_p I_p - j\omega M I_s \quad (1)$$

$$V_s = -j\omega L_s I_s + j\omega M I_p \quad (2)$$

Typical Formulas for Coil Inductance

In this work, we mainly focus in two types of coil shapes.

It is noted that the inductance factor " L " is related to the coil's shape. If the shape is circular, " L " can be written by this relation:

$$L = \frac{(r^2 N^2)}{(8r + \pi W)} \quad (3)$$

W : The winding's width.

r : The winding's radius.

N : The number of rounds.

the following Figure 4 shows the winding characteristics of a circular coil.

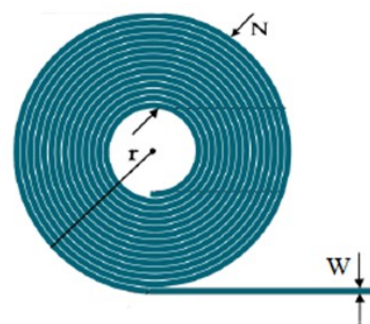


Figure 4. The winding's characteristics of circular coil.

For the rectangular coil shape, the inductance can be expressed as follows:

$$L = K_1 B_0 \frac{Nd_m}{1+K_2\rho} \quad (4)$$

With:

$$\rho = \frac{d_o - d_i}{d_n + d_i} \quad (5)$$

As it is in Figure 7, The spiral's hollowness is reflected in the filling rate ρ . The coil is hollow ($d_o \approx d_i$) in the case of a small model ρ and full ($d_o \gg d_i$). In the case of a large model. Figure 5 shows the rectangular coil winding characteristics (14).

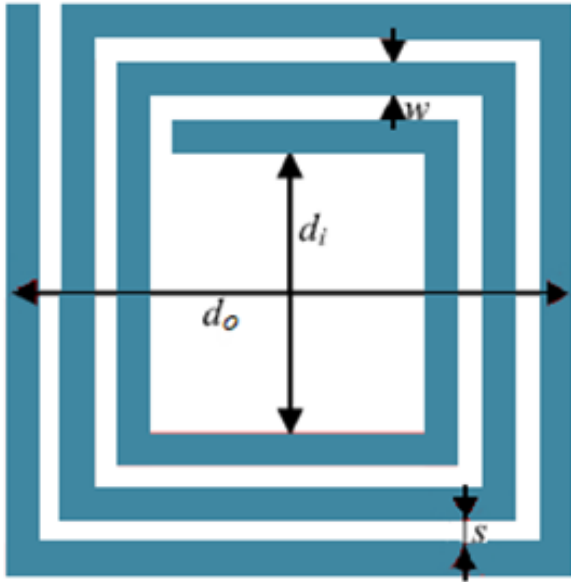


Figure 5. The winding's characteristics of rectangular coil.

Simulation and Results

The 3D model design of the two coils was made on Ansys as it is exposed in Figure 6. In this part, we have tested the effectiveness of

rectangular and circular coil inductive charge couplers, primary, we introduce the rectangular coil design and performance. Table 4 and 5, shows the transmitter and receiver coils parameters respectively.

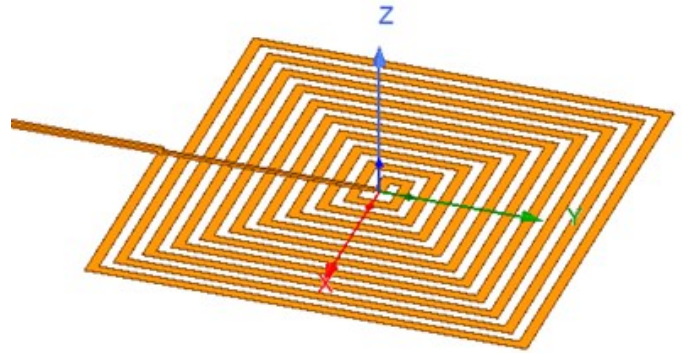


Figure 6. Design of rectangular coil.

Table 4. Properties of the rectangular coil.

Parameter	Value
Distance between turns	6 mm
Turn number	10 turns
Spiral width	3 mm
Spiral thickness	0.3 mm

Table 5. Properties of the circular coil.

