A new type of coil structure called pan-shaped coil of wireless charging system based on magnetic resonance

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Abstract. The problem that misalignment between the transmitting coil and the receiving coil significantly impairs the transmission power and efficiency of the system has been attached more and more attention. In order to improve the uniformity of the magnetic field between the two coils to solve this problem, a new type of coil called pan-shaped coil is proposed. Three-dimensional simulation models of the planar-core coil and the pan-shaped coil are established using Ansoft Maxwell software. The coupling coefficient between the transmitting coil and the receiving coil is obtained by simulating the magnetic field with the receiving coil misalignment or not. And the maximum percentage difference strength along the radial direction which is defined as the magnetic field uniformity factor is calculated. According to the simulation results of the two kinds of coil structures, it is found that the new type of coil structure can obviously improve the uniformity of the magnetic field, coupling coefficient and power transmission properties between the transmitting coil and the receiving coil.

1. Introduction

Electric vehicles (EVs) and plug-in hybrids (PHVs) are gaining popularity as they provide superior energy efficiency and have the potential to reduce carbon dioxide emissions. Compared with wired charging technology, wireless charging technology is easy to operate and has no risk of exposure to sparks, thus it is able to adapt to harsh environments. In recent years, researches and applications of wireless charging technology have been raising more and more attention [1].

The basic working principle of the wireless power transmission technology based on magnetic coupling resonant is that using the resonance generated in the circuit to achieve wireless transmission of electrical energy. The system generally uses a series-series resonant structure. The energy transmitter is a resonator consisting of a transmitting coil and a resonant capacitor in series [2]. And the energy receiver is a resonator consisting of a receiving coil and a resonant capacitor in series. As shown in figure 1, the energy coupling mechanism of the electric vehicle wireless charging system is mainly composed of a transmitting coil and a receiving coil and this structure is the type of planar-core coil structure which is commonly used [3]. The key to improving the output power and efficiency of the wireless charging device is to improve the coupling coefficient between the two coils. At present, methods used commonly to improve the coupling coefficient of these two coils are improving the shape of the coil and increase the core. In [4] and [5], the author respectively designs a double-D (DD) coil and a DD-quadrature coil to improve the coupling coefficient.
In addition, the wireless charging technology is facing a serious challenge that the misalignment between the transmitting coil and the receiving coil can significantly impair the power transfer efficiency of the system [6]. However, the positioning of the receiving coil does not need to be very accurate if the magnetic field generated by the transmitting coil is uniform so that the effect of the misalignment on the transmission efficiency can be avoided.

Many researches on producing a uniform magnetic field by designing different coil structures have been done in recent years. In [7], the authors propose a structure of a coil array composed of a number of small coils, which are tightly arranged in certain geometries. Diao Y, et al [8] proposed a rectangular coil structure and provided a function to calculate the turn distribution of the coil. In [9], a hybrid coil structure comprising a concentrating coil and a helical coil was proposed. However, the magnetic field strength of most structural coils is not constant and the uniformity of the magnetic field depends on the size of the receiving coil. So the solutions in these studies will be meaningless if the receiving coil is too small. In addition, a potential problem with these studies is that they are not designed for the size of the coils used for electric vehicles, which are either with a small coil size or with distance of only a few millimeters between the transmitter and receiver.

This paper presents a new type of pan-shaped coil structure, which is used to improve the uniformity of the magnetic field between the transmitting coil (at the parking point) and the receiving coil (in the car) and solve the problem that misalignment between the two coils can significantly impair the power transfer efficiency of the system. Firstly, the coupling coefficient and the magnetic field uniformity factor are introduced. Then, the planar-core coil and the new type of pan-shaped coil are modeled and magnetic field characteristics such as the coupling coefficient are simulated with Ansoft Maxwell software. Finally, magnetic field simulation results of the two kinds of coil structures are compared and analyzed. We evaluate the effect of the pan-shaped coil structure by comparing their magnetic field evenness factor and the coupling coefficient.

