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Ferrite shielding thickness and its effect on electromagnetic parameters in wireless power transfer for electric vehicles (EVs)

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Abstract

Wireless power transfer (WPT) has become an increasingly popular technology for charging electronic devices wirelessly. One of the key challenges in WPT is increasing efficiency and reducing different losses in coils caused by the higher air gap and coil coupling between the primary and secondary coils. Ferrite shielding is a common technique used to reduce losses and increase the coupling in WPT systems. In this paper, we present an analysis and comparison study of the effect of ferrite shielding thickness (F_T) on the electromagnetic parameters of WPT systems. We investigate the impact of varying the ferrite shielding thickness on parameters such as power transfer efficiency, coupling coefficient (k), and magnetic field strength (B). Our results show that increasing the ferrite shielding thickness can significantly reduce losses and improve the performance of WPT systems. Also, analyze the trade-off between ferrite shielding thickness and power transfer efficiency and provide guidelines for selecting an optimal thickness for a given application. This study provides valuable insights into the design and optimization with weight vs. coupling comparison for WPT systems using ferrite shielding. It can help inform the development of future WPT technologies. The result obtained through simulation, i.e., coil-to-coil efficiency, is 98.88 to 99.7360% at 6.78MHz frequency for a 5-mm- to 50-mm-thick ferrite rectangular coupler using ANSYS Maxwell and ANSYS simplorer software.

Keywords: Electric vehicles (EVs), Ansys Maxwell, Coil geometry, Mutual inductance, Coupling coefficient, Ferrite shielding, Wireless power transfer (WPT), Magnetic coupler

Introduction

Wireless power transfer (WPT) has emerged as a promising technology for powering electronic devices without needing physical connections or batteries [1–5]. One of the critical components of a WPT system is the coupling element, which transfers energy from the primary coil to the secondary coil. In recent years [6], much research has been focused on developing WPT coils and ferrite magnetic couplers that offer high efficiency, low cost, and compact size [7].

WPT coils play a critical role in WPT systems, generating a magnetic field that transfers power wirelessly. In order to achieve high efficiency in WPT systems, it is essential to design the coils to have low resistance, high-quality factor (Q-factor), and high coupling coefficient [8–10]. In a study [11, 12], the authors proposed a new WPT coil design that utilized a high-permeability magnetic material and a non-uniform winding pattern to achieve high Q-factor and coupling coefficient [13–16]. The results showed that the proposed design outperformed conventional WPT coils regarding power transfer efficiency. Another study by [17, 18] investigated the effects of coil geometry on the performance of WPT systems. The authors compared the performance of circular, square, and hexagonal coils and found that the hexagonal coil design offered the highest coupling coefficient and power transfer efficiency [19].

Ferrite magnetic couplers are commonly used in WPT systems to improve coupling between the primary and secondary coils, thereby increasing power transfer efficiency. Ferrite materials are chosen due to their high permeability, low losses, and low cost. In a study [20], the authors proposed a new ferrite magnetic coupler design that utilized a multi-layer structure to improve power transfer efficiency. The results showed that the proposed design outperformed conventional ferrite magnetic couplers regarding power transfer efficiency and voltage regulation. Another study [20] investigated the effects of ferrite magnetic coupler geometry on the performance of WPT systems. The authors compared the performance of rectangular and circular ferrite magnetic couplers and found that the circular design offered a higher coupling coefficient and lower losses.

Overall, the literature suggests that WPT coils and ferrite magnetic couplers play a critical role in the performance of WPT systems [21]. The design of these components can greatly affect the efficiency, cost, and size of WPT systems [20, 22–24]. Further research is needed to optimize these components' design and improve WPT systems' performance.

Another important aspect of WPT coils and ferrite magnetic couplers is their impact on the overall size and weight of the system. Several studies have investigated using compact and lightweight components for WPT systems, which is particularly important for applications such as wearable devices and medical implants. For example, [25] proposed a novel design for a compact and lightweight WPT coil based on a helical structure. They also used a ferrite magnetic coupler to reduce EMI and improve the coil's efficiency. Similarly, [26] proposed a lightweight and flexible WPT coil based on a printed circuit board (PCB) structure and used a ferrite magnetic coupler to improve the coil's coupling coefficient and power transfer efficiency [26].

These studies demonstrate the importance of WPT coils and ferrite magnetic couplers in achieving high efficiency and reducing losses in WPT systems. By selecting the appropriate materials and optimizing the geometry of the components, it is possible to achieve high power transfer efficiency and low loss in a compact and lightweight package. Further research is needed to explore new materials and designs for WPT components and to improve the performance and reliability of WPT systems for various applications, as shown in Table 1.

The rest of the paper is structured as follows: the "Methods" section describes the basic idea of Ansys Electronics (finite element analysis) and coil designing and the modeling of the coil and coupler. In the "Results and discussion" section, we have analyzed all electromagnetic parameters of coil and couplers, and the "Conclusions" section includes results and discussion. Finally, the conclusion is provided in the "Conclusions" section.

Table 1 WPT charging applications with power rating

Device	Power rating (watts)
Electric vehicle (EV) [3]	7.2–22 kW
Medical implant device [6]	0.01–5 W
Mobile phone charger [27]	5–15 W
Electric toothbrush charger	0.5–2 W
Wireless headphone charger	1–3 W
Smartwatch charger	1–5 W
Drone battery charger	50–200 W
Laptop charging pad [27]	30–60 W

Methods

Wireless power transfer efficiency depends on the design parameters of the WPT coil assembly. The computational studies on the WPT-coil modeling and associated design parameters can provide us find the optimal design parameters to attain maximum efficiency. Therefore, before developing the practical WPT-power transfer system, it is advantageous to study the coil modeling and coil parameter design to analyze the coil performance, ensuring maximum efficiency. In this direction, we conducted a detailed simulation study on coil modeling and design in Ansys Maxwell. In Ansys, geometrical modeling is performed using the Maxwell 3D design tab, and then the material properties are assigned. The finite element mesh is created per the requirement of the refinement and the computational facility available (Intel-Corei3, 2.30 GHz, 8 GB RAM). After assigning the boundary conditions, the analysis work is started to solve the model problem developed in the model developing wizard specified by a particular coordinate system. This section explores the design of charging coils for a wireless power transfer (WPT) system using resonant inductive coupling. The magnetic field concentration between the transmission and receiving coils is crucial for effective power transfer. Increasing the number of turns in the coil can increase the magnetizing inductance and the coil's parasitic resistance, decreasing the maximum power transfer. Therefore, a small value of reactive power must be maintained to ensure optimal power transfer between the source and load, and also effective power transfer depends on the shape of the coil and various geometric parameters, so different coil geometries must be designed and compared. Electromagnetic coil assemblies are modeled in Ansys software by incorporating cascaded Polygon segments of equal radius, i.e., 1 mm, and all the segments per turn 36 are assigned with the properties of copper using FEM (finite element method) method to find all the design parameters through the computer simulation.

Coil and coupler designing

For the purpose of this study, both the transmission coil (Tx) and receiving coil (Rx) were designed using the same inductance coil design. The design process was carried out using the ANSYS-Maxwell simulation software, where the transient analysis time domain specification was selected. A table labeled as Table 2 was used to display the user-defined values for the coil design. The focus of the analysis was primarily on the

Table 2 User-defined design parameter of coil

Coil design	Rectangular coil
Polygon segment	8
Polygon radius	1 mm
Start helix radius	10 mm
Radius change	2.5 mm/turn
Pitch	0
Number of turns	10
Segment per turn	36/turn
Excitation current on Coil1 & Coil2	10 A
Mesh maximum element length	200 mm
Vacuum region area	11801600mm^3
Vacuum region volume	2672640000mm^3

design parameters of the Tx coil. However, it was assumed that the design of the Rx coil was similar to that of the Tx coil and hence not explicitly stated.

Designing steps used in Ansys

Initially, we generated a rectangular coil via the Ansys Maxwell software, a preferred coil type for various wireless power transfer applications [15].

