

International Journal of Exergy

ISSN online: 1742-8300 - ISSN print: 1742-8297

<https://www.inderscience.com/ijex>

Exergy-based design and analysis of spiral circular and square coils for EV wireless battery charging application

Balaji Subramanian, Thangavelu Anuradha

DOI: [10.1504/IJEX.2025.10067438](https://doi.org/10.1504/IJEX.2025.10067438)

Article History:

Received:	04 June 2024
Last revised:	28 August 2024
Accepted:	19 September 2024
Published online:	07 January 2025

Exergy-based design and analysis of spiral circular and square coils for EV wireless battery charging application

Balaji Subramanian* and
Thangavelu Anuradha

EEE Department,
KCG College of Technology,
Chennai, Tamil Nadu, India
Email: balaji229@gmail.com
Email: tanura1872@gmail.com

*Corresponding author

Abstract: This paper investigates the impact of misalignment on mutual inductance (MI) in wireless power transfer systems using spiral circular and square coils. Finite element analysis (FEA) and experimental validation compare the performance of square and circular geometry coils. Results show that square coils maintain higher mutual inductance under various misalignments, making them more suitable for practical applications. Experimental results validate simulation data, demonstrating the superiority of square coils for robust WPTS. Analytical and FEM simulations show minimal error for both circular and square coil mutual inductance and coupling coefficients at 200 mm air gap, with square coils exhibiting superior exergetic efficiency.

Keywords: electric vehicle; coupling coefficient; wireless power transfer; mutual inductance; spiral circular; square coil; finite element analysis; FEA.

Reference to this paper should be made as follows: Subramanian, B. and Anuradha, T. (2025) 'Exergy-based design and analysis of spiral circular and square coils for EV wireless battery charging application', *Int. J. Exergy*, Vol. 46, No. 1, pp.13–31.

Biographical notes: Balaji Subramanian is currently working as an Assistant Professor in the Department of Electrical and Electronics Engineering at KCG College of Technology, Chennai. He received his BE in Electrical and Electronics Engineering at the SSN College of Engineering, Chennai and ME in Power Electronics and Drives at the RMK Engineering College. He is currently pursuing his PhD degree at the Anna University, Chennai, Tamil Nadu. His research interests are wireless inductive power transfer for electric vehicles and power converters for electric vehicles.

Thangavelu Anuradha is currently working as a Professor and the Head of the Department of Electrical and Electronics Engineering at KCG College of Technology, Chennai. She has completed her BE in Electrical and Electronics Engineering at the Alagappa Chettiar College of Engineering and Technology, Madurai Kamaraj University and ME in Power Systems Engineering at the College of Engineering, Guindy, Anna University, Chennai. She received her PhD degree in the Faculty of Electrical Engineering from Anna University, Tamil Nadu State. She majorly focuses on developing eco-friendly, cost-effective, easily adaptable advanced power electronic interfaces for hybrid

renewable energy systems for rural electrification projects and IOT, AI, ML based control techniques for electric vehicle and smart grid applications. Her primary research interests are renewable energy systems, power electronics and drives, smart grids and electric vehicle technologies.

1 Introduction

Conventional vehicles have an internal compulsion engine that emits harmful toxic gases. Electric vehicles (EVs) are used to reduce pollution and oil consumption in transportation. In recent years, the fuel energy crisis and environmental safety have led to new research in EVs (Das et al., 2020). The EV provides numerous benefits such as emission-free and smooth operation, and it is better than hybrid cars. EVs have problems such as long plug charging cables that are conductive charging, the availability of charging stations and limited range (Sutopo et al., 2018). The issues faced by conductive charging are reduced by using wireless charging. The wireless power transfer system transfers power from the supply side to the loads without any physical connection. Wireless charging technology is also referred to as inductive charging or cordless charging. In wireless power transfer systems (WIPTS), there are two coils: the first is referred to as the transmitter or source coil, and the second is the receiver or load side coil (El-Shahat et al., 2019). Exergy is a thermodynamic property that measures the maximum useful work that can be extracted from a system under ideal conditions.

The coupling coefficient is an important metric that determines the WIPTS' efficiency. In addition, the distance between the transmitter and receiver coil decides the efficiency of the WIPTS system (Kim and Choi, 2021). In WIPTS, the air gap and the lateral misalignments between the transmitter and receiver coil cause the variation of mutual inductance (MI) and coupling coefficient. The coil misalignments reduce the magnetic flux density compared to perfectly aligned coils (Shi et al., 2020). The study of MI for different misalignments will help to design effective WIPTS for EV charging applications (Song et al., 2020). In recent years, most researchers have focused on coil geometry, coupling coefficients, misalignment tolerance, and air-gap reduction approaches between the coupling coils (Nanda et al., 2020). In order to maintain the system within the resonant frequency range and enable the fast charging process, precise system compensation is imperative (Mosammam et al., 2020).

Most existing works have been carried out on spiral circular coils in EV charging applications. Whereas the square coils are efficient in terms of MI and coupling coefficients, this is the main motivation of this paper. Many of the existing papers failed to elaborate on the effectiveness of the square coils for EV charging applications. However, the wireless inductive power transfer system is an emerging research topic in EV charging applications. In existing works, the performance of coils is examined by connecting full-bridge inverters and half-bridge inverters in the transmitter side of the wireless inductive power transfer system. There are currently no studies on three-phase diode bridge rectifier-based inductive power transmission in EVs. Thus, this proposed work uses the three-phase diode bridge rectifier on the transmitter side to improve the power-sharing model in an electric vehicle. WIPTS has emerged as a promising technology for charging EVs, offering convenience and flexibility. However, maximising energy efficiency is crucial for the widespread adoption of EV wireless charging. This

research investigates the impact of coil geometry on energy efficiency in EV wireless battery charging systems, utilising exergy analysis. The major contribution of this paper is as follows:

- Create a model of the spiral, circular, and square coils in the system with the three-phase diode rectifier, and verify the MI in changing air gaps and coupling coefficients in changing coil inner and outer diameters.
- Examine the reciprocal inductance and coupling coefficient for two distinct coil configurations, such as spiral, circular, and square coils, under varying air gaps and misalignments.
- To analyse two coil geometries, such as spiral circular and spiral square, for vertical misalignment (change of an air gap or over the Z-axis), lateral misalignment (over the X-axis), angular misalignment, the finite element method (FEM) is used. Additionally, the coupling coefficient of the WIPTS is used to measure the impact of changing the internal coil structural parameters.

The organisation of the paper is as follows. Section 2 elaborated on several literature reviews for EV charging applications. The inductive power transfer model is elaborated in Section 3, including an analytical model of WIPT as well as spiral and square coil modelling. The experimental validation of the spiral and circular coils, along with their MI and coupling coefficient, is discussed in Section 4. The conclusion of the paper is given in Section 5.

2 Literature review

Most countries adopt EVs for transportation due to their numerous advantages. Moreover, EV charging applications use spiral circular and square coils for inductive charging. Some of the EV wireless charging applications is listed below.