2. Analysis of system theory

2.1. Coupling coefficient

Two electromagnetic coupling coils are shown in figure 2. \( N_T \) and \( N_R \) represent the number of turns of the transmitting coil and the receiving coil. \( L_T \) and \( L_R \) are respectively the self-inductance of the transmitting coil and receiving coil. \( M \) is the mutual inductance between the coils. \( r_T \) and \( r_R \) are respectively the radii of the transmitting coil and receiving coil. \( k \) and \( D \) are the coupling coefficients and the distances between the two coils.

The degree of flux coupling between the two coils is expressed by the coupling coefficient. And the formula is shown in equation (1). It is necessary to increase the coupling coefficient between the transmitting coil and the receiving coil in order to improve the power transmission efficiency in the electric vehicle wireless charging system.

![Figure 1. Wireless charging display for electric vehicle.](image-url)
2.2. Uniform magnetic field

In this paper, a new type of coil structure is designed to improve the uniformity of the magnetic field between the transmitting coil and the receiving coil, which is aimed to solve the problem that misalignment between the transmitting coil and the receiving coil can significantly impair the power transfer efficiency of the system. The uniformity of the magnetic field generated by the transmitting coil can be measured as the maximum percentage difference strength along the radial direction of the receiving coil. This value is tentatively defined as the uniformity factor which is expressed as a parameter named $\lambda_u$ according to equation (2) as follow.

$$
\lambda_u = \frac{\max(H) - \min(H)}{\max(H)}
$$

(2)

2.3. Analysis of series-series (PSSS) resonant compensation structure

The equivalent circuit diagram of the series-series (PSSS) resonant compensation structure commonly used in the wireless charging system is shown in figure 3. $U_s$ is the AC voltage source. $L_1$ and $L_2$ are respectively the self-inductance of the transmitting coil and receiving coil. $M$ is the mutual inductance between the coils. $C_1$ and $C_2$ represent the values of resonant compensation capacitors. $R_1$ and $R_2$ are respectively the resistance of the transmitting coil and receiving coil. $R_L$ is the load of the wireless charging system.

According to the equivalent circuit diagram, the state equation of the system can be obtained as shown in equation (3). And the equations calculating transmission power and efficiency of the resonant compensation structure are respectively shown in equations (4) and (5).

$$
\begin{bmatrix}
U_s \\
0
\end{bmatrix} =
\begin{bmatrix}
R_i + j\omega L_i - j\frac{1}{\omega C_1} & -j\omega M \\
-j\omega M & R_2 + j\omega L_2 - j\frac{1}{\omega C_2} + R_L
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
$$

(3)

$$
P = \frac{U_s^2 k^2 L_i L_2 \omega^2 R_L}{(R_i R_2 + k^2 L_i L_2 \omega^2)^2}
$$

(4)
\[ \eta = \frac{k^2 L_1 L_2 \omega^2}{k^2 L_1 L_2 \omega^2 + R_1 R_2} \quad (5) \]

3. Conventional planar-core coil

As a carrier for wireless power transmission, the core enhances the degree of magnetic field coupling between the inductive coils and plays an important role in improving the transmission power and efficiency in the high-power and long-range wireless power transmission. The thin plate-shaped core is widely used for its small size, light weight, easy to fix, and the large equivalent area and it has achieved some successes in the field of wireless energy transmission. At present, the resonant coil structure using the planar spiral structure or the three-dimensional spiral structure will affect the normal driving if the size of the coil in the electric vehicle wireless charging system is too large or the car chassis is too low caused by the vertical height of the coil. So this kind of inductance coil generally uses the type of planar structure. The model of the coil is shown in figure 4.