Parameters	Value
Polygon segments	4
Polygon radius	1 mm
Start Helix radius	20 mm
Radius change	2.05 mm
Pitch	0 mm
Turn number	10 turns
Segments per turn	36

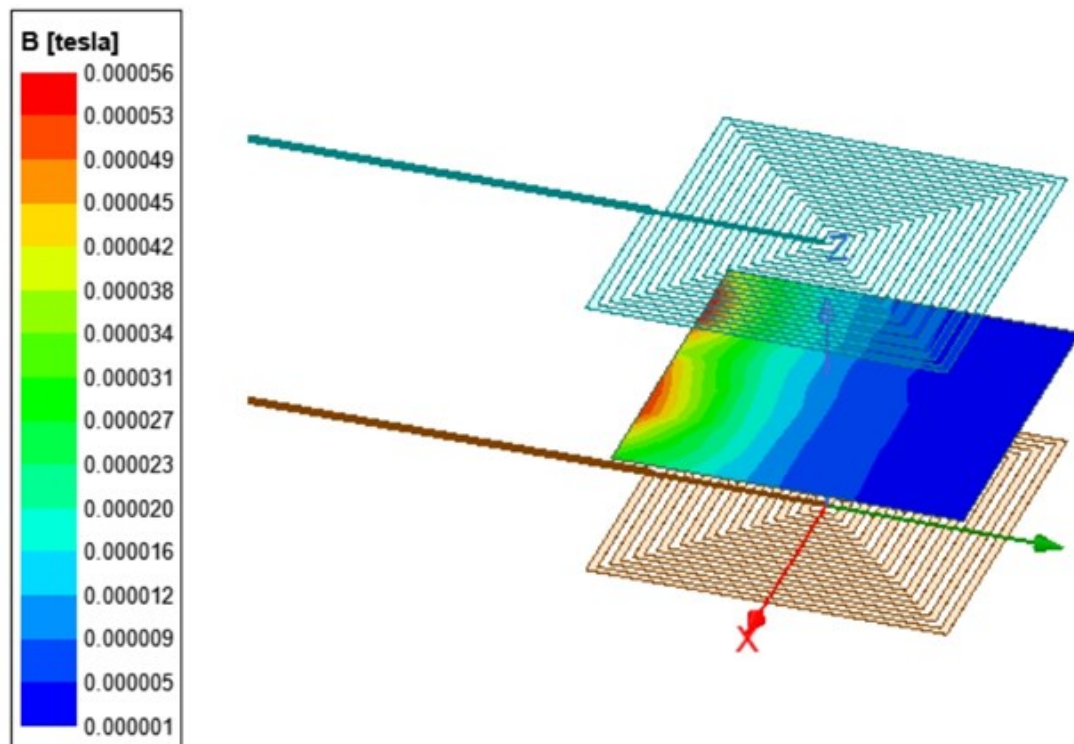


Figure 7. The magnetic field between the transmitter and receiving "rectangular" coils.

Discussion

This study focuses on recent research that compared inductive couplers (11-15), (16, 17), as well as research that examined the performance of coils (18, 19), (20, 21). Figures 7, 8, 9 and 10 show the transmitter and receiver coils in a rectangular and circular shape in ANSYS Maxwell, between the transmitter and receiver coils there is a rectangular plate transparent that was positioned to record the magnetic field that was produced between them. The transmitter and receiver coils for both shapes had equivalent sizes to bounce with better coupling coefficients. From the results of the magnetic fields found in Figures 7 and 10, the further the transmitting coil moves away from the center of the receiving coil, the lower the value of the magnetic field. The blue at the bottom has the smallest value, and the red at the top has the highest value of the magnetic field. In Fig. 8 the

maximum value of the magnetic field equals $56 \mu\text{T}$ and the minimum value equals $1 \mu\text{T}$. In Fig. 11 the maximum value of the magnetic field is equal to 54.927 nT and the minimum value is equal to 19.626 nT . The amount of mutual inductance between the transmitter coils and receiver changes slightly, as shown in Figures 7 and 10, as each coil corresponds to the sum of its inductance and the mutual inductance of the other coil. While there is still flux, the rate changes slightly as the other coil moves closer in the reason for defining the excitation current track. The amount of mutual inductance in Figure 7 decreases from 0.0825 to 0.0175 in z-space equal to 100mm, then it decreases to 0.0050 in z-space equal to 150mm. Finally, it decreases again towards 0.0025 in the z-space equal to 200 mm. And the amount of mutual inductance in Figure 11 decreases from 0.000175 to a value of 0.00004 in the z-space of 100 mm then it decreases until it reaches 0.000025 in the z-space equal to 150 mm. Finally, it decreases again until it reaches 0.000015 in a z-space equal to 200 mm.