In order to ensure the required power transfer for application, Castillo-Zamora et al. (2019) suggested a hexagonal geometry coil design on the secondary side of the wireless power transfer system. That suggested model adopts graphical optimisation of an amended form of the wheeler formula for getting the right parameter. Moreover, the test demonstrates that the suggested model will comply with type-2 system requirements.

To enhance the performance of WIPTS system, the lumped circuit model was suggested by Elnail et al. (2018). That suggested model evaluates plot, slotted and shaped bar cores through the FEM. In addition, the new core structure with optimally shaped bars was suggested in that module. Moreover, the suggested model reduces EMF loss by 44% and core loss by 30%.

Mohamed et al. (2021) have analysed the impacts of the number and position of the square coils in EV charging applications under various internal and external conditions. In that analysis, different configurations have been investigated. Moreover, the magnetic fields were evaluated under the system with different numbers of transmitter and receiver coils in the inductive power transfer system. The system performance under half-bridge inverter topology was discussed.

In order to enhance the WIPTS, López-Alcolea et al. (2019) suggested a magnetic coupler based on single and double-layer rectangular planar coils. That suggested model

provides self-inductance and MI validation for mutually coupled rectangular panels, spiral coils, and the air gap. Both the single and double-layered coil geometries were designed with the consideration of an arbitrary number of turns with circular cross-sectional in the layer.

Yang et al. (2020) estimated the performance of magnetic coils in wireless inductive power transmission with SS compensation topology. In that paper, coil performance was investigated under different variables, such as misalignments and varying air gaps. Different coil configurations, such as door-to-door misalignment and front and rear misalignment were analysed in that paper. Moreover, differently shaped magnetic cores and their coupling coefficients were examined in detail.

Stankiewicz and Choroszucho (2021) presented a comparative analysis of circular and square planer coils in EV applications. That paper analysed the coil performance under maximum efficiency and maximum power transmission to load. Moreover, the performance was investigated under varying turns, the distance between coils and frequency. The comparative analysis shows that circular coils provide more load power under varying ranges of frequency. By analysing the above-mentioned papers, it is found that most existing works adopt hexagonal geometry coils, lumped circuit models, bi-polar magnetic coupled models, Archimedean spirals and unsymmetrical coil pairs. Moreover, the papers that investigated circular and square coils did not focus on variations in variable performance.

Apart from the position and number of coils, the coil configuration is a key factor that improves charging characteristics in EVs. Most papers have failed to elaborate on the impacts of rectifiers on both square and circular coils in EV charging applications. One of the major components of WIPTS is the rectifier. The rectifier greatly influences the efficiency and feasibility of the entire power transfer system. However, limited explorations are conducted in wireless inductive power transfer with various rectifier models. Thus, this paper analyses the performance of square coils in various coil configurations along with the spiral circular coils for the system with three three-phase diode bridge rectifier.

The MI, coupling coefficient, number of turns and misalignments are important parameters for examining the performance of the coils. In previous works, the spiral circular and square coils were not examined for all these parameters. Hence, the proposed work analysed all these parameters for performance evaluation.

3 Series-series WIPT system

Among the various compensation topologies, the SS compensation topology offers higher power transfer efficiency over a wide range of loads. In SS compensation-based WIPTS, resonating capacitors are added to the transmitter and receiver coils. Moreover, the SS topology-based WIPTS maintains the current in the transmitter coil in phase with the supply voltage irrespective of the coils' MI and coupling coefficient (Forato and Bertoluzzo, 2018).

3.1 Analytical modelling of series-series (SS) WIPTS

The SS topology circuit of the WIPTS, shown in Figure 1 consists of a three-phase diode bridge rectifier, high-frequency inverter, transmitter and receiver coils and secondary side

rectifier. The exergy input to the system is primarily from the AC source supplying the rectifier.

The compensation capacitor C_P and C_S are connected in series with the transmitter L_P and receiver L_S coil. The M represents the MI between transmitter and receiver coils. Figure 2 shows the equivalent circuit of SS resonant WIPTS. The transmitter side of SS resonant WIPTS is employed with higher frequency AC voltage from the rectifier. On the receiver side, the high-frequency induced voltage is converted into DC pulse voltage through a diode bridge rectifier, filtered by a capacitor. The exergy output is the useful electrical power delivered to the load (EV battery).

Figure 1 Circuit diagram of the SS wireless inductive power transfer system

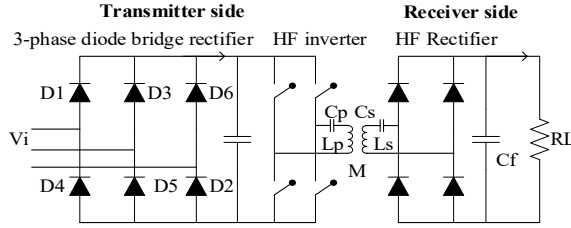
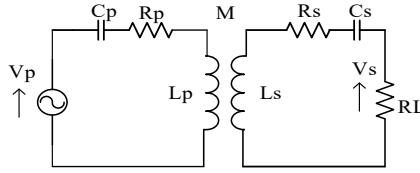


Figure 2 Equivalent circuit of SS WIPTS



The transmitter side voltage is given by the equation in terms of resonant angular frequency ω and MI M .

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

Here, V_p , C_p , R_p and L_p represents the voltage, capacitor, resistance and inductor of the primary side, and similarly V_s , C_s , R_s and L_s represents the voltage, capacitor, resistance and inductor of the secondary side. R_L is the equivalent load resistance. The transmitter and receiver current is represented as I_p and I_s (Kishan and Vinod, 2020). The current on the transmitter side and receiver side is expressed as,

$$I_p = \frac{V_p (Z_s + R_L)}{(Z_s + R_L)(Z_p + R_s) + (\omega M)^2} \quad (2)$$

$$I_s = \frac{V_p (\omega M)}{(Z_s + R_L)(Z_p + R_s) + (\omega M)^2} \quad (3)$$

The reactance of the coupled coil is zero at the resonant condition, and the power output (P_O) is expressed as,

$$P_O = \left| \frac{V_p(\omega M)}{(Z_s + R_L)(Z_p + R_S) + (\omega M)^2} \right|^2 R_L \quad (4)$$

The receiver side power (P_s) is given as,

$$P_s = I_s^2 R_L = \left(\frac{\omega M I_p}{R_L + R_s} \right)^2 R_L \quad (5)$$

Here, I_p and I_s represents the primary current and secondary current, respectively, M represents the MI, R_s and R_L represents the source side and load side resistance, respectively (Forato and Bertoluzzo, 2018). The receiver side power rewritten in terms of coupling coefficient is,

$$P_s = \left(\frac{\omega k \sqrt{L_p L_s} I_p^2}{R_s + R_L} \right) R_L \quad (6)$$

