Novel square spiral Coil for achieving uniform Distribution of magnetic Field

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Abstract. In view of the problems existing in the existing wireless charging technology, the anti-offset performance of the charging region and the system was studied. A primary transmitting coil capable of achieving uniform magnetic field distribution was proposed. The magnetic field strength at a point on the coil axis and above the coil surface was calculated, and the surface current density of the transmitting coil was analyzed to calculate the radius of each turn of the spiral winding coil. Optimized the structure of the transmitting coil, the number of turns and the arrangement of the coils, A square spiral coil having a size of 20 cm × 20 cm and a number of turns of 11 inches was determined. The optimized square spiral coil was modeled by the software comsol5.3 RF module, and the strength and uniformity of the coil surface and axial space magnetic field were simulated. The axial magnetic field on the surface of the coil was measured by a multi-dimensional visual electromagnetic measuring device, and compared with the simulation data, it was proved that the axial magnetic field of the square spiral coil surface satisfied the uniformity requirement.

1. Introduction

At present, science and technology are developing rapidly, and the charging method of portable electronic devices is gradually developing toward the direction of non-contact charging. Traditional chargers have many unfavorable factors, which seriously affect the portable performance of electronic products. In view of the special scenarios where the power transmission mode has higher requirements such as technical economy, flexibility, security, maintainability, etc. the traditional contact power transmission mode can no longer meet the application requirements. Therefore, wireless energy transfer technology has become a hot research topic in the industry, and has achieved a series of phased results. In portable electronic products, electromagnetic induction wireless charging technology has become more mature, but it still has some problems: During the charging process, the transmitting device and the receiving device must be in close contact with each other. When the transmitting coil and the receiving coil are deviated, the transmission efficiency is drastically reduced, and when there is foreign matter between the primary and secondary coils, eddy current heating occurs. The use of electronic products during charging is greatly limited[10], which greatly increases power consumption compared to wired charging.

Therefore, the wireless energy transmission technology must be truly popularized, and the device to be charged must have a certain range of motion during the charging process, which requires increasing the charging area and improving the anti-offset performance. The most important point to
improve the anti-offset performance is that the vertical component of the magnetic induction generated by the transmitting coil should be distributed as evenly as possible on the surface of the coil[1]. Among them, the design of the transmitting coil structure is proposed in the literature[2], which produces a uniformly distributed magnetic field by the combination of the concentrated coil and the helical coil. The schematic diagram is shown in Figure 1. The specific parameters are: 5 turns of concentrated coil, 4 turns of spiral winding, radius of transmitting coil is 75mm, radius of receiving coil is 15mm[2].

![Figure 1](image_url)

Figure 1. (a) Schematic view of the hybrid structure in a three-dimensional view (b) Cross-sectional view (c) Top view

This transmitting coil structure consists of a hybrid structure of concentrated windings and spiral windings. As shown in Fig. 1, the concentrated winding and the spiral winding coil are coaxially different from each other, and the spiral winding is below the concentrated winding. The coil of the mixed structure is composed of upper and lower parts, which increases the thickness of the longitudinal section of the coil and the construction difficulty, and the charging area is too small, and the circular coil is not convenient for processing and use. On this basis, combining the advantages of the above coils, considering the convenience of actual manufacturing, use and design, this paper proposes a new type of square spiral transmitting coil. The square spiral coil was modeled by the software COMSOL5.3 RF module, and the magnetic field strength and uniformity of the coil surface and axial space were simulated. The axial magnetic field of the coil surface is measured by a multi-dimensional visual electromagnetic measuring device, and compared with the simulation data, it is proved that the axial magnetic field distribution of the square spiral coil surface satisfies the uniformity requirement.

