Analysis of the Advantages and Disadvantages of Square and Circular Coils in Wireless Charging Systems for Electric Vehicles

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Abstract. As energy shortage and environmental pollution problems are becoming increasingly serious, Electric Vehicles (EVs) have drawn much more public attention. The charging technology of EVs has also developed, especially Wireless Power Transfer (WPT). Compared to a conductive charging system, its unique advantages are destined to make it the mainstream charging method for EVs in the future. The current relatively advanced method is a magnetic coupling inductive wireless charging system, and the coupled resonant coil is clearly one of the most important components of this structure. This paper aims to analyze the basic structure of magnetic coupling inductive wireless charging systems and the advantages and downsides of the circular and rectangular coils, respectively. The circular coil has more advantages in terms of EMI performance and price, while the rectangular coil has more advantages with regards to impedance matching. This research holds significant importance for optimizing the design of wireless charging systems, as it provides a comprehensive comparison of coil structures to enhance efficiency, reduce costs, and improve electromagnetic compatibility in future EV charging solutions.

Keywords: Magnetic Coupling Inductive Wireless Charging System, Coupled Resonant Coils, Emi, Price, Impedance Matching

1 Introduction

Since the beginning of the 21st century, new energy electric vehicles, especially EVs, have received increasing attention from people. A considerable number of research institutions also regard this as one of the most important fields in the future. However, the current charging problem of EVs has largely hindered their development. Wired charging methods have a significant number of problems, such as high requirements for site conditions, high costs for maintenance of the charging facilities, and potential safety hazards during insertion and extraction. On the other hand, the wireless

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charging method can effectively avoid a proportion of problems of these. For example, it has fewer requirements for the production site, lower costs for maintenance of the charging facilities, and does not generate excessive safety hazards [1][2]. Therefore, the wireless charging method has the potential to become a main charging method in the future.

In the current development process of wireless charging for EVs, the magnetic coupling inductive wireless charging system is the most advanced. For this wireless charging system, the coupled resonant coil is its most important component. Currently, the most common structures of coupled resonant coil are circular coil groups and square coil groups [3]. And through previous investigation and research, the shape has a great impact on the efficiency of energy transmission [4]. Therefore, this article focuses on the basic structure of circular and rectangular coils, and compares the advantages and disadvantages of these two types of coils.

2 Theories About Magnetic Coupling Inductive Wireless Charging System

2.1 Magnetic coupling inductive wireless charging system

WPT converts electrical energy into a relay energy, which is then transmitted over a distance in the air, and then the relay energy is converted back into electrical energy to achieve the effect of contactless charging. the basic energy transmission medium of the focus of this report, magnetic coupling inductive wireless charging system, is an alternating magnetic field. The basic energy conversion mode is electrical energy - magnetic energy - electrical energy.

Figure 1 shows the basic structure of this system, and Figure 2 is a simplified structure of this system for electric vehicles. Firstly, power is supplied by the power grid, and the power factor is improved through Power Factor Correction (PFC) [4]. Secondly, since the AC frequency provided by most national power grids, which is 50-60Hz, is insufficient to support the wireless power transmission system, an AC-DC converter can be used to convert the alternating current into direct current first, and then a high-frequency inverter can generate higher-frequency alternating current [5]. Thirdly, an alternating current is applied to the transmitting coil, causing the transmitting coil to generate an alternating electric field, and the alternating electric field will generate an alternating magnetic field in space. According to Faraday's Law of Electromagnetic Induction, when the alternating magnetic field passes through the areaenclosed by the receiving coil in space, an alternating electric field will be induced in the receiving coil, generating an induced electromotive force, thereby generating a voltage on the receiving coil. Finally, at the end of the receiving coil, the high-frequency alternating current is converted into a direct current that matches the charging device [4-8].

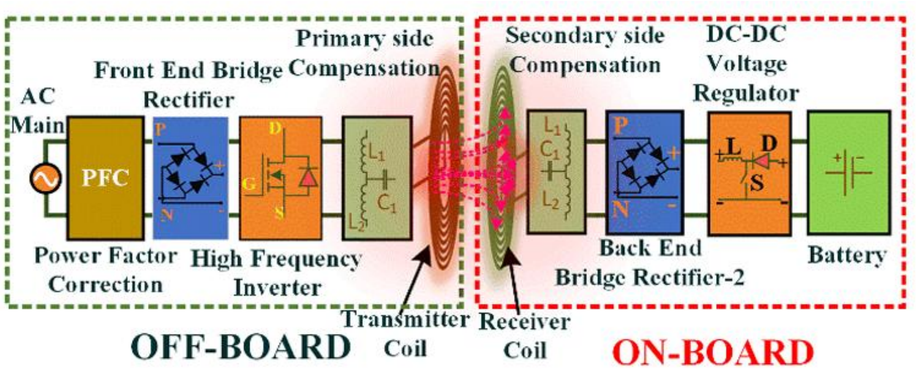


Fig. 1. The basic structure of magnetic coupling inductive wireless charging system[4]