Here, k represents the coupling coefficient, P_s representing receiver side power. The input power (P_p) of the system is given as,

$$P_p = I_p^2 R_p + I_s^2 (R_s + R_L) \quad (7)$$

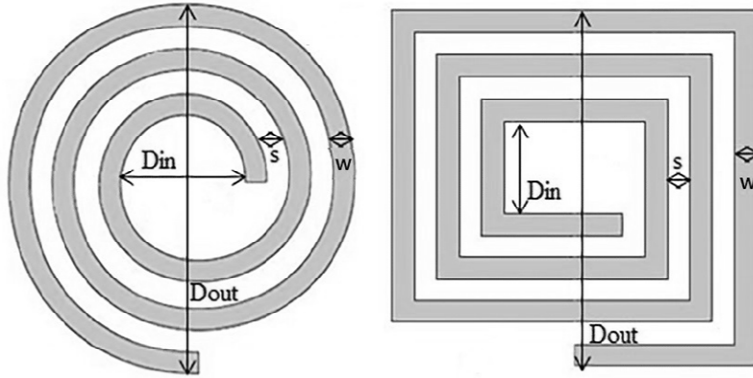
The efficiency (η) of the overall wireless power transfer system is calculated as,

$$\eta = \frac{P_s}{P_p} = \frac{R_s}{\left(\frac{R_p (R_s + R_L)^2}{\omega^2 k^2 L_p L_s} + R_s + R_L \right)} \quad (8)$$

Here, L_p and L_s representing the inductance of the primary side and secondary side, respectively. Equation (6) and equation (8) represents the output power and efficiency of the system related to the coupling coefficient. Moreover, the coupling coefficient changes according to the air gap and misalignment between coils. The coupling coefficients and MI is changed with coil design parameters.

3.2 Analytical modelling of spiral circular coil and square coil

The spiral circular coils and the square coils are elaborated on in this section. The spiral coil exhibited the highest exergy destruction, primarily due to its complex geometry and increased magnetic field leakage. The circular coil demonstrated moderate exergy destruction, with losses primarily attributed to resistive heating in the coils and coupling misalignment. The square coil exhibited the lowest exergy destruction, indicating its superior energy efficiency. The compact design and reduced magnetic field leakage of the square coil contributed to its lower losses. The self-inductance of these coils is calculated using the modified wheeler formula. For calculation purposes, the transmitter and receiver coils are assumed to be identical. Moreover, the spiral circular and square coils are estimated under the same length and area. The coil geometry of the spiral circular and square is shown in Figure 3.

Figure 3 Coil geometry of spiral circular and square


The self-inductance of the spiral circular coil is given as,

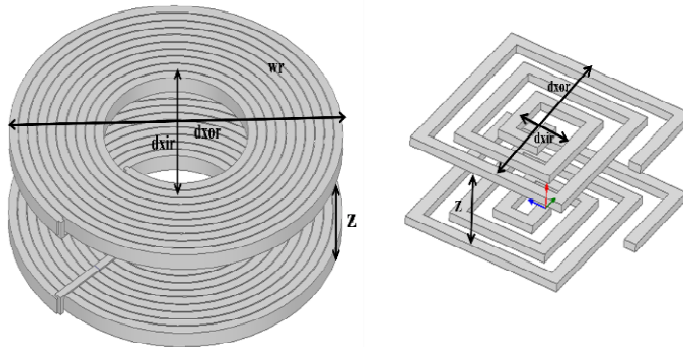
$$L_{cir} = \frac{\mu_0 N^2 d_{av}}{2} \left(\ln \left(\frac{2.46}{\rho} + 0.2\rho^2 \right) \right) \quad (9)$$

where the coil parameters d_{in} denotes the inner diameter of the coil, d_{out} is the outer diameter of the coil, S denotes spacing between turns, W denotes the width of the coil, μ_0 denotes the permeability in free space ($1.26 \times 10^{-6} \text{ T} - \text{m/At}$), ρ denotes the fill factor of the coil and N denotes the number of turns (Hussain and Woo, 2021).

The self-inductance of the spiral square coil is given as,

$$L_{squ} = \frac{1.27 \mu_0 N^2 d_{av}}{2} \left(\ln \left(\frac{2.07}{\rho} + 0.18\rho + 0.2\rho^2 \right) \right) \quad (10)$$

where d_{av} represents the average coil diameter, ρ represents the fill factor of the coil. The MI of the spiral circular coil is found using the coil configuration shown in Figure 4. The MI (M) between the coils with an air gap distance of z . The exergetic efficiency of the three coil geometries was calculated as the ratio of exergy output to exergy input.

Figure 4 MI calculation of spiral circular and square coil


By using these equations, the MI of the circular and square coils is found analytically.

3.3 Different coil configurations

This section explains the possible variation in coil misalignment. The different coil configurations used in WIPT are elaborated in the literature (ElGhanam et al., 2020), which considers both coupling coefficient and MI parameters important for modelling WIPTS. The MI of the coils is examined for perfectly aligned, lateral (X-axis) misalignment, angular misalignment and combined lateral and angular misalignment. The coil configurations are 3D modelled using ANSYS Maxwell 18.0.0, which is shown in Figure 5 and Figure 6. The perfect alignment of the spiral circular coil depicts the perfect alignment of the transmitter and receiver coil, which means coinciding axes of a flat surface. The misalignment implies that two coils are separated by a distance in a common axis (Srinivasa Rao Nayak et al., 2018; Zhu and Lorenz, 2018).

Figure 5 Spiral circular coil configurations: (a) perfect alignment, (b) X-axis misalignment, (c) angular misalignment, (d) both X-axis and angular misalignment (see online version for colours)

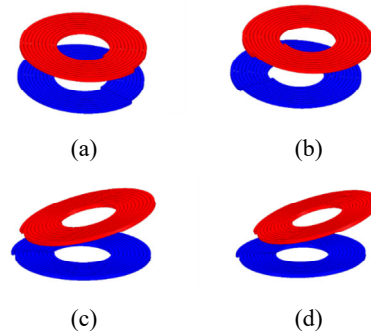
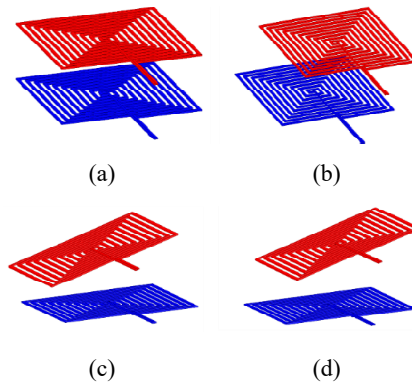


Figure 6 Square coil configurations: (a) perfect alignment, (b) X-axis misalignment, (c) angular misalignment, (d) both X-axis and angular misalignment (see online version for colours)