2. Calculation of magnetic field distribution of square spiral coil

The method of optimal hybrid coil design proposed in[2] is to use a concentrated winding coil to mix with a planar spiral winding coil. The coils of these two structures are the most commonly used transmitting coils for wireless energy transmission. Currently, the most used coils are circular coils, but the circular transmitting coils have low basic magnetic flux heights, and the primary and secondary coils are highly dependent on primary and secondary coils. The spacing between the coils and the distance between the centers of the two coils[11], which reduces the distance of electrical energy transmission and the ability to resist deflection. Although conventional circular coils have been shown to produce stronger magnetic field strength than square coils[14], square coils produce a more uniform magnetic field on and around the surface[12]. In this paper, the magnetic field distribution of the surface of the transmitting coil will be studied based on the structure of the square coil. The magnetic field is an important medium for the electrical energy transfer of wireless energy transfer systems. It is important to study the magnetic field distribution on the coil surface[13]. Next, calculate the magnetic field strength generated by the square coil. According to Biot-Savar's law, a magnetic field generated by a straight current carrying wire at a certain point P in space[6] is as shown in Equation (1). A single-turn square coil can be regarded as a four-segment current-carrying straight wire, which can be used for each straight wire. Calculation, vector superposition, can get the general expression of the magnetic field distribution of the square coil[3]-[5].
The magnetic field distribution of the square coil can be solved by the formula (1).

In the formula (1), \( \mu_0 = 4\pi \times 10^{-7} \text{ N} \cdot \text{A}^{-2} \) is the vacuum permeability, \( I \) is the current intensity, and \( d \) is the distance from the point \( P \) to the wire. \( \theta_1, \theta_2 \) is the angle between the ends of the wire and the point \( P \). The magnetic field distribution of the square coil can be solved by the formula (1).

\[
B = \frac{\mu_0 I}{4\pi d} \left( \cos \theta_1 - \cos \theta_2 \right) \quad (1)
\]

2.1 Calculation of magnetic field strength on the central axis of a square spiral coil
The center of the square coil is the coordinate origin, and the \( x \)-axis, \( y \)-axis, and \( z \)-axis are respectively shown in Figure 2. The side length is \( 2l \), and the magnetic current intensity generated by the AB-side current at point \( P \)[7]

\[
d = \sqrt{l^2 + z^2} \quad (2)
\]

\[
\cos \theta_1 = \cos \angle PAQ = \frac{QA}{PA} = \frac{l}{\sqrt{2l^2 + z^2}} \quad (3)
\]

\[
\cos \theta_2 = -\cos \angle PBQ = \frac{QB}{PB} = -\frac{l}{\sqrt{2l^2 + z^2}} \quad (4)
\]

\[
B_{AB} = \frac{\mu_0 I}{4\pi \sqrt{l^2 + z^2}} \left( \frac{l}{\sqrt{2l^2 + z^2}} + \frac{l}{\sqrt{2l^2 + z^2}} \right) = \frac{2\mu_0 Il}{4\pi \sqrt{l^2 + z^2} \sqrt{2l^2 + z^2}} \quad (5)
\]

![Figure 2. Square single turn coil](image)

The four sides of the square coil \( B_{BC} = B_{CD} = B_{DA} = B_{AB} \), \( B_{AB} \) and \( B_{CD} \), \( B_{BC} \) and \( B_{DA} \) are respectively symmetric about the \( z \)-axis, canceling each other out of the component perpendicular to the \( z \)-axis, and the components along the \( z \)-axis are superimposed on each other:

\[
B = 4B_{AB} \cos \angle PQO = \frac{2\mu_0 I l^2}{\pi \left(l^2 + z^2\right) \sqrt{2l^2 + z^2}} \quad (6)
\]

The magnetic induction produced by the coil at a point above the central axis is equal to:

\[
B_i = \frac{2\mu_0 I l^2}{\pi \left[l^2 + (a + z)^2\right] \sqrt{2l^2 + (a + z)^2}} \quad (7)
\]