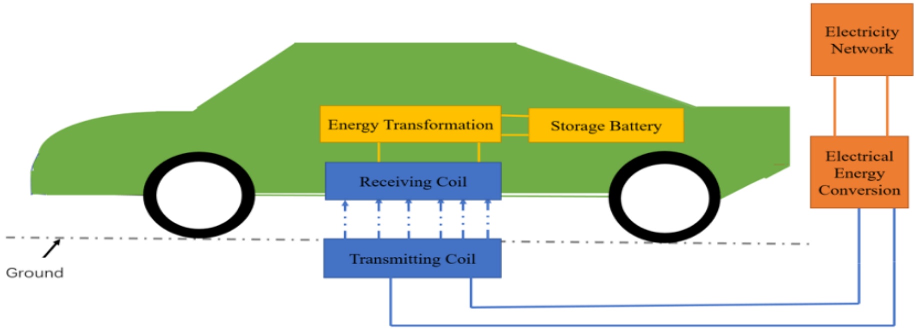


Fig. 2. Simplified structure of magnetic coupling inductive wireless charging system for electric vehicles [9]

2.2 Coupled resonant coil

Figure 3 shows the coupled resonant coil using Blender software. Coupled resonant coil usually consists of four parts: a conductive wire coil wound with Litz wire, a ferrite layer for improving the coupling coefficient and magnetic shielding, a support layer for fixing the position of the ferrite layer, and Aluminum Shielding Layer [10, 11].

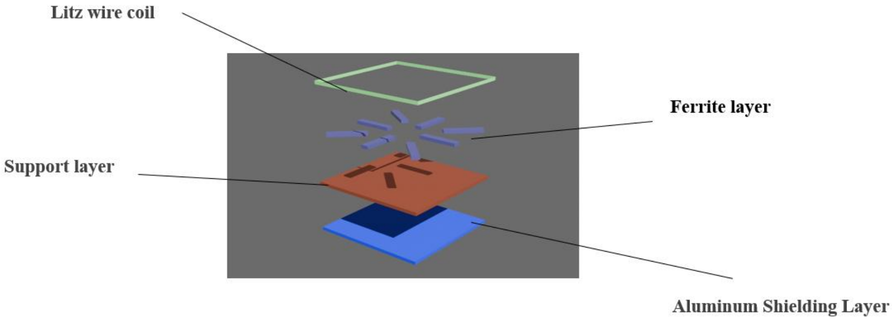


Fig. 3. Coupled resonant coil

At present, the two typical coil groups used in the electric vehicle industry are the circular and rectangular coils. The characteristics of these two coils will be outlined below.

3 Basic Structure of Two Coils

3.1 Circular coils

Figure 4 shows the planar circular coil. As a monopole magnetic energy coil, its main magnetic circuit mainly radiates outward from the center of the spatial structure.

Fig. 4. The circular coil

By applying the Biot-Savart law and through simulation, the basic form of the magnetic field of the circular coil in the most ideal state is shown in Figure 5. Through this simulated magnetic field diagram, it is obvious to find several characteristics of it. Firstly, as this coil is axisymmetric, the magnetic field distribution is centrosymmetric and axisymmetric. Secondly, the magnetic field intensity is the greatest at the center and decreases outward. Moreover, when moving away from the circular coil, the magnetic field is gradually similiar to the magnetic dipole field. The symmetry of the magnetic field makes it more regular in the far-fiel. Finally, at the center position, the magnetic field direction is perpendicular to the plane of the coil, and due to the continuous symmetry of the coil, the magnetic field is relatively uniform near the center.