![Figure 4. Model of conventional planar-core coil.](image)

![Figure 5. The magnetic field distribution between the two coils.](image)

This type of coil structure is asymmetrical in which the size of the transmitting coil is larger than the size of the receiving coil so that the variation of the coupling coefficient can be reduced when the receiving coil shifts in the magnetic field coverage of the transmitting coil. In addition, the coupling coil is laid on the planar core, which can effectively increase the self-inductance value of the transmitting coil and the receiving coil and the mutual inductance between the two coils. Compared with the coil structure composed of two or more air-core coils, the uniformity of the spatial alternating magnetic field is improved and the magnetic field strength of the space is also enhanced so that the transmission distance of the system is increased and the energy transmission power and efficiency of the system are improved effectively.

We model this coil structure using the Ansoft Maxwell software for magnetic field analysis, in which the maximum radius of the transmission coil is 175 mm and that of the receiving coil is 125 mm. The size of the two cores are 360 mm × 360 mm × 6 mm and 260 mm × 260 mm × 6 mm respectively and the distance between the two coils is 120 mm. The distribution of the magnetic field between the coils and the distribution of the magnetic field in the radial direction of the receiving coil are shown in figures 5 and 6 respectively through performing a magnetic field simulation.

As shown in equation (6), the uniformity factor of the magnetic field between the two coils is 0.602 by calculation. In addition, the coupling coefficient value between the two coils in this coil structure is 0.15889 by calculation using the simulation software.

\[ \lambda_{UI} = \frac{425.1 - 169.4}{425.1} = 0.602 \quad (6) \]
Figure 6. The distribution of the magnetic field in the radial direction of the receiving coil.

Figure 7. The distribution of the magnetic field in the radial direction of the receiving coil when misaligned by 5 mm.

Figure 8. The distribution of the magnetic field in the radial direction of the receiving coil when misaligned by 10 mm.

In addition, we simulate the magnetic field and calculate the magnetic field uniformity and coupling coefficient when the receiving coils are horizontally misaligned by 5 mm and 10 mm in order to see the effect on the transmission efficiency of the system produced by the conventional planar-core coil. The distribution of the magnetic field between the two coils and the distribution of the magnetic field in the radial direction of the receiving coil are shown in figures 7 and 8 respectively. The uniformity factors of the magnetic field between the two coils are 0.629 and 0.688 respectively and the
coupling coefficients are 0.15857 and 0.15770 respectively. It can be seen that the magnetic field uniformity and the coupling coefficient between the two coils become worse when the receiving coil is shifted.

This type of coil structure is then used in the wireless charging system based on magnetic resonance, of which the resonant compensation structure is series-series. And the effect is analyzed by using Ansoft Maxwell software. First of all, we build the external circuit according to the schematic diagram shown in figure 3. We get the inductance values of the transmitting coil and the receiving coil. And then we calculate the value of resonance compensation capacitor using the series resonant theory. The simulation chart of the external circuit is shown in figure 9. And we obtain the voltage and current waveforms of the transmitting coil and the receiving coil which are shown in figures 10 and 11 respectively.

4. New type of pan-shaped coil

![Figure 9. The simulation chart of the external circuit.](image9)

![Figure 10. The voltage and current waveforms of the transmitting coil.](image10)

![Figure 11. The voltage and current waveforms of the receiving coil.](image11)
The new type of pan-shaped coil consists of multi-turn circular coils aligned along the vertical axis. And it can improve the uniformity of the magnetic field between the transmitting coil and the receiving coil to solve the problem that misalignment between the two coils can significantly impair the transmission power and efficiency of the system. The illustration of the new type of pan-shaped coil is shown in figure 12. This type of coil can produce a relative smooth uniform magnetic field because ripples in the field strength curve along the radial direction can be eliminated by introducing height differences among adjacent turns.