2.2 Calculation of spatial magnetic field strength of square spiral coil
Spatial magnetic field analysis of a single-turn square coil:
As shown in Fig. 3, let the point $P(x, y, z)$ be in the positive direction of the $x$, $y$ and $z$ axes, and the magnetic field strength derived from the AB edge at point $P$ be calculated as follows:

$$d = PQ = \sqrt{(l-x)^2 + z^2}$$  \hspace{1cm} (8)

$$\cos \theta_1 = \cos \angle PAB = \frac{PQ}{AQ} = \frac{l+y}{\sqrt{(l-x)^2 + (l-y)^2 + z^2}}$$  \hspace{1cm} (9)

$$\cos \theta_2 = -\cos \angle PBQ = \frac{BQ}{BP} = -\frac{l-y}{\sqrt{(l-x)^2 + (l-y)^2 + z^2}}$$  \hspace{1cm} (10)

Putting the above three formulas into the formula (1), to give:

$$B_{AB} = \frac{\mu_0 I}{4\pi \sqrt{(l-x)^2 + z^2}} \left[ \frac{l+y}{\sqrt{(l-x)^2 + (l+y)^2 + z^2}} + \frac{l-y}{(l-x)^2 + (l-y)^2 + z^2} \right]$$  \hspace{1cm} (11)

Approximately think that $B_{AB}$ is perpendicular to PQ, that is, $B_{AB}$ is in the plane perpendicular to the $y$-axis, and the angle with the $x$-axis is $\angle QPS$; the angle with the $z$-axis is $\angle PQS$, and the expression of the three components of $B_{AB}$ can be obtained[3]:

$$B_{ABx} = B_{AB} \cos \angle QPS = B_{AB} \frac{PS}{PQ} = B_{AB} \frac{z}{\sqrt{(l-x)^2 + z^2}} = \frac{\mu_0 I_z}{4\pi \sqrt{(l-x)^2 + z^2}}$$  \hspace{1cm} (12)

$$= \frac{\mu_0 I_z}{4\pi \left( (l-x)^2 + z^2 \right)} \left[ \frac{l+y}{\sqrt{(l-x)^2 + (l+y)^2 + z^2}} + \frac{l-y}{(l-x)^2 + (l-y)^2 + z^2} \right]$$

$$B_{ABx} = B_{AB} \cos \left( \frac{\pi}{2} \right) = 0$$  \hspace{1cm} (13)

$$B_{ABz} = B_{AB} \cos \angle PQS = B_{AB} \frac{SQ}{PQ} = B_{AB} \frac{1-x}{\sqrt{(l-x)^2 + z^2}}$$  \hspace{1cm} \hspace{1cm} \hspace{1cm} (14)

Similarly, due to the symmetry of the square coil, at any point on the non-axis, the two current-carrying lines produce partially canceled magnetic field components $B_x$, $B_y$, which are almost negligible compared to $B_z$[8]. Only the axial magnetic field $B_z$ can be discussed. The magnetic field strength generated by the four current-carrying straight wires is vector superimposed, and the magnetic induction $B_z$ generated by the single-turn coil at the $P$-point is obtained as follows:
Through the above analysis, the intensity of the magnetic field generated at a point above the surface of the single-turn coil can be calculated, and the spatial distribution of the magnetic field can be understood. It is found through experiments that the more coil turns, the larger the self-inductance coefficient of the coil. At this time, there will be a small series capacitance value, and the component parameters will have a serious impact on the system. Therefore, the number of coil turns should not be too much, and through experimental and theoretical analysis, when the number of turns of the spiral winding is equal to the number of turns of the concentrated winding, the magnetic field strength generated by the coil is the strongest. The more turns of the spiral winding, the stronger the coupling degree, the higher the efficiency of wireless energy transfer. Therefore, the concentrated winding is taken as 5 turns.