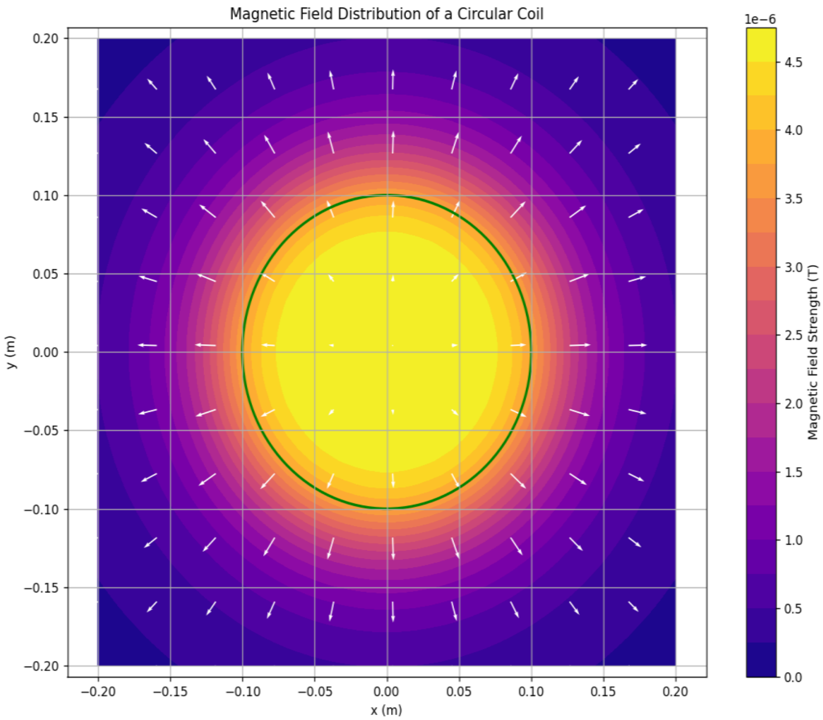


Fig. 5. Magnetic Field Distribution of a circular coil

3.2 Rectangular coils

Figure 6 shows the rectangular coil. It is also a monopole magnetic energy coil. However, their magnetic field distribution are significantly different.

Fig. 6. The rectangular coil

As shown in Figure 7, still applying the Biot-Savart law for simulation, the basic characteristics of the magnetic field of a planar rectangular coil under the most ideal conditions can be obtained. Firstly, because it is composed of four straight wires, it is centrosymmetric and axissymmetric. In addition, the magnetic field direction changes sharply at the corners of the coil, which is not as smooth as that of a circular coil. Finally, when moving away from the coil, the magnetic field is similar to a magnetic dipole field, but the attenuation is more irregular than that of a circular coil.

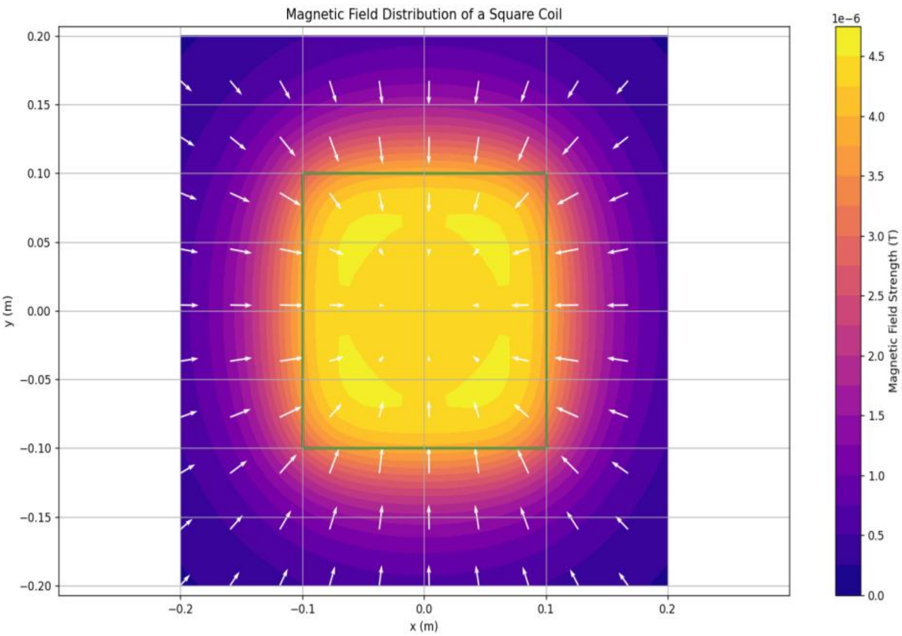


Fig. 7. Magnetic Field Distribution of a rectangular coil.