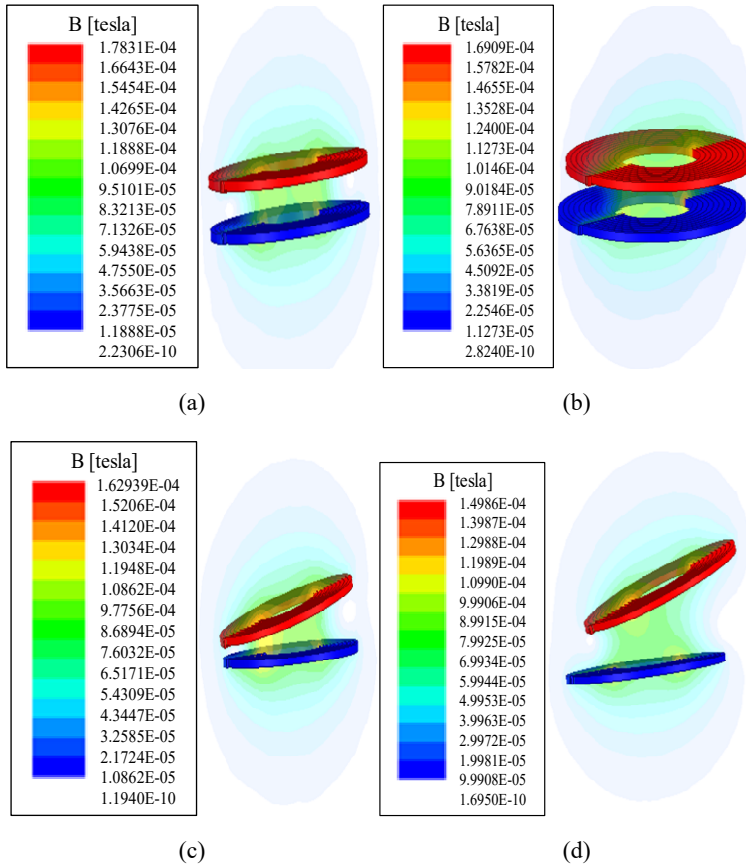
The perfectly aligned coil has reduced distance between the coils; thus, the flux linkage with the receiver is increased. At the same time, the coupling between the coils is increased, which also improves the MI. Meanwhile, the receiver coil is moved some distance from the transmitter coil's vertical direction, leading to the reduction of MI and

flux linkages. During this misalignment, the coupling between the coils is reduced, and the transmitter and receiver coils are located in a parallel plane that varies horizontally. In this case, the MI depends on the vertical and horizontal distance depicted in Figure 5(b). Figure 5(c) depicts the angular misalignment of coils, in which the MI depends on a vertical distance, horizontal distance and tilted angle. The above-mentioned misalignment topologies are similar to the square coil misalignment depicted in Figure 5.

3.3.1 Magnetic flux density distribution between coils

The magnetic FLUX density is defined as the number of force lines passing through a material's unit area. The existing magnetic shields are employed above the receiver and below the transmitter, offering a short flux return path for the magnetic field above and below the transmitter. The short flux path has minor effects on the magnetic flux pattern in the air gap region between the transmitter and receiver. Moreover, the magnetic material is designed with image methods, in which the additional current is a mirrored version of the original current to replace the magnetic material.

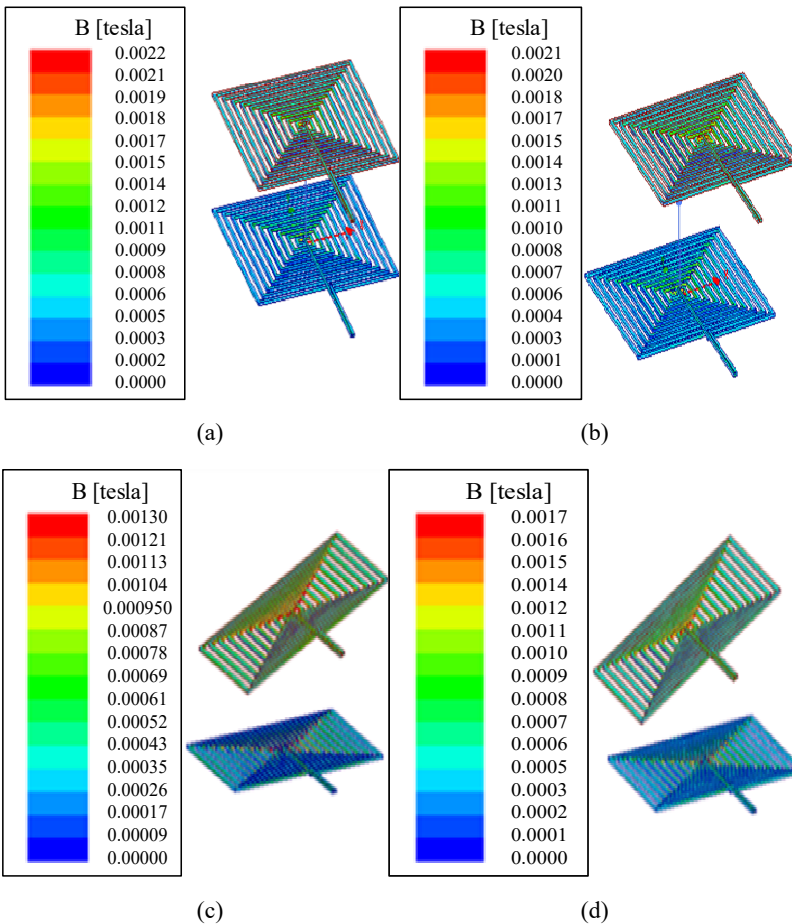
Figure 7 Coil configurations of circular geometry, (a) perfect alignment, (b) lateral misalignment of 30 mm, (c) angular misalignment (15°), (d) angular and lateral misalignment (15° and 30 mm) (see online version for colours)



The magnetic flux density is different in all places because of varied core shapes. The magnetic flux density between the coils is examined by the FEM tool ANSYS Maxwell simulation. The surface spiral coil topology reduces air gap centre magnetic flux density, which adopts an operating frequency of MHz. Increasing the operating frequency also increases the voltages required, whereas the current is reduced to supply the power; thus, the air gap centre magnetic flux density is degraded. The FEM simulation is carried out for air gaps ranging from 0 mm to 200 mm between the coils. The X-axis misalignment was taken as 30 mm, and the angular misalignment is 15°. The magnetic field misalignment between circular coils of different misalignment configurations is depicted in Figure 7. By analysing Figure 7, it is observed that the field distribution is higher for perfectly aligned coils.

The distribution of the magnetic flux density between the square coils is shown in Figure 8. Figure 8 shows the magnetic flux density distribution during perfect alignment, lateral misalignment, angular misalignment and combined angular and lateral misalignment.

Figure 8 Coil configurations of square geometry, (a) perfect alignment, (b) lateral misalignment of 30 mm, (c) angular misalignment (15°), (d) angular and lateral misalignment (15° and 30 mm) (see online version for colours)



The flux density distribution of different coil misalignment configurations demonstrates that the flux density is reduced while the receiver coil moves away from the transmitter coil. As a result, the MI is reduced when the inductance is directly proportional to the flux linkages.

4 Result and discussion

The comparison of different coil geometry for different coil misalignments is discussed in this section. MI is examined for different coil misalignments caused by varying air gaps between the coils. Moreover, the coupling coefficients are examined by varying the inner diameter and outer diameter of both the spiral circular and square coils.

4.1 Experimental validation of MI

The circular and square coils are developed in the laboratory for comparing the analytical and FEM simulation results. The coils used in the laboratory model are 0.1 mm/660 strands of Litz wire. In order to evaluate the effectiveness of the coil configurations, different misalignments are created for developed coils. The designed laboratory model of the circular coil with different misalignments is depicted in Figure 9. In Figure 9(a), the spiral coils are designed without any misalignment. In contrast, Figure 9(b) is designed with the X-axis misalignment of the spiral circular coil, and Figure 9(c) shows the angular misalignment between the spiral circular coils.