- Use the Ansys Electronics Desktop application and create a new project and define the working environment by selecting the relevant units, lengths, and frequency.
- Start with the design of the rectangular copper coil. Draw the shape of the coil using the "Draw" feature and then extrude it to the desired height using the "Extrude" feature.
- Set the material properties of the copper coil using the "Material" feature. This will define the electrical conductivity and other properties of the copper coil.
- Define the excitation of the coil using the "Excitation" feature. This will allow you to specify the frequency and voltage of the input signal.
- Perform a simulation to verify the performance of the copper coil. You can analyze the electromagnetic parameters such as the coil's voltage, current, and magnetic field strength using the "Results" feature.
- Design the ferrite coupler shielding. Draw the shape of the coupler using the "Draw" feature and extrude it to the desired height using the "Extrude" feature and set the material properties of the ferrite coupler using the "Material" feature. This will define the magnetic properties of the ferrite material.
- Add the ferrite coupler to the copper coil simulation model and specify the boundary conditions using the "Boundary" feature. This will simulate the coupling between the copper coil and the ferrite coupler.
- Perform a simulation to verify the performance of the WPT rectangular copper coil and ferrite coupler shielding design. Analyze the electromagnetic parameters such as the voltage, current, and magnetic field strength using the "Results" feature.

The author designed a rectangular coil of 10 turns with ferrite shielding as shown in Fig. 1.

Analysis of electromagnetic parameters

Wireless power transfer (WPT) coils are designed to transfer electrical power wirelessly from a source to a load. Electromagnetic parameters play a critical role in the performance of WPT coils. The key electromagnetic parameters analyzed in this design of WPT coils are the induction of coils, coupling between transmitting and receiving coils, and mutual inductance.

Misalignment analysis

Misalignment in wireless power transfer (WPT) systems can occur due to various factors such as positioning errors, environmental changes, and mechanical vibrations. Misalignment can cause a significant reduction in power transfer efficiency and lead to overheating electromagnetic interference, and other issues. A theoretical model can be developed using electromagnetic field theory to analyze the misalignment of WPT coils.

The theory of misalignment analysis of WPT coils involves using Maxwell's equations and the laws of electromagnetic induction to model the behavior of the magnetic field and the power transfer between the coils. WPT systems generally consist of transmitter and receiver coils separated by a distance or air gap z as shown in Fig. 2; also, it is shown how the coupling coefficient will change according to the different air gaps with different ferrite thicknesses, and Fig. 3 shows mutual inductance variation with air gap for different ferrite thicknesses.

Under ideal alignment conditions, the magnetic field generated by the transmitter coil induces a voltage in the receiver coil, generating a magnetic field that repels the transmitter field. This interaction results in a resonant coupling between the two coils, leading to efficient power transfer. However, when the two coils are misaligned, the magnetic fields no longer interact optimally, decreasing power transfer efficiency. The degree of misalignment can be quantified by the distance offset between the two coils along the x, y, or z axis or by the rotational angle between the two coils around one or more axes.

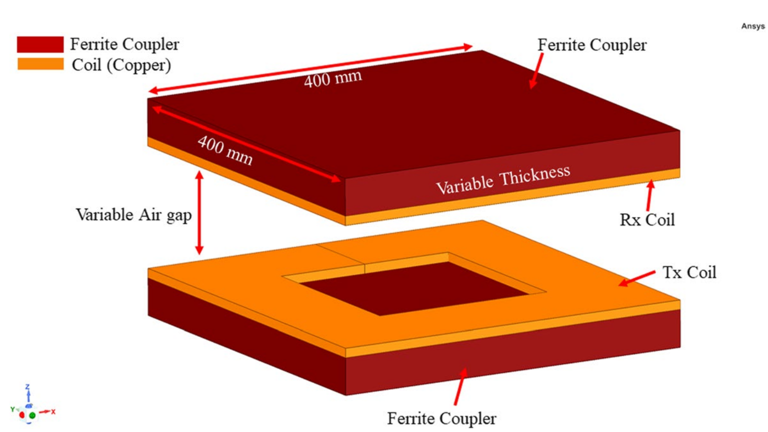

Fig. 1 Rectangular coil of 10 turns with ferrite shielding

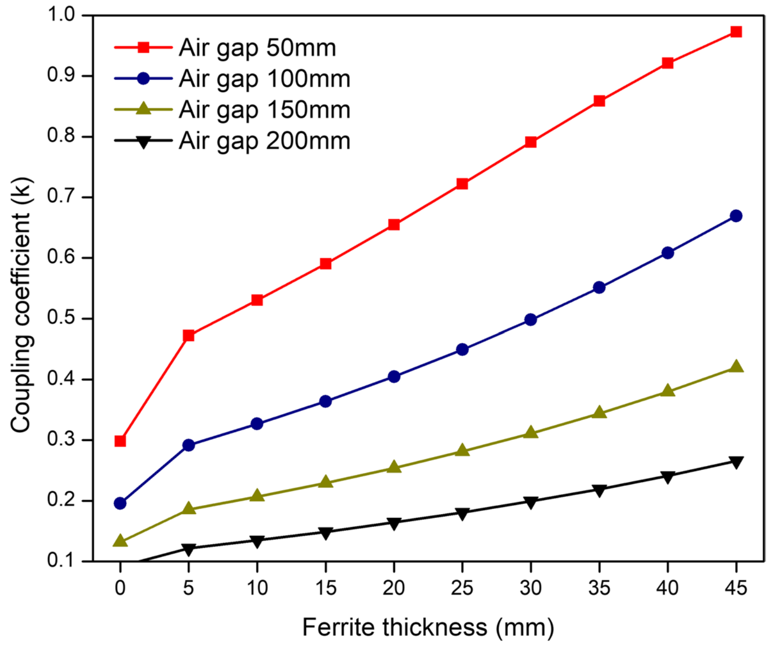

Fig. 2 Coupling coefficient (*k*) vs. Ferrite thickness for a different air gap between Tx and Rx coil

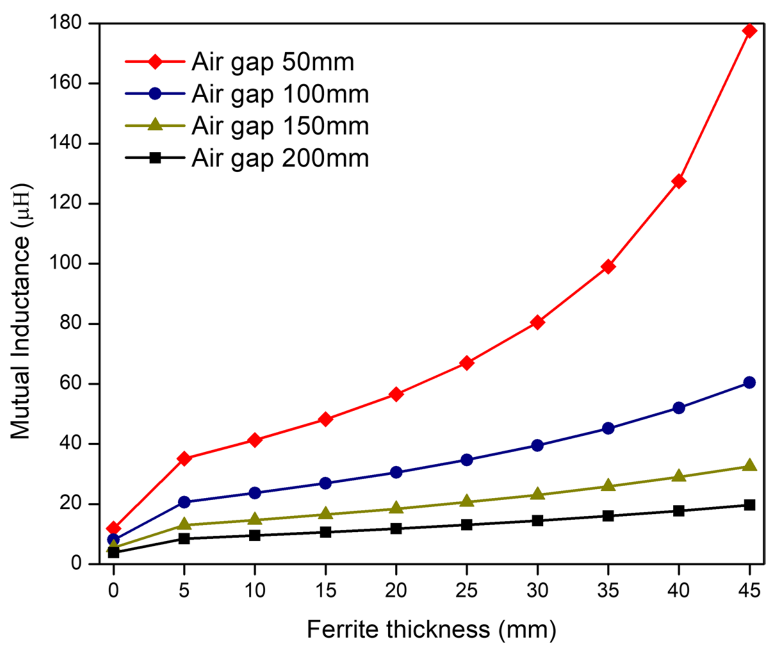

Fig. 3 Mutual inductance (M) vs ferrite thickness for a different air gap between Tx and Rx coil

A model has been developed to analyze the misalignment of WPT coils using electromagnetic simulation software, such as Ansys Maxwell or Ansys HFSS. The model involves defining the geometry and material properties of the coils, setting up the simulation parameters, and introducing a misalignment in the system. The simulation results can then be analyzed to determine the impact of the misalignment on the magnetic field distribution, power transfer efficiency, and other key system parameters. Overall, the misalignment analysis of WPT coils is an essential aspect of designing and optimizing wireless power transfer systems, helping to ensure reliable and efficient power transfer under various operating conditions.

Horizontal misalignment

Horizontal misalignment in wireless power transfer (WPT) systems occurs when the transmitter (Tx) and receiver (Rx) coils are shifted along the x-axis shown in Fig. 4. This can cause a reduction in power transfer efficiency due to the change in the magnetic coupling between the coils. In addition to horizontal misalignment, changing the thickness of the ferrite coupler can also affect the magnetic field distribution and power transfer efficiency.