3.3 Comparative analysis of magnetic field distributions

Table 1. Comparison of the two coils' magnetic field

Characteristic	Circular	Rectangular
Symmetry	axissymmetric and centrosymmetric	axissymmetric and centrosymmetric
Magnetic intensity	uniform in the center and decreases outward	uniform in the center but sharp in the corner of the rectangular
Central Magnetic Field	have maximum value in the center and is perpendicular to the coil	perpecndicular to the coil but not uniform comparing with circular coil's
Magnetic Far Field	similar to magnetic dipole field and is uniform	similar to magnetic dipole field but is not uniform

As shown in table 1, there are four obvious difference comparing rectangular coils and circular coils. Firstly, both circular and rectangular coils are axissymmetric and centrosymmetric, while the symmetry of circular coils' field is better than rectangular field's due to the geometric characteristics of circles and rectangle. Secondly, the central magnetic field changes of both circular and square coils are relatively uniform, but the changes at the corners of square coils are more intense. At the same time, the directions of the central magnetic fields of both circular and square coils are perpendicular to the magnetic field direction, but the distribution of square coils is not as uniform as that of circular coils. Finally, the magnetic far fields of both types of coils are approximately magnetic dipole fields, but the attenuation of circular coils is more regular.

4 Performance Comparison in Electric Vehicle Charging

4.1 Tolerance of misalignment

Different Conditions. Due to the fact that drivers cannot ensure that they place their EVs where receiving coils exactly in alignment with transmitting coils when parking, it is not only necessary to consider the transmission characteristics when the transmitting and receiving ends are aligned, but also to analyze their efficiency when there is misalignment. The misalignment conditions can be roughly divided into three types: axial misalignment, lateral misalignment and angular misalignment [10,12]. This essay will concentrate on lateral misalignment and angular misalignment

Lateral misalignment refers to the situation where the two coils are offset horizontally. Only in the horizontal direction is there an offset situation. This situation mostly exists when the driver cannot park the electric vehicle at the exact position. Angular misalignment is that there is an angle deviation between the transmitting coil and the receiving coil, and the receiving coil and the transmitting coil are not paralle, especially when the parking position is uneven.

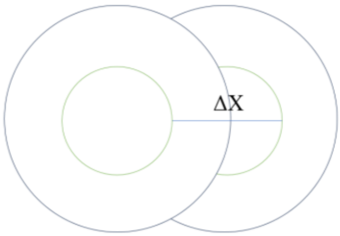
Lateral Misalignment. Table 2 outlines the width of the vehicle models of different brands. The width of the receiving coil on the vehicle should also be approximately the same as the width of the vehicle. The average vehicle width in the table is 1.9 meters [13-18]. In the following models, for the convenience of statistics and calculation, it is assumed that the coil width is 2 meters. Furthermore, a large amount of data indicates that the external diameter should be twice the internal diameter [19].

Table 2. Width of different vehicle models[13-18]

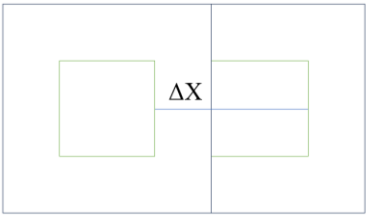
Vehicle Name	width/m
Mercedes-Benz 2023 EQE 500 4MATIC SEDAN	2.1
Tesla 2023 Model 3	2.1
Hyundai 2024 Kona	1.8
Chevrolet 2023 Bolt EV	1.8
Toyota 2024 Prius	1.8
Average overall width of the cars	1.9

This article assumes two different shapes of coils as a circular one with a central hollow and a square one with a central hollow. It is assumed that the diameter of the circular coil is 2 meters, the inner diameter of the hollow part of the circular coil is 1 meter, and the side length of the square coil is also 2 meters, with the inner square part having a side length of 1 meter.

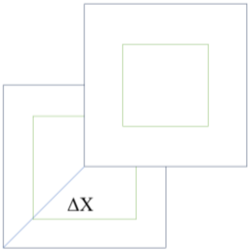
As shown in Figure 8, (a) is the situation of lateral misalignment of the circular coil. Due to the centrosymmetry of the circular coil in shape, the lateral misalignment of the circular coil is independent of the moving direction. For the square coil, (b) is the complete rightward lateral misalignment of the square coil, and (c) is the 45° upward-right lateral misalignment of the square coil. Due to the shape characteristics of the square, angles in (b) and (c) are two extreme values of the angle of lateral misalignment of the square coil.