The designed laboratory model of the circular coil with different misalignments is depicted in Figure 10. In Figure 10(a), the coils are designed without any misalignment between them, whereas Figure 10(b) shows the X-axis misalignment of square coils. Moreover, the angular misalignment of square coils is depicted in Figure 10(c).

Figure 9 Developed spiral circular coils with misalignments, (a) perfect alignment, (b) X-axis misalignment, (c) angular misalignment, (d) Both X-axis and angular misalignment (see online version for colours)

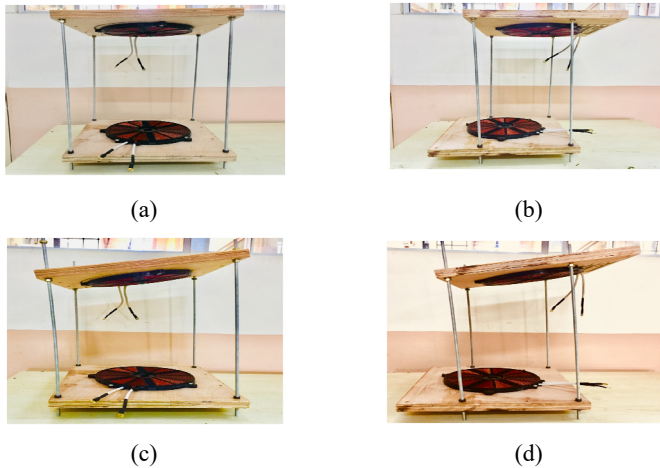
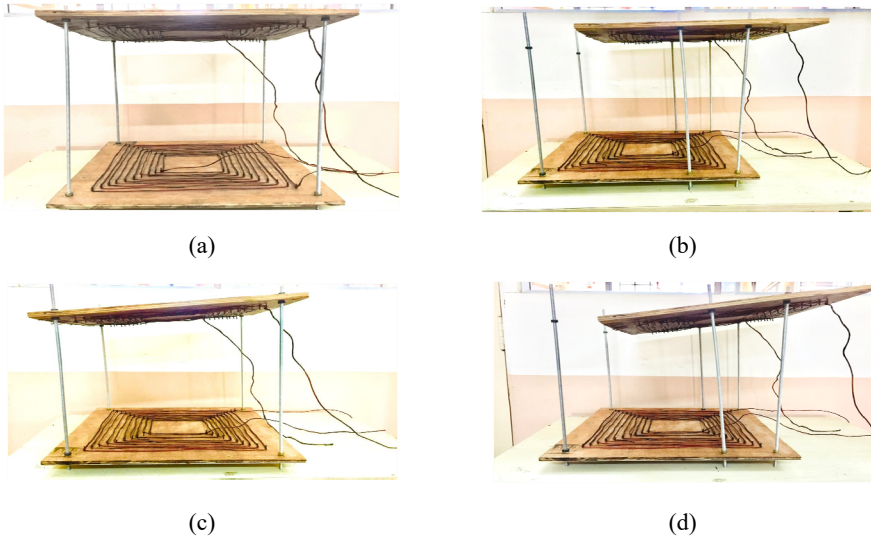


Figure 10 Developed spiral square coils with misalignments, (a) perfect alignment, (b) X-axis misalignment, (c) angular misalignment, (d) both X-axis and angular misalignment (see online version for colours)



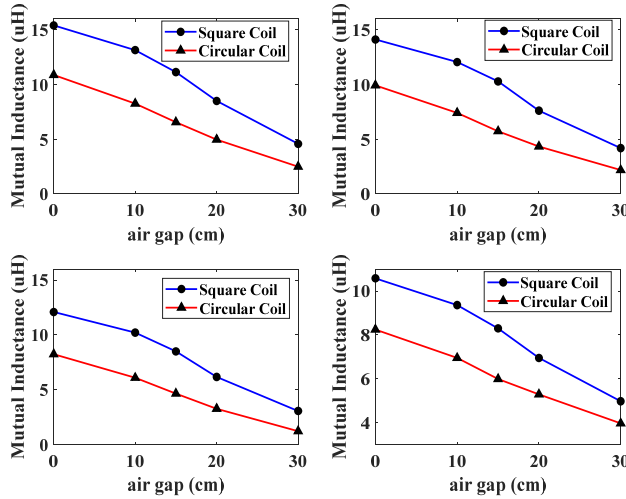
4.2 Simulation evaluation of different coil geometry

The comparative analysis is done through analytical FEM simulation to validate the accuracy of MI of different coil alignments of transmitter and receiver coil in WIPTS. The MI obtained from the FEM simulation for circular and square geometry configurations is compared, and variation is shown in Figure 11. The perfectly aligned coil has more MI compared to other misalignments. The MI and coupling coefficient drop as the air gap distance varies between coils for misalignments. The square coil has tolerance for X-axis misalignment, angular misalignment and a combination of angular and X-axis misalignment, as shown in Figures 11(a), 11(b), 11(c) and 11(d).

In Figure 11, the MI of the coils is examined for different air gap ranges from 0 cm to 30 cm. The result analysis shows that the MI of both the square and circular coil is decreased with the increase of air gap. At the same time, it can be seen that the MI of the coils is increased with the misalignment of coils. Moreover, the MI of the coils is higher in combined misalignment of both the angular and lateral. At the same time, it is observed that the square coils are more efficient than the circular coils, which have higher magnetic flux density for varied air gaps for different misalignment configurations.

The MI between the circular coils is 12 μH , while the coil is perfectly aligned. The MI during 30 mm lateral misalignment lies between 11–12 μH and 10 μH in 15° angular misalignment; moreover, in 15° and 30 mm misalignment lies between 8–9 μH . Whereas the MI between the square is coil lies between 13–14 μH in perfect alignment, in 30 mm lateral misalignment, it lies between 14–15 μH , and 13 μH in 15° angular misalignment moreover, in 15° and 30 mm misalignment, that is 10.5 μH . By analysing the results, it is observed that the square coils offer higher MI in various misalignments.