The most important point to improve the anti-offset capability is that the coil surface has an axial component of uniformly distributed magnetic induction. By discretizing the current density of the continuous distribution, the current distribution is approximated by a finite number of coils of the same current with different radii. Assume that the equivalent current distribution of the \( N \)-turn coil is used. We divide the area under the current density curve into \( N \) equal parts, and a coil replaces each aliquot. The coefficient \( k \ (0 \leq k \leq 1) \) determines the position at which the aliquot is placed, when \( k=1 \), the turns coil is placed at the right end of the replaced part, \( k=0 \), placed at the left end. The expression for obtaining the radius of the \( n \)th coil is:

\[
f_n = k \sqrt{1 - \left( \frac{N-n}{N} \right)^2} + (1-k) \sqrt{1 - \left( \frac{N-n+1}{N} \right)^2}
\]

By adjusting the value of \( k \), the distribution of the axial component of the magnetic induction intensity of the square spiral coil surface is more uniform, and the coefficient of variation of the vertical component of the magnetic induction intensity (standard deviation divided by the mean value) is taken as the objective function to minimize it, and the determination of \( k \) can be determined. The value, from which the radius of the spiral winding coil can be calculated, resulting in a new square spiral coil. The coil comprises two structures: a concentrated winding and a spiral winding. The two structures are on the same plane and are wound by a complete Litz wire. The "concave" magnetic field distribution produced by the square concentrated coils can be compensated for by the "convex" magnetic field distribution produced by the square planar spiral windings. By designing and optimizing parameters such as the number of turns and dimensions of the spiral winding, a more uniform magnetic flux distribution can be achieved. The final complete coil adopts 11-inch coil.
structure, the outer 5 turns coils are tightly combined, the middle 6-turn coils form a spiral type, the four corners of each turn coil are angled, and the progressively dense and tapered structure is extracted from the center (This structure has been patented). Figure 4 shows the final coil structure with a total number of turns of 11.

Figure 4. Space diagram of square spiral coil

The four corners adopt a folding structure to reduce the influence of the four-corner mutation and prolong the service life of the wire. In order to calculate the simplification, the corner of the wire is approximated as a straight wire for calculation. The side length of the concentrated winding is 2l, the current is I, and the midpoint of the central axis of the coil is taken as the coordinate origin. Calculate the axial magnetic field strength at a point above the surface of the square coil, and find the induction intensity Bz generated by the single square current-carrying coil as the formula (15).

The square spiral coil has 5 turns concentrated windings, each side is equal in length, and the current in the same direction is passed, ignoring the influence of the magnetic field between the wires, that is, 5 times Bz. The magnetic field strength of the middle square spiral winding needs to calculate the magnetic field strength of each winding separately. It can be obtained by simply substituting the side length of each turn into the formula (15) and then superimposing it on the vector. Since the formula is too long, it will not be described again. It is assumed that the distribution of the magnetic field of the coil surface is uniform, that is, the axial magnetic induction at a certain point can be approximated as the axial magnetic induction of the entire coil surface. Therefore, taking the point (0,0,0), the magnetic field strength of the single-turn square coil at this point can be obtained by the formula (17):

\[ B_z = \frac{\mu_0 I}{\pi} \left( \frac{1}{\sqrt{2}} + \frac{1}{2} \right) \]  

(17)

Let the side length of each spiral winding be equal to 2l1, 2l2, ..., 2l6, and the concentrated winding is 2l, and the electromagnetic induction intensity B_{z0} of the 11-turn square spiral coil at (0, 0, 0) is

\[ B_{z0} = 5 \frac{\mu_0 I}{\pi} \left( \frac{1}{\sqrt{2}} + \frac{1}{2} l_1 \right) + \frac{\mu_0 I}{\pi} \left( \frac{1}{\sqrt{2}} + \frac{1}{2} l_2 \right) + \frac{\mu_0 I}{\pi} \left( \frac{1}{\sqrt{2}} + \frac{1}{2} l_3 \right) + \ldots + \frac{\mu_0 I}{\pi} \left( \frac{1}{\sqrt{2}} + \frac{1}{2} l_6 \right) \]  

(18)

This method (due to the complexity of the formula, no longer calculated here) combined with the coil system modeling and simulation analysis, optimize the coil parameters, can design the coil for specific magnetic field strength requirements, coil side length and space area. Next, the uniformity of the axial magnetic field distribution on the coil surface is analyzed by simulation.

3. Modeling and Simulation Analysis of Square Spiral Coil System

After the above theoretical analysis, the electromagnetic spiral simulation software COMSOL5.3 is used to simulate the square spiral coil proposed in this paper, in which the excitation voltage is 100V and the frequency is 2MHz.