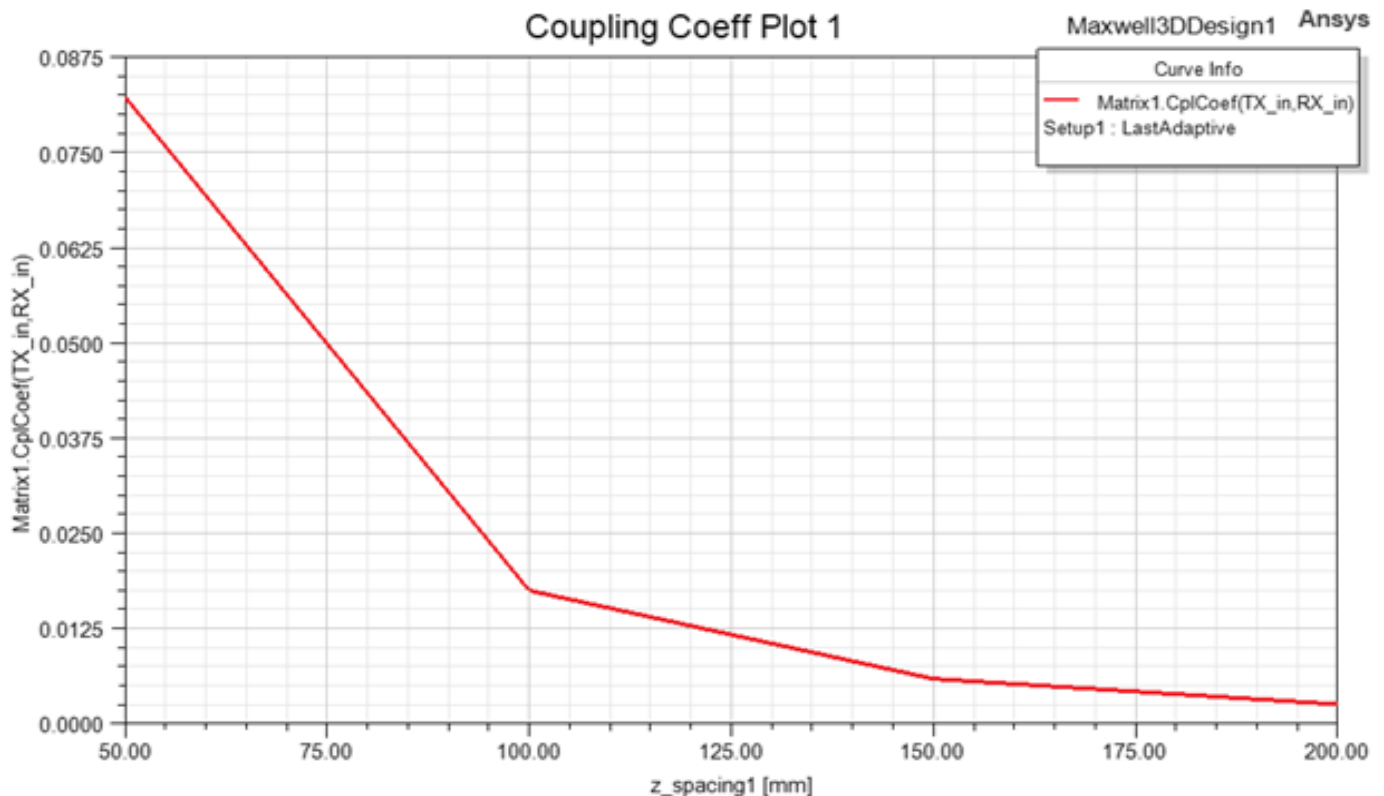


Figure 8. Mutual inductance between transmitter and receiver rectangular coils.