(a)



(b)



(c)

Fig. 8. (a)the lateral misalignment of circular coils; (b) complete rightward lateral misalignment of square coils; (c) 45° upward-right lateral misalignment of the square coil

In order to investigate the effect of coils' shapes on the tolerance of misalignmen, this article will make a graph showing the ratio of the overlapping part of the actual position and the ideal alignment position to the total area of the coil, and the relationship with the horizontal offset distance (ΔX in Figure 9). As shown in Figure 9(a), when completely offset to the right, from the distance of lateral misalignment of 0 meters to the maximum value of 2 meters, except for the cases of complete overlap and complete separation, the proportion of the overlapping part of the square coil is always higher than that of the circular coil. Moreover, as shown in Figure 9(b), when the coil is offset 45° to the right upwards horizontally, within most of the displacement distance, the overlapping part of the square coil is larger than that of the circular coil. Since the effective mutual inductance area ratio in the offset condition can roughly reflect the mutual inductance, it can be preliminarily predicted that the influence of lateral misalignment on the square coil is smaller than that on the circular coil.

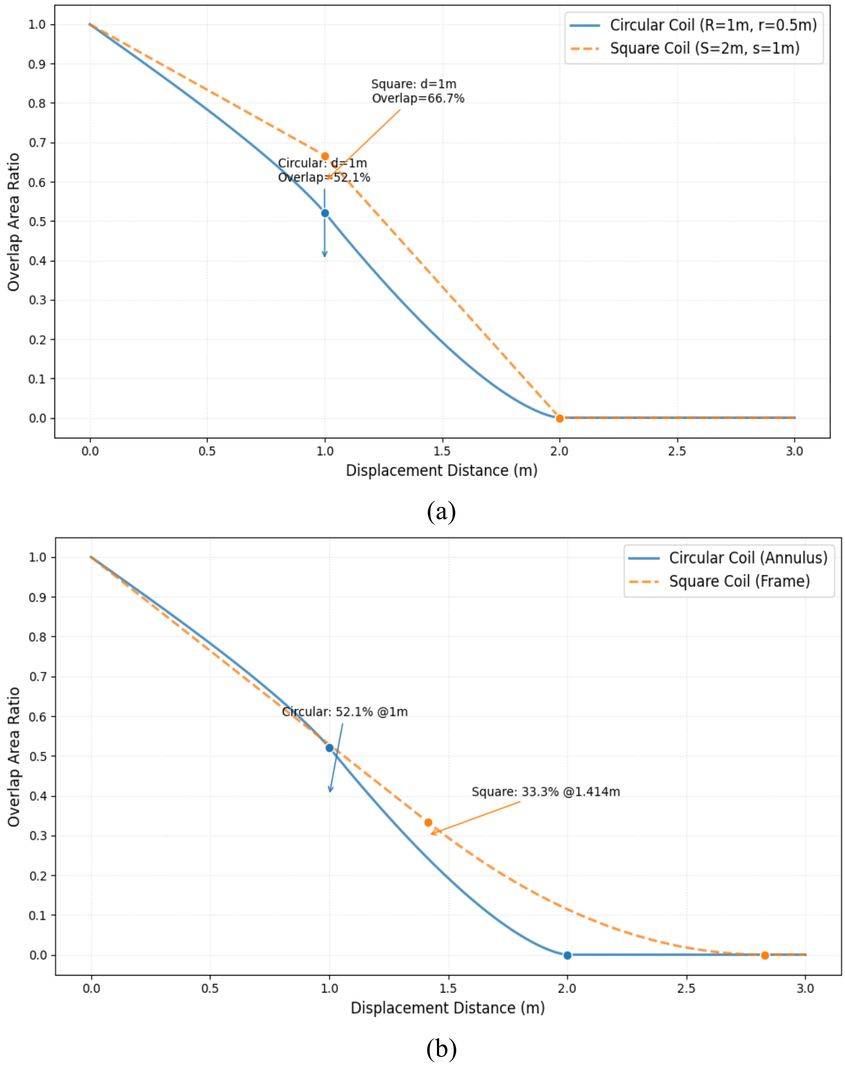


Fig. 9. (a)complete rightward lateral misalignment; (b) 45° upward-right lateral misalignment

Under the condition that other factors are kept consistent, the team led by Zhichao Luo conducted an actual study on the mutual inductance values of two coils with respect to the horizontal displacement distance. Through the experimental data, it can be concluded that the percentage of mutual inductance decrease of the rectangular coil under lateral misalignment is smaller than that of the circular coil [10,11].