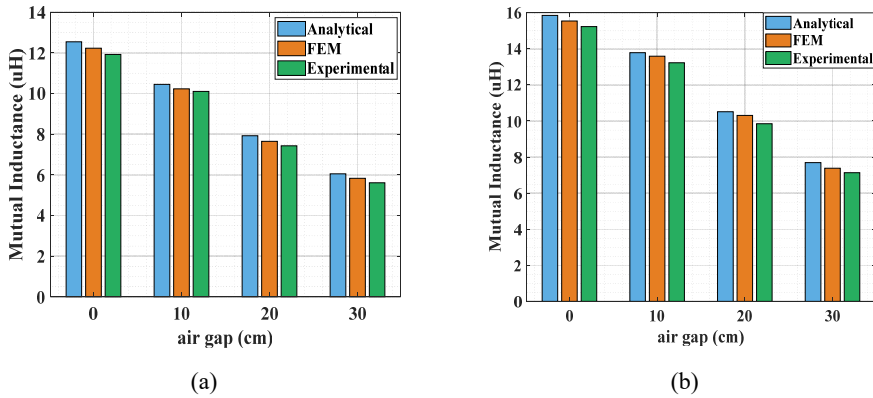
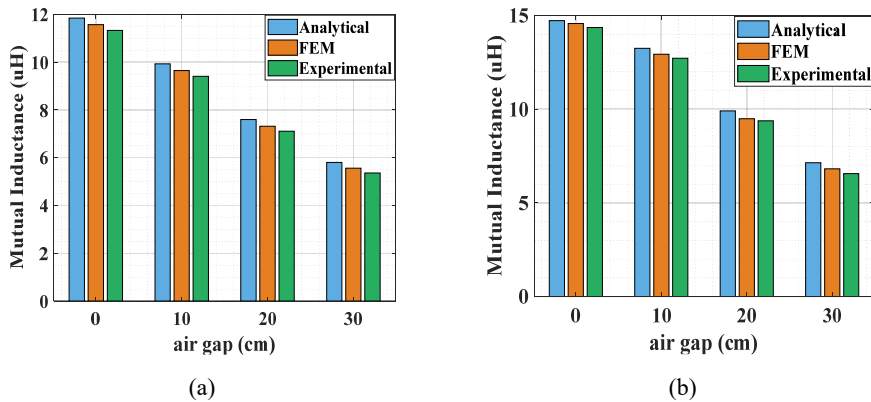
Figure 11 MI in terms of air gap, (a) perfect alignment, (b) lateral misalignment of 30 mm, (c) angular misalignment (15°), (d) angular and lateral misalignment (15° and 30 mm) (see online version for colours)



4.3 Comparison of MI

This section compares the analytical, experimental and FEM simulation results. Here, the lateral misalignment of 30 mm and angular misalignment of 15% is used for validation. The result is taken in terms of various coil misalignments in varying air gaps between the coils. The MI validation in terms of the different air gaps of spiral circular and circular in perfect alignment is depicted in Figure 12. While the air gap between the coils is 10 cm at perfect alignment, the MI obtained by the circular coil lies between 10–11 μH in analytical, experimental and FEM simulation models. Whereas the air gap between the square coils is 10 cm at perfect alignment, the MI obtained by the square coil lies between 13–14 μH in analytical, experimental and FEM simulation models. The analysis of results shows that the MI is higher for the spiral circular and square coils with no air gap. Then, the MI is decreased with the increasing air gap between the coils. Moreover, it is observed that the MI is higher in square coils for an increased air gap between the coils.

The MI is examined for varying air gaps is depicted in Figure 13. While the air gap between the circular coils is 10 cm at X-axis misalignment, the MI obtained by the circular coil lies between 9–10 μH in analytical, experimental and FEM simulation models. Whereas the air gap between the square coils is 10 cm X-axis misalignment, the MI obtained by the square coil lies between 11–14 μH in the analytical, experimental and FEM simulation model. The result analysis shows that MI in X-axis misalignment in both the spiral circular and square coils is decreased with the increasing air gap between the coils. Moreover, it is observed that the analytical and experimental evaluation of MI is almost similar. Furthermore, the square coils are observed to provide higher MI in terms of X-axis misalignment.

Figure 12 MI validation in terms of air gap at perfect alignment for (a) circular, (b) square coil (see online version for colours)**Figure 13** Validation of MI of air gap at X-axis misalignment, (a) circular coil, (b) square coil structure (see online version for colours)

The MI in angular misalignment of both circular and square coils in terms of the varying air gap is depicted in Figure 14. While the air gap between the circular coils is 10 cm at angular misalignment, the MI obtained by the circular coil lies between 8–9 μH in analytical, experimental and FEM simulation models. Whereas the air gap between the square coils is 10 cm at singular misalignment, the MI obtained by the square coil lies between 11–12 μH in analytical, experimental and FEM simulation models. From the result analysis, it is observed that the MI of the circular coil is reduced more than that of the square coils. While there is no air gap between the coils, the MI of circular coils in FEM simulation is 10 μH , whereas the square coils provide 13 μH . Furthermore, the MI is reduced with the increasing air gap, whereas the square coils provide higher MI than the circular coils.

The MI of both the X-axis and angular misalignment of spiral circular and square coils are obtained from analytical, experimental and FEM simulation is depicted in Figure 15. While the air gap between the circular coils is 10 cm at both the angular and X-axis misalignment, the MI obtained by the circular coil lies between 7–8 μH in analytical, experimental and FEM simulation models. Whereas the air gap between the

square coils is 10 cm at both the angular and X-axis misalignment, the MI obtained by the square coil lies between 9–10 μH in analytical, experimental and FEM simulation models. The result analysis shows that the MI of coils is decreased with increasing air gaps during the X-axis and angular misalignment.

Figure 14 MI in terms of air gap at angular misalignment (a) circular coil, (b) square coil structure (see online version for colours)

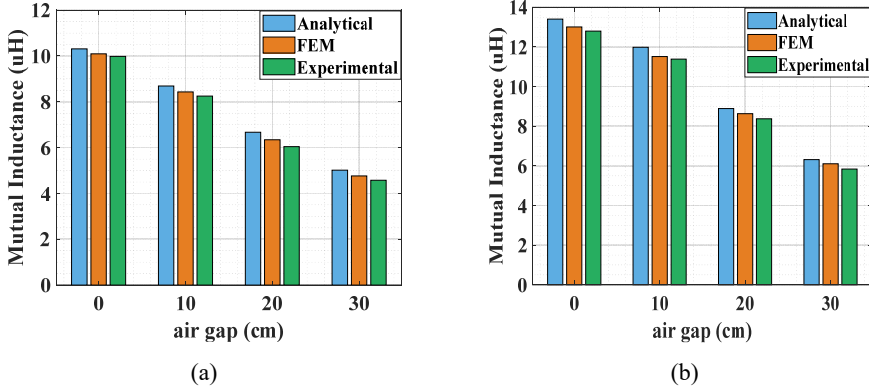
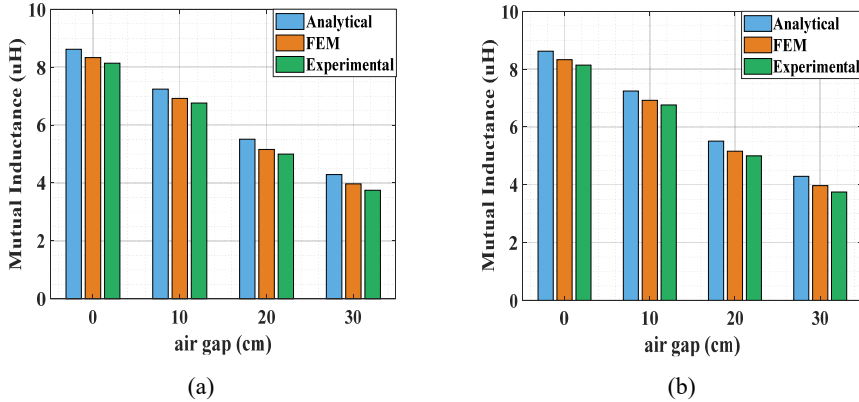


Figure 15 MI in terms of air gap at both X-axis and angular misalignment, (a) circular coil, (b) square coil structure (see online version for colours)



From the above result analysis, it is demonstrated that the coupling coefficient is decreased when the distance between the coil is increased, which reduces the MI between the coils. In various misalignment categories, the square coils provide higher MI in terms of varying air gaps.