Figure 5 shows the simulation results. In a, it can be seen that the uniformity of the magnetic field distribution is good during the horizontal change of 1 cm above the surface of the coil, and there is only a slight depression at the center point of the coil.

However, there is only a slight difference in the flux density values from other points. The magnetic flux density mode of the coil surface is shown in Figure b, and it can be clearly seen that the
magnetic flux density of the surface of the coil is substantially uniform. The position where the excitation is added causes the peak in the lower right corner, and the peak at the corner of the coil is attributed to the superposition effect of the field, and the edge effect causes a significant drop in the magnetic field at the edge of the coil.

Figure 5. (a) Magnetic flux density mode curve (b) Coil surface magnetic flux density mode (c) Magnetic flux density mode at 1.5 cm above coil surface (d) Coil cross section Magnetic flux density mode

4. Measuring device measures the axial magnetic field on the coil surface

The square spiral coil is hand-wound by the Litz wire to reduce the resistance loss due to proximity and skin effects[9]. Figure 6 shows a picture of the test device. The magnetic induction of the axial direction of the coil surface is measured by a multidimensional visual measuring device.
In Figure 6, a is a measuring station of the multi-dimensional visual measuring device, and b is a control device. Figure 8 is a physical diagram of the coil, measured from the center of the left end of the coil as the starting point, from left to right, measured in a straight line perpendicular to the direction of the left end of the wire. In order to avoid the human error during production and the error caused by the measurement of the equipment, this paper makes a plurality of square spiral coils, one by one, and selects the coil with more uniform surface magnetic field distribution. In this experiment, a total of 12 square spiral coils were fabricated. After measurement, nine better quality coils were selected to construct a wireless charging launch platform. Figure 7 shows the actual winding of the coil, which is first measured with a field probe. When the current is 1A, Figure 8 is obtained.

As can be seen from Figure 6, the scan results of the magnetic field distribution are consistent with the simulation results. In order to make the results more intuitive, a multi-dimensional visual electromagnetic measuring device is used to perform one-dimensional scanning on the wound coil surface. In Figure 7, the center position of the left end of the coil is taken as the starting point. From left to right, the magnetic field strength is measured along a straight line perpendicular to the direction of the left end wire. Figure 9 shows the magnetic induction measurement curves of multiple coils.
Figure 9. Magnetic induction measurement curve of multiple coils

In Figure 9, 12 square spiral coils are numbered 1-12, and the measurement results of the magnetic intensities of the 12 coil surfaces are shown in the figure. Where a is the measurement result of the first 6 coils, b is the measurement result of the last 6 coils, and c is the measurement curve of 12 coils. Since the coil edge has a large error during the measurement process, the data portion corresponding to the offset of 2.2 cm-17.8 cm is selected, and the surface magnetic induction intensity distribution of most coils is uniform. Among them, only the measurement data of No. 6, No. 10 and No. 12 coils are quite different.

The experimental data obtained by the experimental instrument is basically consistent with the simulation results. Considering the influence of human measurement error and many interference factors in the laboratory, the error is also within a reasonable range.

5. Conclusion

This paper analyzes the problems existing in the existing wireless charging technology, focusing on the problem that the charging area is small and the primary and secondary coils have poor anti-offset capability. Firstly, the magnetic field strength formula on the axis of the square coil and at a certain point in the space is calculated and inferred. The spatial distribution of the magnetic field is obtained, and the coil parameters are optimized to obtain a new coil structure. The flux density mode on different sections was simulated by COMSOL5.3 simulation, and the distribution of magnetic field uniformity on the surface of the coil was visually depicted. The axial magnetic field uniformity of the new coil surface was demonstrated. The simulation analysis data is basically consistent with the experimental measurement results. It proves that the surface of the square spiral coil has a uniform axial magnetic field distribution, which increases the area of the charging area and improves the anti-offset capability of the system during charging. Uniform power delivery can be achieved without changing the receiving efficiency due to the placement position of the receiving device.

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