A theoretical analysis can be conducted using electromagnetic field theory to model the effect of horizontal misalignment and changes in ferrite coupler thickness on WPT coil performance. This involves solving Maxwell's equations for the magnetic field and power transfer between the Tx and Rx coils, considering the impact of the air gap and ferrite material.

The offset distance between the Tx and Rx coils along the x-axis can quantify the misalignment. The magnetic field distribution and power transfer efficiency can be analyzed using simulation software such as Ansys Maxwell or Ansys HFSS by introducing the misalignment and changing the ferrite coupler thickness while keeping the air gap between the coils constant.

The simulation results, as shown in Figs. 5 and 6, can be used to optimize the design of the WPT system, such as by adjusting the thickness of the ferrite coupler to improve the magnetic coupling between the coils and compensate for the misalignment. By accurately modeling the effect of horizontal misalignment and ferrite coupler thickness changes, the efficiency and reliability of WPT systems can be improved, leading to more effective and sustainable wireless power transfer.

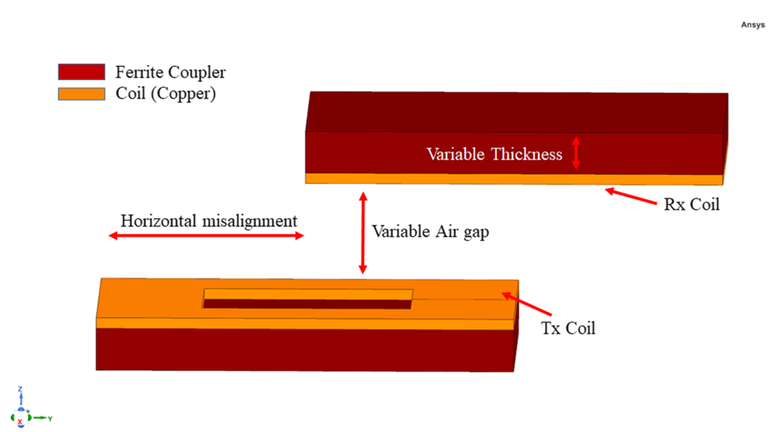

Fig. 4 Horizontal misalignment of coil and coupler for different mm

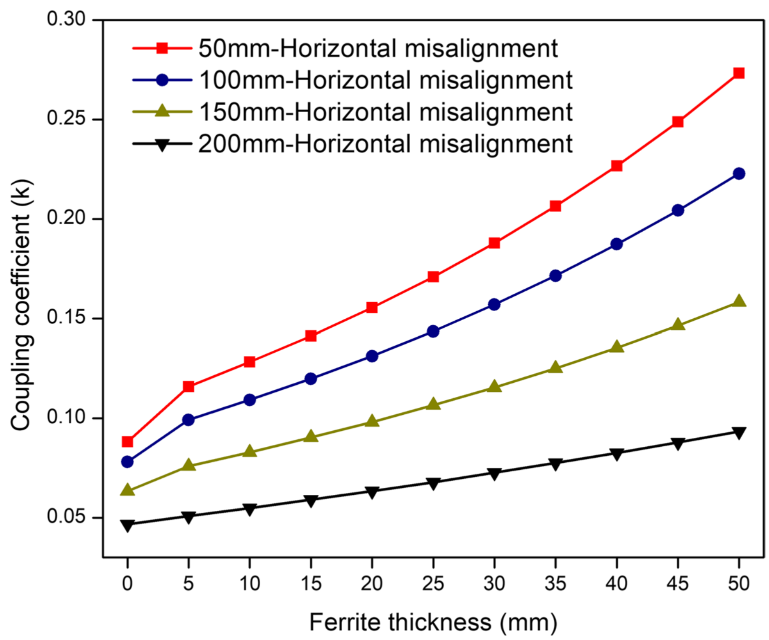

Fig. 5 Coupling coefficient (*k*) vs. ferrite thickness for different horizontal misalignment

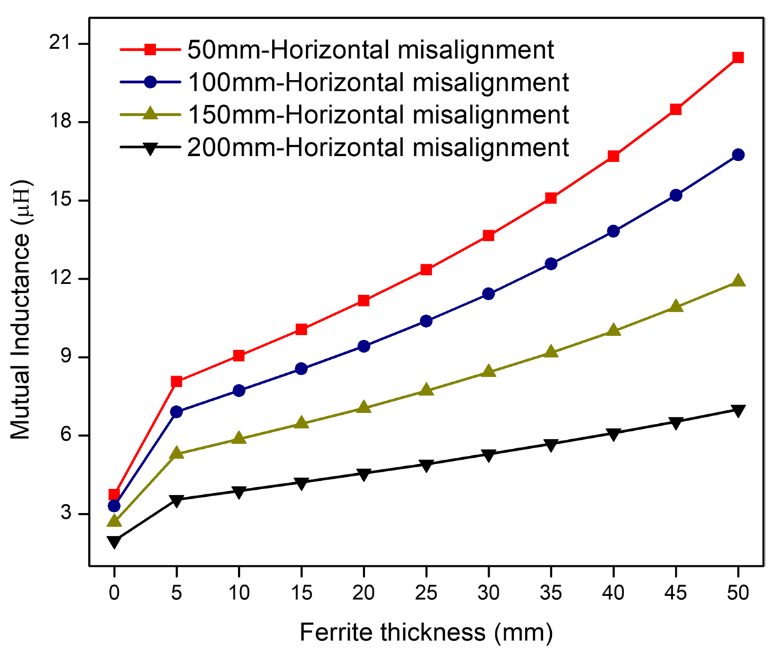

Fig. 6 Mutual inductance vs. ferrite thickness for different horizontal misalignment

Angular misalignment

Angular misalignment in wireless power transfer (WPT) systems occurs when the transmitter (Tx) and receiver (Rx) coils are rotated with respect to each other, as shown in Fig. 7. This can cause a reduction in power transfer efficiency due to the change in the magnetic coupling between the coils. In addition to angular misalignment, changing the thickness of the ferrite coupler can also affect the magnetic field distribution and power

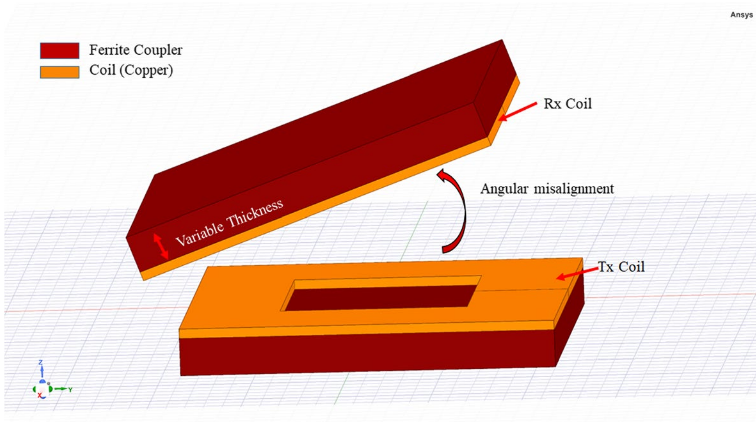

Fig. 7 Angular misalignment of coupler and coil for different degrees

transfer efficiency. Theoretical analysis can be conducted using electromagnetic field theory to model the effect of angular misalignment and changes in ferrite coupler thickness on WPT coil performance. This involves solving Maxwell's equations for the magnetic field and power transfer between the Tx and Rx coils, considering the impact of the air gap and ferrite material.

The rotational angle between the Tx and Rx coils around one or more axes can quantify the angular misalignment. The magnetic field distribution and power transfer efficiency can be analyzed using simulation software such as Ansys Maxwell or Ansys HFSS by introducing the misalignment and changing the ferrite coupler thickness while keeping the air gap between the coils constant.

Table 3 and Figs. 8 and 9 show all the above comparisons of the coil in terms of the coupling coefficient (k) and mutual inductance (M) for different air gaps with variable thickness of ferrite shielding. In Table 3, we see significant improvement in results regarding the coupling coefficient (k) and mutual coupling coefficient when we increase the thickness of ferrite shielding on the coil.