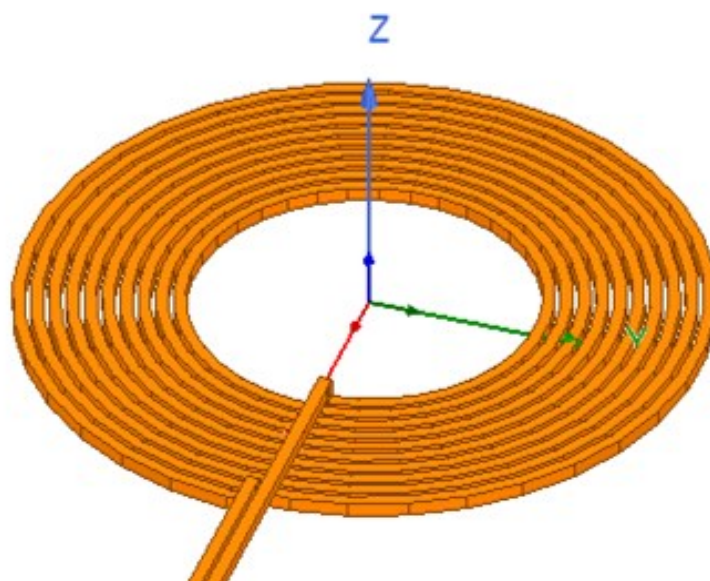


Figure 9. Design of circular coil.

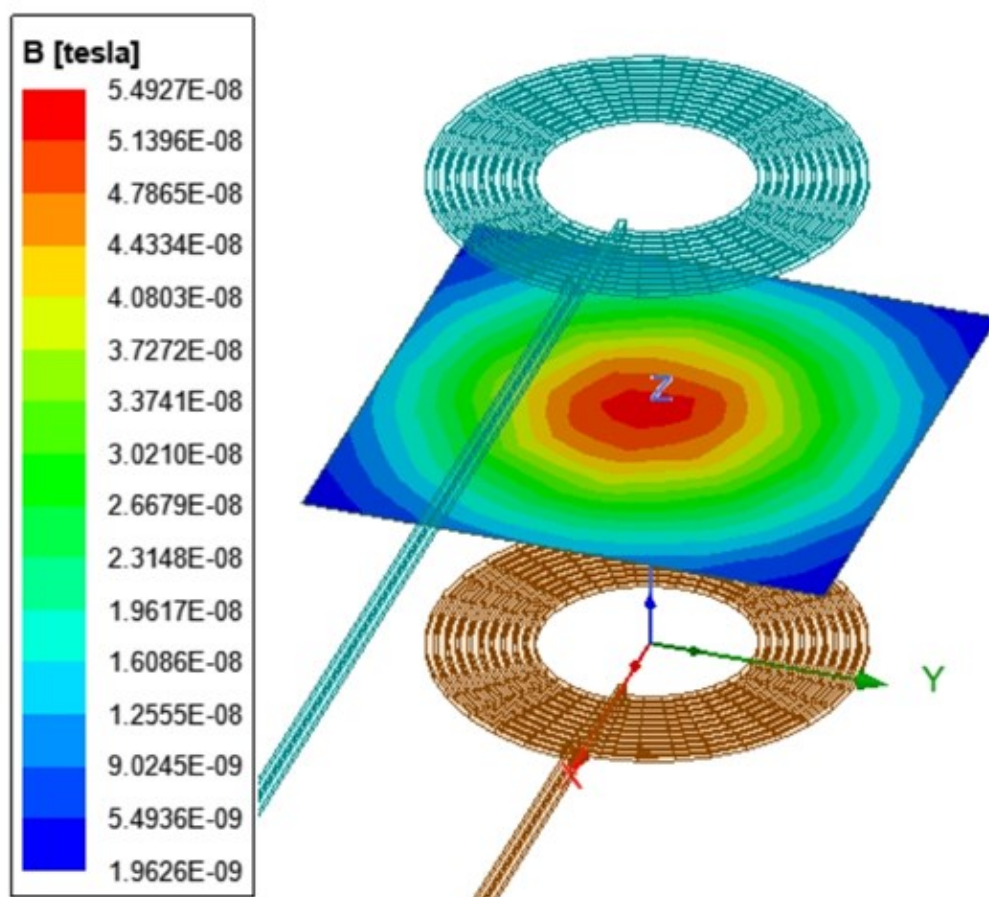


Figure 10. The magnetic field between the transmitter and receiving "circular" coils.