4.4 Effects of coupling coefficients for the number of turns

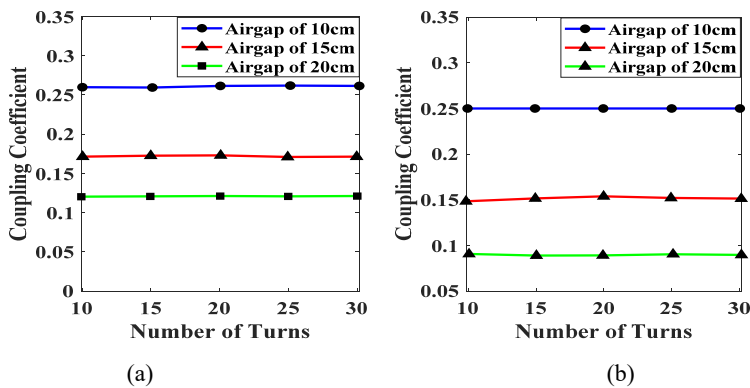
The number of coil turns varies to examine the effectiveness of the coupling coefficient. For this study, the outer diameter and inner diameter are selected as 300 mm and 240 mm, respectively. The turns of the transmitter side coil are set to 15, whereas the receiver side coil turns are varied from 10 to 30. The simulation results shown in this section

indicate that there is a small change in the coupling coefficient when the number of turns varies.

4.4.1 Effect of outer side and inner side diameter on coupling coefficient

The parameters of the transmitter coil are kept fixed as discussed above, and for this study, the inner side diameter is kept fixed at 150 mm, and the outer diameter is varied from 180 mm to 300 mm for the receiver coil. The coupling coefficient for various turns is depicted in Figure 16. The effects of coupling coefficients in terms of some coil turns are validated. While the air gap between the circular coils is 10cm and the number of turns is 15, the square coil's coupling coefficient lies between 0.25–3, whereas the circular coil offers a coupling coefficient of 0.25. From the result analysis, it is observed that the coupling coefficient is increased with the increasing outer diameter of the coil.

Figure 16 Coupling coefficient in terms of number of turns, (a) square coil, (b) circular coil (see online version for colours)



In the later analysis, the outer diameter of the receiver coil is set as 300 mm, and the inner diameter of the coil is varied from 150 mm to 240 mm then; the result is depicted in Figure 17. While the air gap between the circular coils is 10cm and the outer diameter of the coil is 180 mm, the square coil's coupling coefficient lies between 0.15–0.2, whereas the circular coils provide coupling coefficients in the ranges between 0.15–2. The result analysis shows that the coupling coefficients are decreased with a varied inner diameter of the coil.

The coupling coefficient is examined for fixed outer side diameter, and the varying inner side diameter of the coil is depicted in Figure 18. While the air gap between the circular coils is 10 cm and the inner diameter of the coil is 180 mm, the square coil's coupling coefficient lies between 0.1–0.15, whereas the circular coils provide coupling coefficients in the ranges between 0.2–0.25. The result analysis shows that the coupling coefficient of the square and circular coils decreases with the increasing inner side diameter.

The coupling coefficients are measured for varying diameters, as depicted in Figure 18. From the above analysis, it is concluded that the coupling coefficient of square and circular coils is reduced with the coil's increasing outer and inner diameter. By analysing the coupling coefficients of both the spiral circular and square coils, it is observed that the coupling coefficient is decreased with increasing diameter. Moreover, it

is analysed that the spiral circular coils have lower coupling coefficients than square coils.

Figure 17 Coupling coefficient in terms of the outer diameter of coil, (a) square coil, (b) circular coil (see online version for colours)

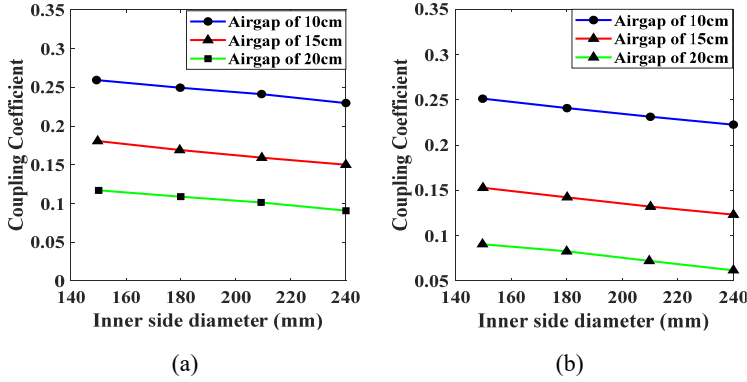
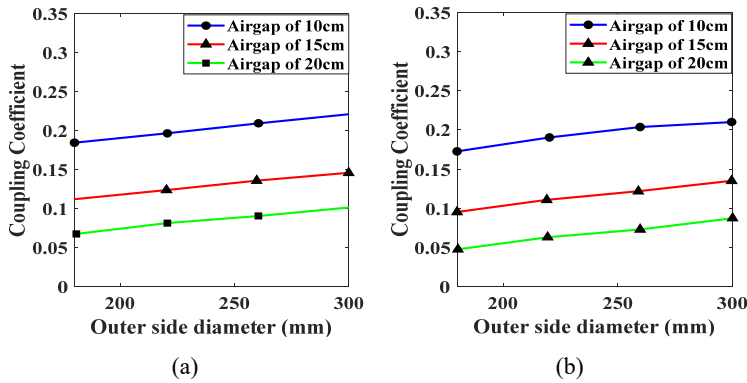


Figure 18 Coupling coefficient in terms of the inner diameter of coil, (a) square coil, (b) circular coil (see online version for colours)



The square coil demonstrated the highest exergetic efficiency of 90%, indicating the most efficient energy conversion. The circular coil achieved an exergetic efficiency of 85%, demonstrating moderate energy efficiency. The spiral coil exhibited the lowest exergetic efficiency of 80%, suggesting higher energy losses compared to the other geometries. These results highlight the superior energy efficiency of the square coil geometry, making it a promising candidate for EV wireless battery charging applications. The higher exergetic efficiency of the square coil can be attributed to its reduced magnetic field leakage and more efficient coupling of energy between the transmitter and receiver.

The error calculation of the circular coil's MI and coupling coefficients in analytical and FEM simulation values at the air gap of 200 mm was evaluated. Results show that the percentage of error of MI is lower for the circular coils, which is 2.09%. Moreover, the error of the coupling coefficient is also reduced in a circular coil, which is 0.02%. The error calculation of the square coil's MI and coupling coefficients in analytical and FEM simulation values at the air gap of 200 mm was analysed. Analysing reveals that the

percentage of error in MI is lower for square coils, at 2.05%. Moreover, the error of the coupling coefficient is also reduced in a square coil, which is 0.019%. Comparing the error calculation of both circular and square coils demonstrates that the square coils are better than the circular coils.