Weight and losses analysis

Several factors must be considered to perform a weight and loss analysis of a ferrite coupler for wireless power transfer (WPT). Here are some key points to consider in the analysis:

- *Ferrite material properties*: The choice of ferrite material will significantly impact the weight and losses of the coupler. Different ferrite materials have different permeability, resistivity, and saturation magnetization, which affect their performance in WPT systems.
- *Coupler design*: The physical design of the ferrite coupler, such as its shape, size, and winding configuration, will affect its weight and losses. The design should be optimized to minimize losses while achieving efficient power transfer.
- *Operating frequency*: The operating frequency of the WPT system will impact the ferrite coupler's losses. Higher frequencies generally increase losses due to eddy currents and hysteresis losses in the ferrite material.

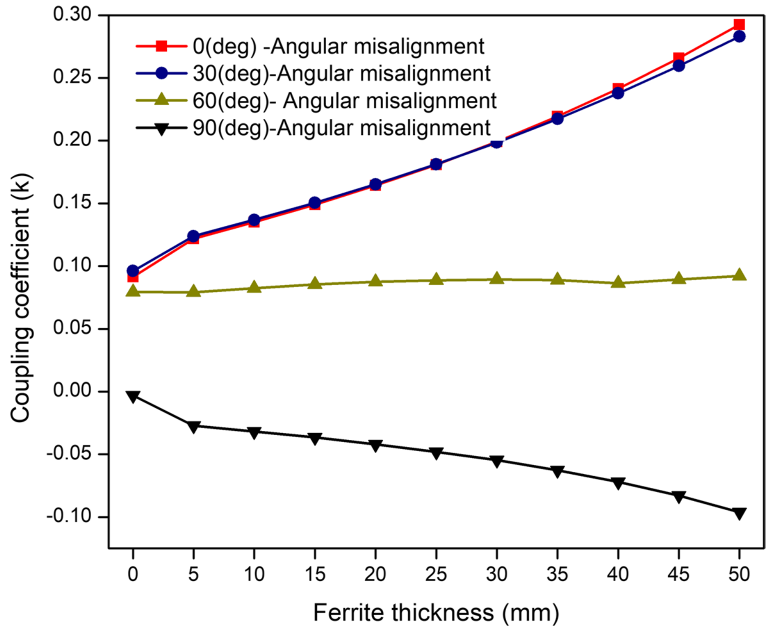

Fig. 8 Coupling coefficient (*k*) vs. ferrite thickness for different angular misalignment

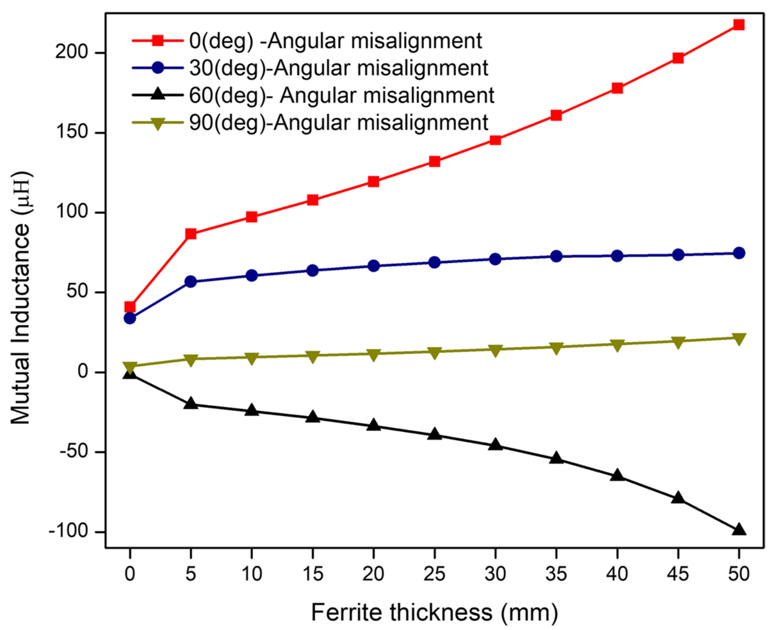

Fig. 9 Mutual inductance vs. ferrite thickness for different angular misalignment

Weight of ferrite

To calculate the weight of the ferrite coupler, we need to find the volume of the coupler first:

$$\text{Volume} = \text{length} \times \text{width} \times \text{height}$$

$$\text{Volume} = 400\ \text{mm} \times 400\ \text{mm} \times 20\ \text{mm}$$

$$\text{Volume} = 3{,}200{,}000\ mm^3$$

Table 3 Comparison of coupling coefficient (*k*) and mutual inductance (*M*) for different thickness of ferrite shielding of coil with different air gaps

Coil	z-(mm)	F_T-(mm)	*k*	M-(μH)	L-(μH)
		0	0.29817	11.9139	40.00
		5	0.47226	35.1383	74.34
		10	0.53017	41.3085	78.00
		15	0.59048	48.2171	81.60
	50	20	0.65458	56.5240	86.30
		25	0.72197	66.9508	92.70
		30	0.79084	80.5109	101.70
		35	0.85857	99.0489	115.31
		40	0.92125	127.4293	138.34
		45	0.97293	177.5978	182.40
		0	0.19582	8.1322	41.54
		5	0.2917	20.65681	70.92
		10	0.32683	23.71778	72.61
		15	0.36408	26.92272	73.97
	100	20	0.40487	30.53601	75.39
		25	0.44928	34.69088	77.15
		30	0.49803	39.50752	79.37
		35	0.5511	45.18491	81.94
		40	0.60834	52.02325	85.46
		45	0.66944	60.41944	90.27
		0	0.13228	5.5706	42.04
		5	0.18565	12.96439	69.81
		10	0.20691	14.70779	71.02
		15	0.22953	16.49878	71.87
Rectangular	150	20	0.25421	18.46125	72.51
		25	0.28137	20.64115	73.29
		30	0.31124	23.07157	74.12
		35	0.34402	25.83776	75.13
		40	0.38005	28.98805	76.35
		45	0.41978	32.58788	77.69
		0	0.09154	3.87767	42.29
		5	0.12183	8.47255	69.50
		10	0.13505	9.52868	70.45
		15	0.14903	10.61717	71.20
	200	20	0.1643	11.783	71.77
		25	0.18088	13.06014	72.20
		30	0.19921	14.46152	72.64
		35	0.21932	16.02393	73.30
		40	0.24145	17.75982	73.43
		45	0.26576	19.70046	73.88

Next, we need to convert the density from grams per cubic centimeter to grams per cubic millimeter, as it is a more common unit of density. Density= 5 $g/cm^3 = 0.005$ g/mm^3

Now, we can calculate the weight of the coupler using the formula: weight = volume × density

Table 4 Weight of ferrite coupler for $5g/cm^3$density

Thickness of coupler	Volume	Weight (kg)
5 mm	$800000mm^3$	4
10 mm	$1600000mm^3$	8
15 mm	$2400000mm^3$	12
20 mm	$3200000mm^3$	16
25 mm	$4000000mm^3$	20
30 mm	$4800000mm^3$	24
35 mm	$5600000mm^3$	28
40 mm	$6400000mm^3$	32
45 mm	$7200000mm^3$	36
50 mm	$8000000mm^3$	40

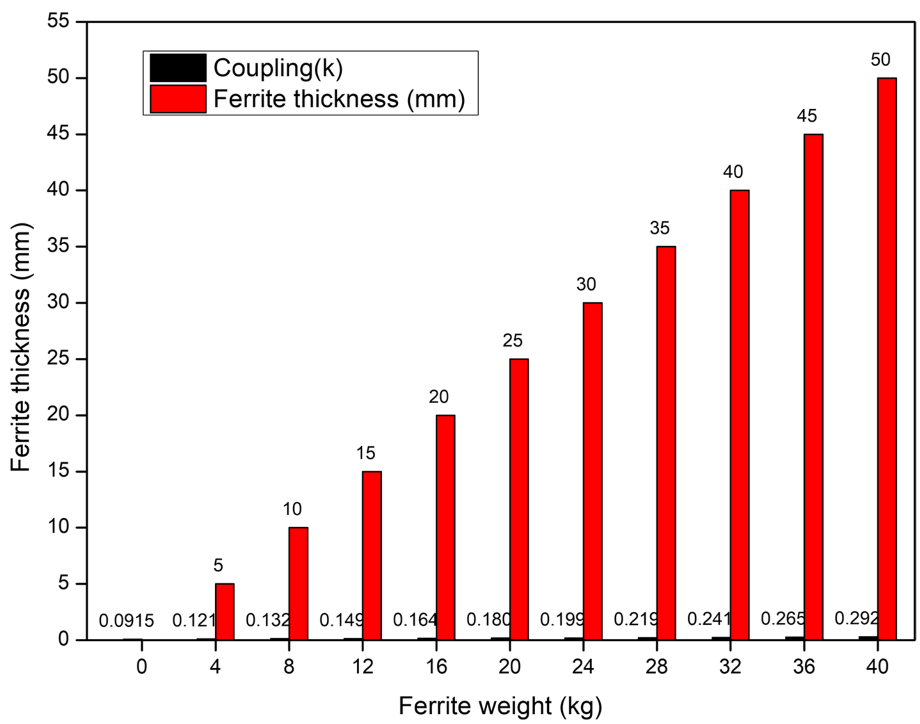

Fig. 10 Graph of rectangular ferrite shielding weight and coupling (*k*) for different thickness