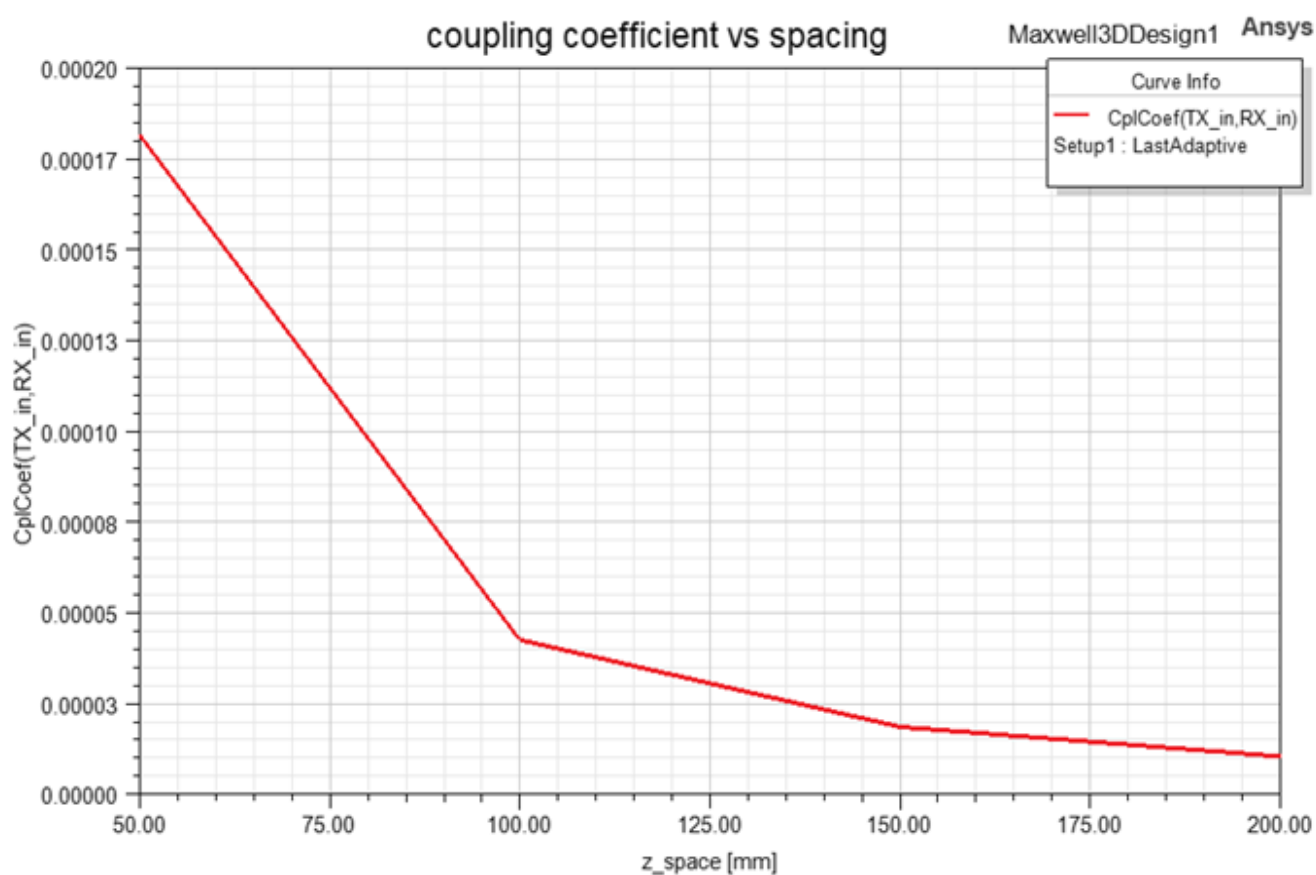


Figure 11. Mutual inductance between transmitter and receiver circular coils.

Conclusion

In this work, we presented the mathematical model that drives the system and the different compensation topologies, and we made a comparison between the different coupler topologies of the IPT system.

Finally, we simulated these models of rectangular and circular coils on Ansys software to find out the best-performing coil.

The Future Outlook of EV Charging

Growing electric vehicle sales provide strong evidence of continued improvement in charging infrastructure. The introduction of high voltage off-board DC chargers with advanced power electronics in recent years has made it possible to charge larger amounts of data while keeping the network's current values and the charger's component limitations in check. These chargers are distinguished by their increased power density and efficiency. Consequently, there is now much less waiting time needed for a full recharge. And future advancements in semiconductor and battery technologies will cause it to drop even further. Eventually, as electric vehicles become more widely available, a smart grid with real-time energy flow regulation and information distribution capabilities will emerge. Consequently, the utilization of intelligent charging methodologies and ideas like V2G and DWPT will be made possible. Additionally, as the decarbonization of the transportation sector necessitates an increase in the production of zero-carbon electricity, the impending widespread integration of electric vehicles and the ensuing rise in energy consumption will boost the continuous exploitation of RESs.

Competing interests

The authors declare no competing interest.

Data information

No data to be share

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