5 Conclusions

This study investigated the MI and coupling coefficient of spiral circular and square coils under various misalignments. Analytical, experimental, and FEM simulation results were compared, demonstrating good agreement. Square coils exhibited higher MI and coupling coefficient compared to circular coils, particularly under misalignment conditions. Additionally, square coils displayed slightly better accuracy in simulations. The proposed work analyses MI for various coil misalignment configurations and spiral circular and square geometry air gaps in ANSYS Maxwell FEM simulation. MI for square coils ranged from 12 μH to 8–9 μH under different misalignment conditions, while circular coils exhibited lower values. The coupling coefficient of square coils also showed better tolerance to parameter variations, making them a promising candidate for wireless charging applications. Square coils show better accuracy with 2.05% MI error and 0.019% coupling coefficient error compared to circular coils (2.09% MI error, 0.02% coupling coefficient error) at 200 mm air gap in analytical and FEM simulations. This experimental validation demonstrates that the square coil geometry offers the highest exergetic efficiency and superior performance in terms of MI and coupling coefficient under various misalignment conditions. While this study provides valuable insights into the performance of spiral circular and square coils under various misalignment conditions. For instance, the manufacturing tolerances of the coils could have influenced the experimental results. Future work will investigate the shape optimisation of coils for EV charging applications.

References

- Balaji, S. and Sundari, P.D. (2023) 'COMSOL FEA modeling of square and circular coil for inductive power transfer in electric vehicle systems', *2023 Third International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT)*, Bhilai, India, pp.1–4.
- Castillo-Zamora, I.U., Huynh, P.S., Vincent, D., Perez-Pinal, F.J., Rodriguez-Licea, M.A. and Williamson, S.S. (2019) 'Hexagonal geometry coil for a WPT high-power fast charging application', *IEEE Transactions on Transportation Electrification*, Vol. 5, No. 4, pp.946–956.
- Das, H.S., Rahman, M.M., Li, S. and Tan, C.W. (2020) 'Electric vehicles standards, charging infrastructure, and impact on grid integration: a technological review', *Renewable and Sustainable Energy Reviews*, Vol. 120, p.109618.
- ElGhanam, E.A., Hassan, M.S. and Osman, A. (2020) 'Design and finite element modeling of the inductive link in wireless electric vehicle charging systems', in *2020 IEEE Transportation Electrification Conference & Expo (ITEC)*, IEEE, pp.389–394.
- Elnail, K.E., Huang, X., Xiao, C., Tan, L. and Haozhe, X. (2018) 'Core structure and electromagnetic field evaluation in WPT systems for charging electric vehicles', *Energies*, Vol. 11, No. 7, p.1734.
- El-Shahat, A., Ayisire E., Wu, Y., Rahman, M. and Nelms, D. (2019) 'Electric vehicles wireless power transfer state-of-the-art', *Energy Procedia*, Vol. 162, pp.24–37.

- Forato, M. and Bertoluzzo, M. (2018) 'Modified series-series compensation topology for WPT systems', in *2018 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (Wow)*, IEEE, pp.1–6.
- Hussain, I. and Woo, D.K. (2021) 'Self-inductance calculation of the Archimedean spiral coil', *Energies*, Vol. 15, No. 1, p.253.
- Kim, M. and Choi, J. (2021) 'High-frequency, mid-range wireless power transfer system using critical coupling coefficient adjustment', in *2021 IEEE Applied Power Electronics Conference and Exposition (APEC)*, IEEE, pp.714–719.
- Kishan, D. and Vinod, M. (2020) 'Analysis of mutual inductance between asymmetrical spiral circular coils of WIPTS for EV battery charging', in *2020 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT)*, IEEE, pp.1–5.
- López-Alcolea, F.J., Del Real, J.V., Roncero-Sánchez, P. and Torres, A.P. (2019) 'Modeling of a magnetic coupler based on single-and double-layered rectangular planar coils with in-plane misalignment for wireless power transfer', *IEEE Transactions on Power Electronics*, Vol. 35, No. 5, pp.5102–5121.
- Mohamed, N., Aymen, F., Issam, Z., Bajaj, M., Ghoneim, S.S. and Ahmed, M. (2021) 'The impact of coil position and number on wireless system performance for electric vehicle recharging', *Sensors*, Vol. 21, No. 13, p.4343.
- Mosammam, B.M., Mirsalim, M. and Khorsandi, A. (2020) 'Modelling, analysis, and SS compensation of the tripolar structure of wireless power transfer (WPT) system for EV applications', in *2020 11th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC)*, IEEE, pp.1–5.
- Nanda, N.N., Yusoff, S.H., Toha, S.F., Hasbullah, N.F. and Roszaidie, A.S. (2020) 'A brief review: basic coil designs for inductive power transfer', *Indones. J. Electr. Eng. Comput. Sci.*, Vol. 20, No. 3, pp.1703–1716.
- Raju, A.D.J., Manohar, S.S. and Raj, M.A. (2016) 'Estimation of inductance for sine and cosine shape spiral coils', *International Journal of Applied Engineering Research*, Vol. 11, No. 5, pp.3663–3669.
- Shi, Y., Wang, X. and Qian, L. (2020) 'Analysis and optimization for coil misalignment in wireless power transfer', in *2020 IEEE 15th International Conference on Solid-State & Integrated Circuit Technology (ICSICT)*, IEEE, pp.1–3.
- Sivaraju, S.S., Chitra, J., Anuradha, T. and Pandian, A. (2023) 'An intelligent load balancing strategy for energy cost minimization in EV applications', *Electric Power Components and Systems*, Vol. 52, No. 7, pp.1200–1218.
- Song, J., An, H., Li, Y., Zhang, C. and Liu, G.Q. (2020) 'Modeling and experimental analysis of three-dimensional cross coil structure for misaligned wireless power transfer system', *Progress in Electromagnetics Research C*, Vol. 106, pp.89–103.
- Srinivasa Rao Nayak, P., Kishan, D. and Annaiah, P. (2018) 'Investigation of MI between circular spiral coils with misalignments for EV battery charging', *IET Science, Measurement & Technology*, Vol. 12, No. 7, pp.844–850.
- Stankiewicz, J.M. and Choroszucho, A. (2021) 'Comparison of the efficiency and load power in periodic wireless power transfer systems with circular and square planar coils', *Energies*, Vol. 14, No. 16, p.4975.
- Sutopo, W., Nizam, M., Rahmawatie, B. and Fahma, F. (2018) 'A review of electric vehicles charging standard development: study case in Indonesia', in *2018 5th International Conference on Electric Vehicular Technology (ICEVT)*, IEEE, pp.152–157.
- Yang, Y., Cui, J. and Cui, X. (2020) 'Design and analysis of magnetic coils for optimizing the coupling coefficient in an electric vehicle wireless power transfer system', *Energies*, Vol. 13, No. 16, p.4143.
- Zhu, G. and Lorenz, R.D. (2018) 'Achieving low magnetic flux density and low electric field intensity for a loosely coupled inductive wireless power transfer system', *IEEE Transactions on Industry Applications*, Vol. 54, No. 6, pp.6383–6393.