Weight $= 3{,}200{,}000\ mm^3 \times 0.005\ g/mm^3$

Weight $= 16{,}000$ g or 16 kg

Therefore, the weight of the ferrite coupler is approximately 16 kg.

As we can see in Table 4 and Fig. 10, weight and coupling for different thicknesses of ferrite.

Losses

- *EM loss*——Ferrite couplers are used to transfer power between the primary and secondary coils in WPT systems. The EM loss in ferrite couplers is primarily due to hysteresis losses and eddy current losses. Hysteresis losses occur when the magnetic field in the ferrite material causes the magnetic domains to flip, generating heat. Eddy current losses occur due to the circulation of electrical current in the ferrite material, which also generates heat. The amount of EM loss in ferrite couplers is directly proportional to the frequency of the WPT system. Therefore, optimizing the ferrite material's permeability and selecting the appropriate frequency can help reduce the EM loss EM loss is an important factor to consider in the design of WPT systems. Reducing the resistance of the copper coils, optimizing the ferrite material's permeability, and selecting the appropriate frequency can help minimize the EM loss in WPT systems.
- *Ohmic loss*——The copper coils and ferrite couplers are used in WPT systems to transfer power between the primary and secondary coils. Ferrite materials have a high magnetic permeability, which allows them to efficiently couple the magnetic fields between the primary and secondary coils. However, ferrite materials can also resist the flow of electrical current, resulting in ohmic loss. The amount of ohmic loss in a ferrite coupler is directly proportional to its resistance, which can be reduced by selecting a ferrite material with low electrical resistance or optimizing the size and geometry of the coupler.

WPT circuit analysis

Figure 11 shows electric vehicles' wireless power transfer circuits. Various compensation topologies have been suggested in the scientific literature to control the coils operating

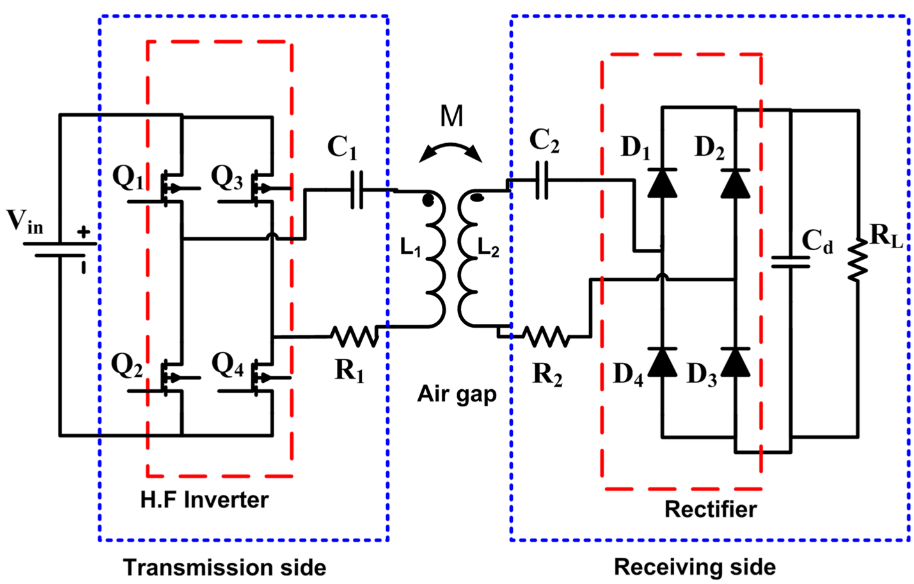

Fig. 11 WPT circuit diagram for electric vehicles

at the same frequency. These compensation networks are situated between the transmitting coil and the inverter on the off-board side and between the receiving coil and the rectifier on the on-board side. The four main compensation topologies are series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP), as shown in Fig. 12. Some new topologies are also proposed in the literature, including LCL and LCC compensation [28]. The SS topology is the only one where the coupling coefficient variation does not affect the primary capacitance. Furthermore, it achieves high and stable transfer efficiency at low mutual inductance, making it the most suitable choice for use in variable load conditions.

As shown in Fig. 12, a series-series compensation network is commonly used in wireless power transfer (WPT) systems to improve the power transfer efficiency between the transmitter and the receiver. The compensation network is in series with the transmitter and load (receiver) coils.

The mathematical analysis of a series-series compensation network for WPT can be performed using the following circuit model, where the transmitter and receiver coil voltages are V_s and V_r, respectively. L_s and L_r are the self-inductance of the transmitter and receiver coils, respectively. Lm is the mutual inductance between the transmitter and receiver coils. C_s and C_r are the compensation capacitors placed in series with the transmitter and receiver coils. Assuming that the transmitter and receiver coils are closely coupled (i.e., $Lm >> Ls, Lr$), the equivalent circuit model can be simplified to the following: the resonant frequency of the system can be calculated as:

$$\omega_0 = \sqrt{\frac{1}{L_1 C_1}} = \sqrt{\frac{1}{L_2 C_2}} \tag{1}$$

$$c_1 = \frac{1}{\omega^2 L_1} \tag{2}$$

$$c_2 = \frac{1}{\omega^2 L_2} \tag{3}$$

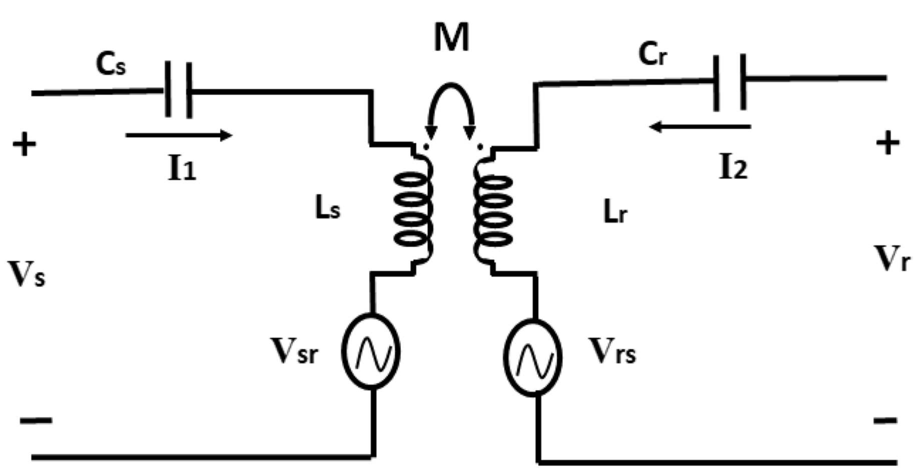

Fig. 12 Series-Series compensation circuit diagram

The voltage transfer function of the system can be derived as:

$$V_s = Z_{T1}I_1 - j\omega MI_2 \tag{4}$$

$$j\omega MI_1 = Z_{T2}I_2 \tag{5}$$

The impedances of the transmitter and receiver coils are represented by Z_{T_1} and Z_{T_2}, respectively. These values can be calculated or expressed using a particular method or formula as:

$$Z_{T1} = \frac{1}{j\omega C_1} + R_1 + j\omega L_1 \tag{6}$$

$$Z_{T2} = \frac{1}{j\omega C_2} + R_2 + R_L + j\omega L_2 \tag{7}$$

$$P_{in} = \frac{V_s I_1 = R_1 \times (R_2 + R_L) + (\omega M)^2}{R_2 + R_L} \times {I_1}^2 \tag{8}$$

$$P_{out} = R_L {I_L}^2 = R_L \times \frac{(\omega MI_1)^2}{(R_2 + R_L)^2} \tag{9}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{R_L \times (\omega M)^2}{(R_2 + R_L) \times \left[R_1 \times (R_L + R_2) + (\omega M)^2\right]} \tag{10}$$