The coupling coefficient (K) represents the degree of magnetic coupling between the transmitting coil and the receiving coil. The higher the coupling coefficient value the higher the energy transmission efficiency [4]. Chunting Chris Mi et al. obtained the graphs of the coupling coefficient of the rectangular coil and the circular coil varying with the horizontal displacement. They concluded that within the range of 0-

200mm of horizontal offset, the coupling coefficient of the circular coil is always higher than that of the square coil, which also indicates that the energy transmission efficiency of the circular coil in the case of horizontal position offset is higher than that of the square coil. The results of both papers can lead to the conclusion that the square coil has better tolerance of lateral misalignment, which is similar to the prediction result obtained previously based on the overlapping area proportion [8].

Angular misalignment. In the WPT, compared with the horizontal offset distortion, when the inclination angle is relatively large, the influence of the angular misalignment on the transmission efficiency is more obvious [4].

However, considering the parking offset situation in real life, the inclination angle range is usually only between 5° and 30°, and the discussion and comparison scope should also be limited to this range[10]. As the inclination angle increases, the mutual inductance between the coils of the rectangular coil and the circular coil will increase, but the increase is not significant, especially within the range of 15° inclination, the mutual inductance between the coils basically remains unchanged[10]. Thus, whether it is the rectangular coil or the circular coil, there is no obvious difference of effects of angular mislignmant on different coils[10].

4.2 EMI and EMF Exposure

EMI and EMF Exposure. In the WPT, EMI refers to the phenomenon that in the process of wireless charging, the generated magnetic field is not fully utilized for energy transmission but spreads to the magnetic field outside this power transmission system. This phenomenon not only causes energy loss but also has certain impacts on the electromagnetic equipment inside the vehicle and in the surrounding environment[5].

What is more, this phenomenon can also have adverse effects on the human body. According to the ICNIRP regulations, the internal electric field limit set is 1.35×10-4 f, where f is the electric field frequency, and the general public limit is 83 V/m, while the similar ICNIRP limit for magnetic field is 27 μT [20]. Therefore, in the process of considering the WPT, we should try to minimize the effects of EMF exposure. When comparing and analyzing these two coils, it can be found that there are differences between them two coils.

Results from experiments. The team of Zhichao Luo used magnetic field probes and magnetic field testers to measure the magnetic field at multiple positions around two coils, and used current probes combined with oscilloscopes to obtain the currents in the transmitting and receiving loop sides [10]. According to the experimental data, when other factors are kept consistent, the difference in magnetic field intensity between the center of the transmitting coil and the center of the receiving coil (magnetic field intensity of the center of the transmitting coil - magnetic field intensity of the center of the receiving coil) of the rectangular coil is much greater than that of the circular coil[10]. When analyzing the magnetic field intensity at the same distance from the coil, the magnetic field intensity at 200 mm positions in all directions of the rectangular coil is greater than that of the circular coil. In most cases, the external magnetic field intensities of the receiving and transmitting ends of the rectangular coil are greater than those of the circular coil[10].

Chunting Chris Mi mainly conducted the measurement of magnetic field intensity at the center position of the launch coil, which was 900 mm away. The final conclusion was the same as that in [10], that is, the magnetic field intensity of the rectangular coil at this position was greater than that of the circular coil. Through these two experiments, it can be concluded that the EMI and EMF exposure of the rectangular coil was more obvious than that of the circular coil [8].

4.3 Price

Jeonggi Son selected coils whose external diameters were approximately twice as large as their internal diameters as the research subjects based on [20]. They controlled the external and internal diameters of circular and square coils to be consistent and maintained a doubling relationship, and kept them under the same conditions. Finally, they found that the volume of circular coils was much smaller than that of rectangular coils, and the self-inductance values of the two were basically the same. This indicates that under the same effect, circular coils cost less than rectangular coils.

5 Conclusion

This article compares the basic magnetic field distribution and characteristics of rectangular coils and circular coils in the WPT, and makes comparisons regarding the tolerance of misalignment, EMI and EMF exposure, and prices of the two types of coils. The final result of this study shows that rectangular coils have greater advantages in tolerance of misalignmen, while circular coils have less impact on the electromagnetic equipments and individuals' bod, and have more advantages in terms of price.

The results of this study are helpful for electric vehicle manufacturers to preliminarily understand the safety characteristics of the two systems and design with optimization based on the characteristics of their own products. At present, many more advanced coil structures have emerged. In the future, by continuously combining these coils to concentrate their advantages, the efficiency of magnetic coupling induction wireless charging technology will increase rapidly.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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