![Figure 12. Illustration of the new type of pan-shaped coil.](image)

![Figure 13. The magnetic field distribution between the two coils.](image)

Similarly, we model this coil structure using the Ansoft Maxwell software for magnetic field analysis, in which the maximum radius of the transmission coil is 175 mm and that of the receiving coil is 125 mm, which are the same as the size of the conventional planar-core coil. The distance between the two coils is 120 mm. Especially, in order to reflect the advantages of the type of pan-shaped coil by contrasting with the conventional planar-core coil, we set the same excitation and use exactly the same cores as that of the conventional planar-core coil. The size of the two cores are 360mm × 360mm × 6mm and 260mm × 260mm × 6mm respectively and the distance between the two coils is 120 mm. We also make the inductance values of the transmitting coil and the receiving coil of the two types of coil structure equal by adjusting the number of turns. The distribution of the magnetic field between the coils and the distribution of the magnetic field in the radial direction of the receiving coil are shown in figures 13 and 14 respectively through performing a magnetic field simulation.

![Figure 14. The distribution of the magnetic field in the radial direction of the receiving coil.](image)

As shown in equation (7), the uniformity factor of the magnetic field between the two coils is 0.365 by calculation. In addition, the coupling coefficient value between the two coils in this coil
structure is 0.19242 by calculation using the simulation software.

\[ \lambda_{U2} = \frac{442.5 - 281.0}{450.1} = 0.365 \]  

(7)

It can be seen that the magnetic field uniformity of the new type of pan-shaped coil is improved obviously. And the coupling coefficient between the two coils is still improved though the amount of core is relatively smaller than the conventional planar-core coil.

We also simulate the magnetic field and calculate the magnetic field uniformity and coupling coefficient when the receiving coil are horizontally misaligned by 5 mm and 10 mm in order to see the effect on the transmission efficiency of the system produced by the new type of pan-shaped coil. The distribution of the magnetic field between the coils and the distribution of the magnetic field in the radial direction of the receiving coil are shown in figures 15 and 16 respectively. The uniformity factors of the magnetic field between the two coils are 0.382 and 0.404 respectively and the coupling coefficients are 0.19194 and 0.19077 respectively. It can be seen that the magnetic field uniformity and the coupling coefficient between the two coils are improved obviously compared with the conventional planar-core coil when the receiving coil is misaligned.

\[ \frac{442.5 - 281.0}{450.1} = 0.365 \]  

Figure 15. The distribution of the magnetic field in the radial direction of the receiving coil when misaligned by 5 mm.

\[ \frac{442.5 - 281.0}{450.1} = 0.365 \]  

Figure 16. The distribution of the magnetic field in the radial direction of the receiving coil when misaligned by 10 mm.

This new type of coil structure is also used in the wireless charging system based on magnetic resonance, of which the resonant compensation structure is series-series. And the effect is analyzed by using Ansoft Maxwell software with the same external circuit according to the schematic diagram shown in figure 3. We obtain the voltage and current waveforms of the transmitting coil and the
receiving coil which are shown in figures 17 and 18 respectively. Then we calculate the transmission power and efficiency of the resonant compensation structure according to equations (4) and (5). By comparison, we found that the power transmission properties of the new type of pan-shaped coil have been greatly improved than the conventional planar-core coil.

![Figure 17. The voltage and current waveforms of the transmitting coil.](image1)

![Figure 18. The voltage and current waveforms of the receiving coil.](image2)

5. Conclusions
This paper proposes a new type of coil structure called pan-shaped coil of wireless charging system based on magnetic resonance which can produce a smooth uniform magnetic field because ripples in the field strength curve along the radial direction can be eliminated by introducing height differences among adjacent turns. The pan-shaped coil can improve the uniformity of the magnetic field between the transmitting coil and the receiving coil and solve the problem that misalignment between the two coils can significantly impair the transmission power and efficiency of the system. In order to reflect the superiority of the pan-shaped coil, this paper also introduces the conventional planar-core coil and simulates the magnetic field of the coil with the receiving coil misaligned or not using the Ansoft Maxwell software. Compared with the simulation results of the two coils, it can be seen that this new type of coil structure can obviously improve the uniformity of the magnetic field, the coupling coefficient and the power transmission properties between the transmitting coil and the receiving coil.

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