Assuming the condition R_L is greater than or equal to R_2, the efficiency can be expressed as:

$$\eta \simeq \frac{1}{1 + \frac{R_1 R_L}{(\omega M)^2}} \tag{11}$$

Also, we can represent efficiency in terms of supply and receiving voltage as:

$$\frac{V_r}{V_s} = \frac{j\omega L_r C_r}{1 - \omega^2 L_s L_r C_s C_r + j\omega (C_s + C_r)(L_s + L_r)} \tag{12}$$

where ω is the angular frequency of the system, $\omega = 2\pi f$. The power transfer efficiency of the system can be calculated as:

$$\eta = \left(\frac{V_r}{V_s}\right)^2 \frac{L_r}{L_s + L_r} \tag{13}$$

The efficiency of a DC-DC wireless power transfer (WPT) system can be defined as the proportion of the output power (Pout) that is effectively absorbed by the load resistance R_L in comparison to the input power P_{in} [29]. As per theory, the maximum power transfer efficiency can be represented by a specific equation. The theoretical equation of maximum power transfer efficiency is expressed:

$$\eta = \frac{{I_2}^2 R_L}{{I_1}^2 R_1 + {I_s}^2 R_2 + {I_2}^2 R_L} \tag{14}$$

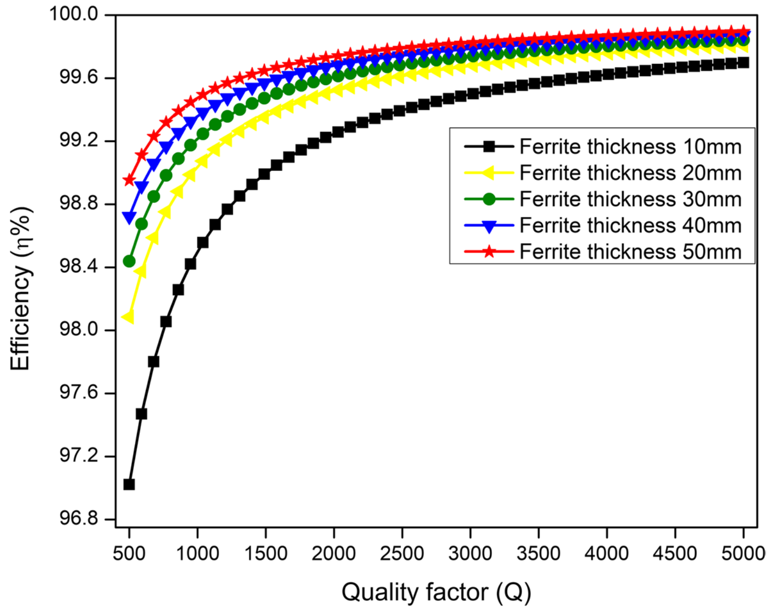

Fig. 13 Efficiency vs quality factor graph for 6.78 MHz resonance frequency for different thickness of ferrite

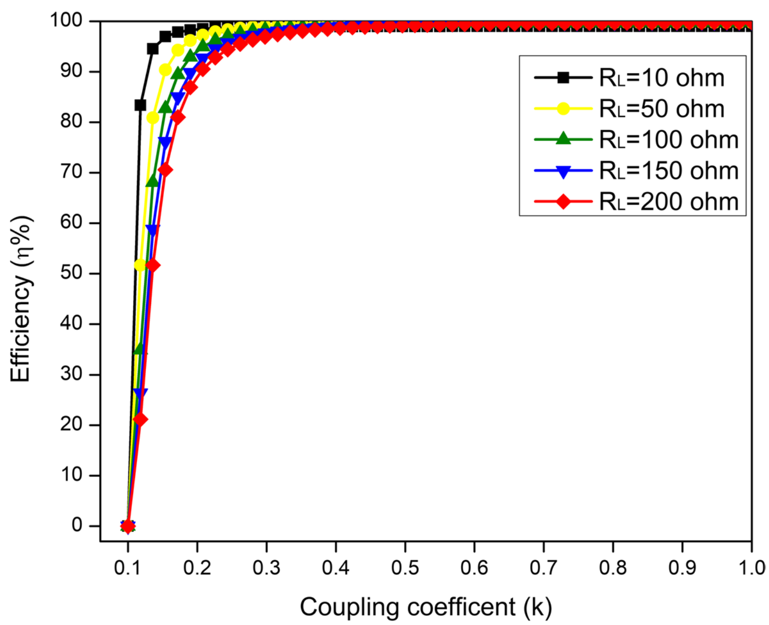

Fig. 14 Efficiency vs coupling coefficient graph for 6.78 MHz resonance frequency for different load resistance R_L

In Eq. 14, we use the symbols R_1 to represent the primary series resistance and R_2 to represent the load series resistance. The graph in Figs. 13 and 14 depicts the simulated values, showing the relationship between theoretical efficiency and two key factors: the quality factor (Q) and the coupling coefficient.

Power transfer efficiency can also be expressed by calculating the quality factors of both coils. Specifically, the quality factor of the primary coil can be defined as $Q_1 = (\omega * L_1)/R_1$, where ω represents the angular frequency, L_1 is the inductance of the primary coil, and R_1 stands for the primary coil's resistance. Similarly, for the secondary coil, the quality factor can be determined as $Q_2 = (\omega * L_2)/R_2$, with ω being the angular frequency, L_2 representing the inductance of the secondary coil, and R_2 denotes the resistance of the secondary coil.

The efficiency imparted can be stated as:

$$\eta = \frac{I_2{}^2 R_L}{I_1{}^2 R_1 + I_2{}^2 R_2 + I_2{}^2 R_L} = \frac{R_L}{R_2 + R_L + \frac{(R_2 + R_L)^2}{k^2 Q_2 Q_1 R_2}} \tag{15}$$

To find the theoretical maximum efficiency as shown in Fig. 15 here, we have to use the differential method, partial differentiation of Eq. (15) concerning load R_L and R_2 after solving the equation. We get maximum power transfer efficiency in terms of quality factor (Q) and coupling coefficient (k) [30].

$$\eta_m = \frac{k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k^2 Q_1 Q_2}\right)^2} \tag{16}$$

where it is important to note that the values of Cs and Cr should be chosen to maximize the power transfer efficiency at the resonant frequency while ensuring that the circuit does not become unstable due to the presence of the compensation capacitors. From using Eqs. 1, 2, and 3, we have found the input capacitance value for different frequencies as 5.5 MHz resonance frequency, the input capacitance is 1167.14 pF, $R_1 = R_2 =$ 0.20 ohm and quality factor =1276.7, for 6 MHz, capacitance is 980.72 pF, $R_1 = R_2 =$

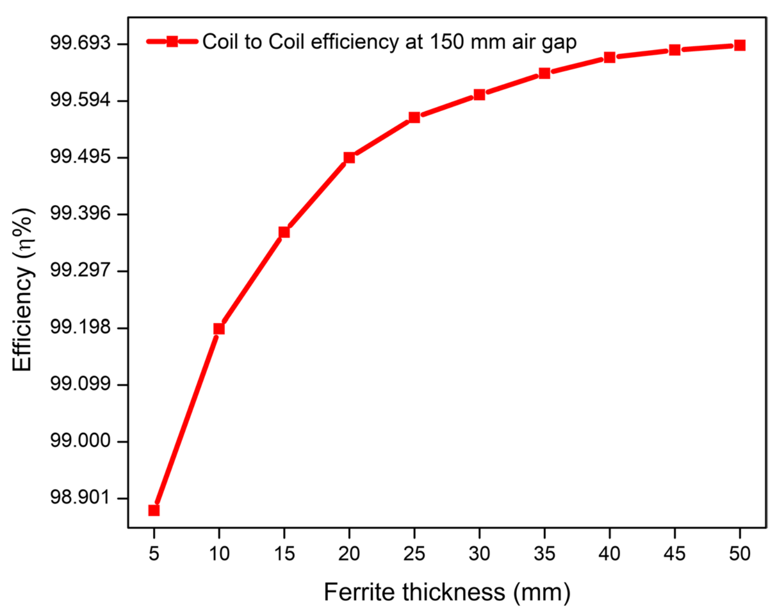

Fig. 15 Efficiency vs coupling coefficient graph for 6.78 MHz resonance frequency for different load resistance R_L

0.20 ohm, quality factor = 1355.261 and for 6.78 MHz capacitance is 768.05 pF and $R_1 = R_2 = 0.20$ ohm, resistance quality factor 1530.88.

Results and discussion

The results of the study conducted on the ANSYS Electronics Desktop software showed that the shielding of ferrite material of different thicknesses (F_T) varies the mutual inductance (M) coupling (k) and magnetic flux (B) between the coils as shown in the above section. After that, design a reduced equivalent circuit can be defined to determine the efficiency between coil to the coil using ANSYS Simplorer. The study found that the efficiency varies with frequency and capacitance value; a graph of efficiency vs. frequency was generated for the 5.5 MHz, 6 MHz, and 6.78 MHz resonance frequencies.

Shown in Fig. 15 is the ferrite coupler and coil loss analysis, in Figs. 16 and 17 the magnetic field distribution for different ferrite thicknesses, and in Fig. 18 an ohmic loss for different thicknesses of ferrite.

We have used a reduced equivalent circuit to find the efficiency between coil and the coil using Ansys Simplorer as series-series, series-parallel, parallel-series, and parallel-parallel as shown in Fig. 19. The graph showed in Figs. 20 and 21 a peak efficiency of 99.7260% at the resonance frequency of 6.78 MHz. These findings suggest that the coupling is required according to the optimized weight of the coupler for higher power transfer between coil to coil. Also, we can analyze the efficiency of the different compensation networks for different thicknesses of ferrite shielding as shown in Table 5. ANSYS Simplorer can be a valuable tool in designing and optimizing wireless power transfer systems by accurately predicting the efficiency of such systems at different frequencies. Further studies can be conducted to validate these results and optimize the design of wireless power transfer systems for various applications (Fig. 22).

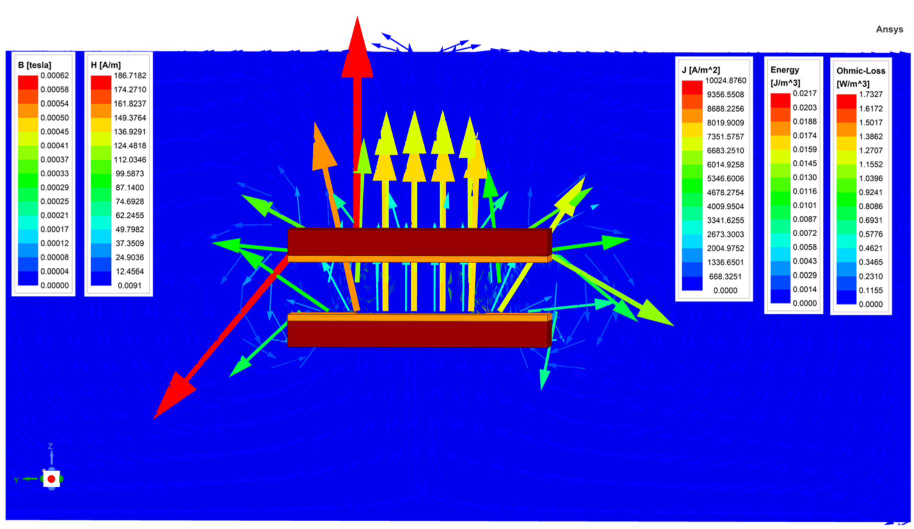

Fig. 16 Ferrite coupler and coil loss analysis using Ansys software

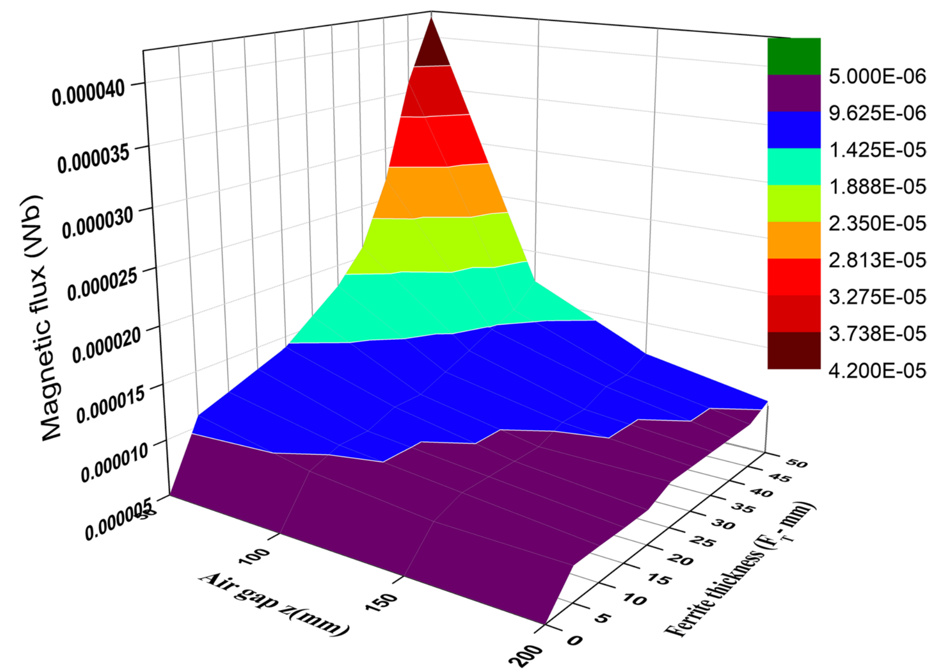

Fig. 17 Magnetic flux distribution graph with ferrite thickness and air gap (*z*) variation

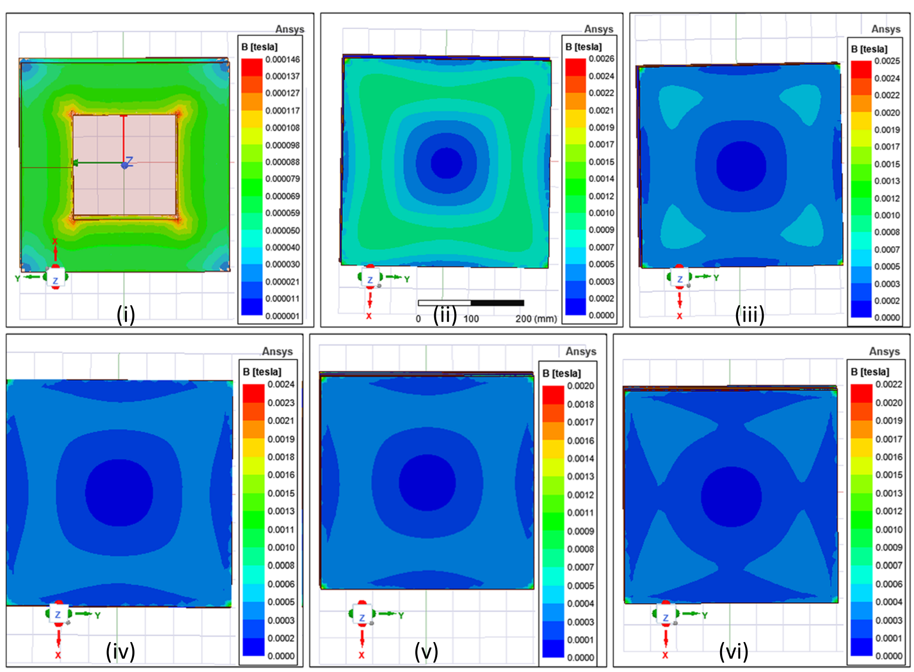

Fig. 18 Magnetic flux (*B*) distribution for different thicknesses of ferrite at 5.5 MHz frequency as (i) without ferrite, (ii) 10-mm thickness, (iii) 20-mm thickness, (iv) 30-mm thickness, (v) 40-mm thickness, and (vi) 50-mm thickness

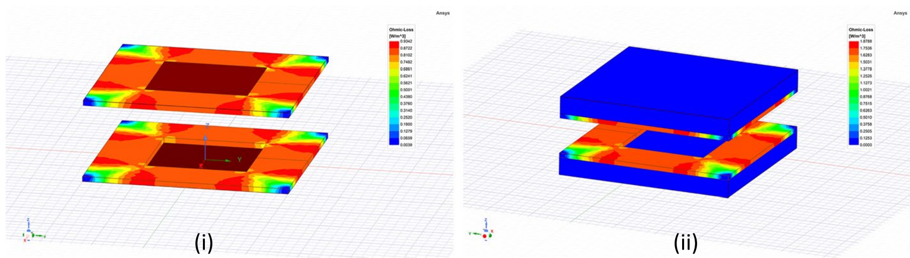

Fig. 19 Ohmic loss for different thickness of ferrite at 5.5 MHz frequency as (i) without ferrite, i.e., 0 mm thickness of ferrite, and (ii) 50-mm thickness

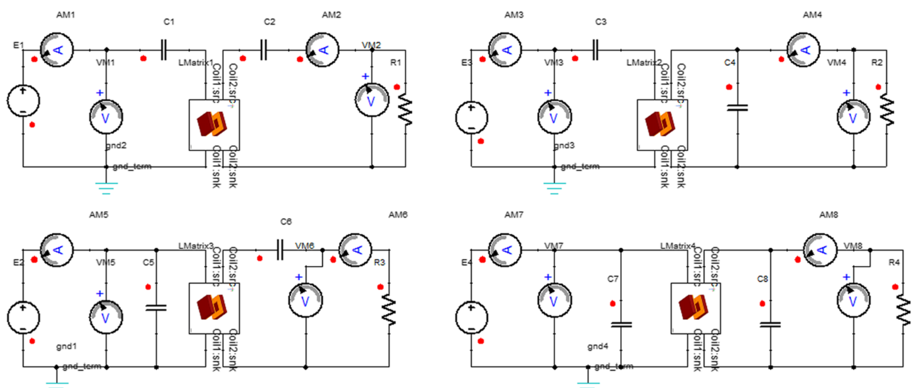

Fig. 20 Reduced equivalent circuit to find the efficiency between coil to the coil using Ansys Simplorer as series-series, series-parallel, parallel-series, and parallel-parallel

Conclusions

This study highlights the importance of ferrite shielding in WPT systems, as low coupling and high coil losses reduce the WPT system's efficiency. Ferrite shielding is a widely used technique for reducing losses and increasing coupling in coils in WPT systems. Still, the optimal thickness of the ferrite shield depends on various factors, such as the geometry of the coils and the required power transfer efficiency. Our study provides insights into the trade-offs between ferrite shielding thickness and other electromagnetic parameters and offers guidelines for selecting an optimal thickness for a given application.

In addition, this study demonstrates the potential of WPT systems for wireless charging of electronic devices in various applications such as electric vehicles, wearable devices, and medical implants. WPT offers a convenient and efficient way to charge devices without physical connections or batteries, simplifying device design and reducing maintenance costs. However, further research is needed to improve the efficiency

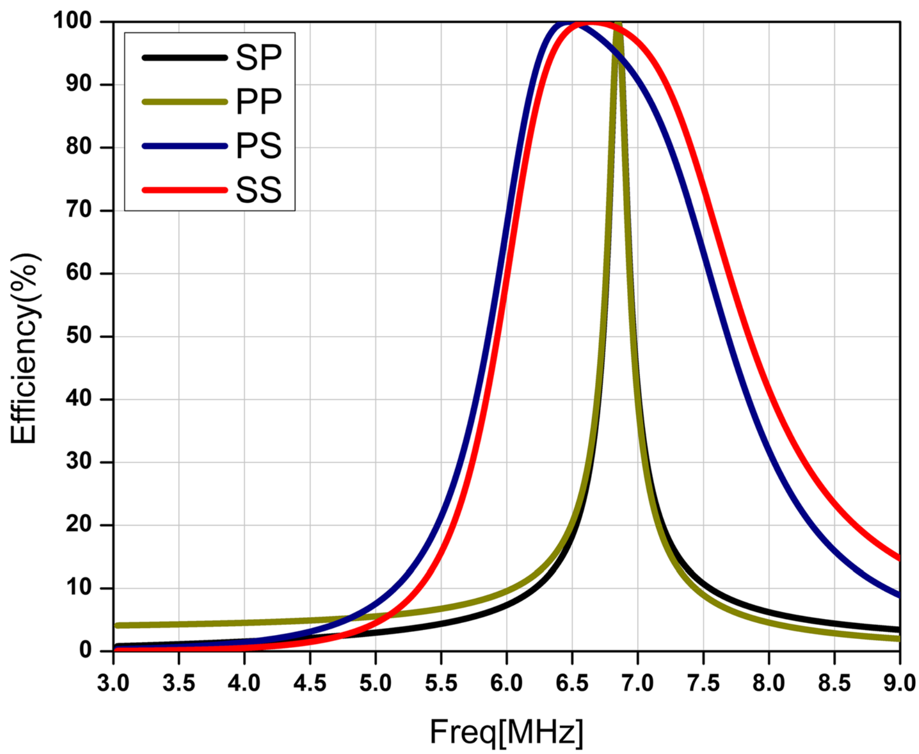

Fig. 21 Efficiency vs frequency graph for 6.78 MHz resonance frequency for four compensation networks (i) series-series, (ii) series-parallel, (iii) parallel -series (iv), and parallel-parallel at 200-mm air gap

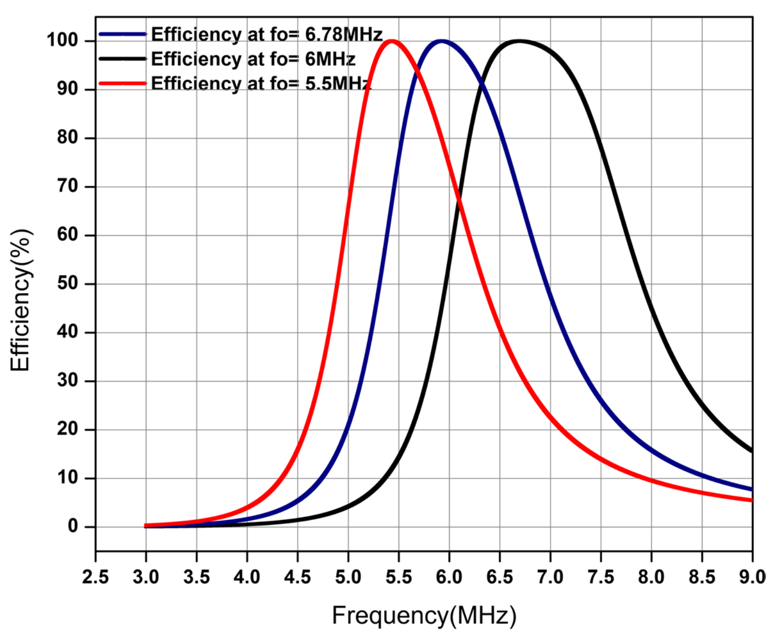

Fig. 22 Efficiency vs frequency graph for 5.5 MHz, 6 MHz, and 6.78 MHz resonance frequency at 200-mm air gap

Table 5 Coil to Coil efficiency for different compensation network at 40mm thickness of ferrite

Compensation network	Frequency (fo)	Air gap (z)	Ferrite thickness (F_T)	Coil-coilη
Series-series (SS)				99.702
Series-parallel (SP)				69.784
Parallel-series (PS)	6.78 MHz	150 mm	40 mm	95.328
Parallel-parallel (PP)				67.387

and performance of WPT systems and to address safety concerns related to electromagnetic radiation and heating.

Overall, this study contributes to the growing body of research on WPT systems and highlights the importance of careful design and optimization of WPT components such as ferrite shielding. By improving the performance and efficiency of WPT systems, we can enable a wide range of applications that can benefit from wireless charging technology.

Abbreviations

WPT	Wireless power transfer
EV	Electric vehicle
SS	Series-series
SP	Series-parallel
PS	Parallel-series
PP	Parallel-parallel
Tx	Transmission coil
Rx	Receiving coil
F_T	Ferrite thickness

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Declarations

Competing interests
The authors declare that they have no competing interests.

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