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Analysis of Magnetic Field in Wireless Charging System of Electric Vehicle

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Abstract: In this paper, the structure and working principle of the magnetically coupled resonant radio energy transmission system for electric vehicle are briefly introduced. Then, according to Biot-Savart Law, the magnetic field generated by the energy emission coil in the wireless charging system is deduced, analyzed and calculated in detail. Finally, the distribution of the magnetic field intensity generated by the emission coil is obtained. This provides a theoretical reference for the positioning requirements between the transmission coil and the receiving coil in the wireless charging system of EV.

1. Introduction

Electric vehicle wireless charging technology is to transmit electric energy in the form of high-frequency alternating magnetic field to the electric energy pickup mechanism at the receiving end of the vehicle running on the ground within a certain range through the electric energy transmitting coil buried or installed on the ground, so as to supply power to the on-board energy storage equipment

The common form of electric vehicle wireless charging system is magnetic coupling resonance wireless power transmission system (Abbreviated as MCR-WPT). The overall system composition is shown in Figure 1. The working principle of the system: The system consists of rectifier filter circuit, high frequency inverter circuit, drive circuit, control circuit, signal feedback mutual inductor, resonant capacitor, transmission coil, receiving coil, high frequency rectifier and load, which converts municipal power into direct current. Among them, 220 V municipal power input is filtered by rectifier to get DC voltage, and then the full bridge inverting circuit is used to provide specific frequency AC for the launch coil. The launch coil and the receive coil form two LC resonant circuits with the resonant capacitance, respectively. By designing the physical parameters and the resonant capacitance values of the two coils, the inherent frequency of the two coils equals the operating frequency of the system, and the system works in a resonant state. Magnetic field coupling resonance occurs between the transmitting coil and the receiving coil, which generates a high frequency alternating magnetic field. The alternating magnetic field radiates to the receiving coil, which generates an inductive current and enables wireless transmission of energy[2].

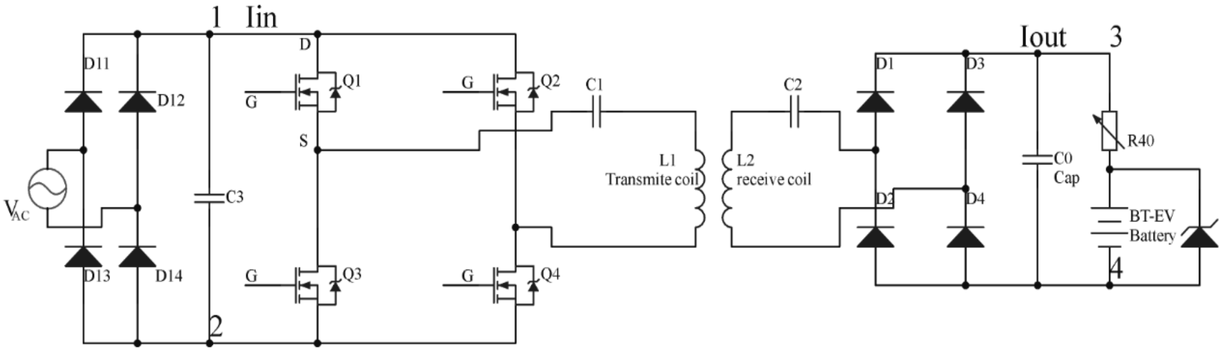

Figure 1: MCR-WPT System Component Circuit Diagram

In this MCR-WPT system, the emitter coil is installed on the ground floor, and the receiver coil is installed on the chassis of the electric vehicle. From the working principle, the energy transmission performance of the wireless charging system is very sensitive to the position relationship between the emitter coil and the receiver coil. So what relative position should be between the emitter coil and the receiver coil to achieve the maximum efficiency of the wireless transmission of energy? To solve this problem, first of all, the distribution of the electromagnetic field formed by the coil is analyzed.

2. Math model of magnetic field in rectangular power-on coil

As shown in the figure, according to formula (1), Biot Savart law, through geometric analysis and mathematical operation, as shown in figure 2, the magnetic induction intensity generated by a section of current carrying straight wire CD at any point P (x, y, z) in its magnetic field space is as shown in formula (2).

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l}\times\hat{r}}{r^2} \tag{1}$$

$$B = \frac{\mu_0 I}{4\pi r}(\cos\alpha_1 - \cos a_2) \tag{2}$$

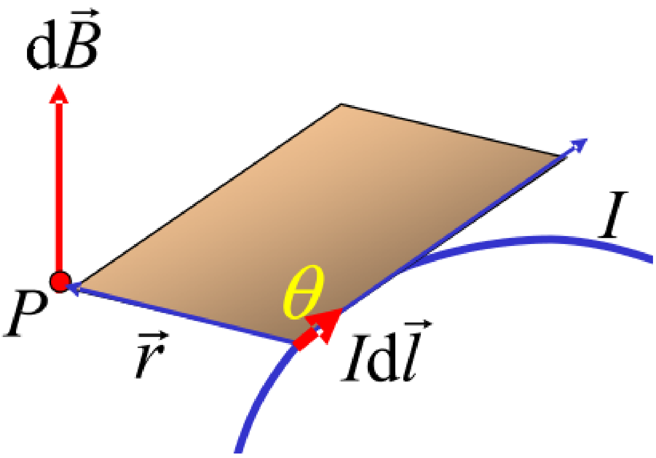

Figure 2: Schematic diagram of magnetic induction intensity generated by current carrying straight wire at any point in space

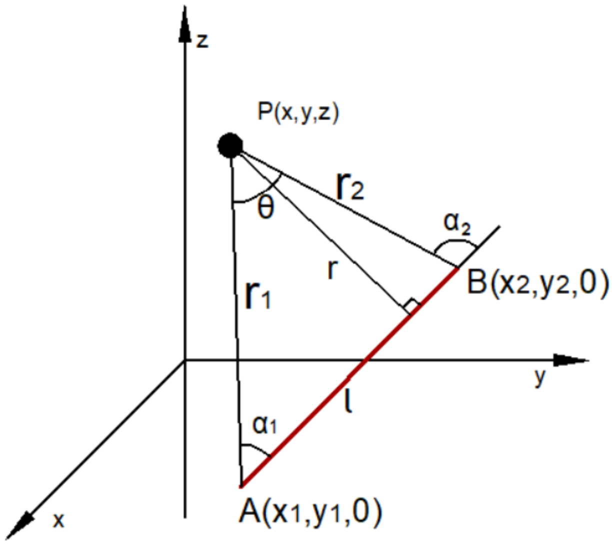

Figure 3: Analysis diagram of magnetic induction intensity at point P

Where, the length of current carrying conductor AB is LFigure 3, and the vectors from point P to both ends of conductor A, B are R1 and R2 respectively; The direction of magnetic induction intensity at point P and R1 × The direction of R2 is the same, that is, the direction conforms to the right-hand rule of multiplying two vectors.

After mathematical calculation, three components of magnetic induction intensity at point P in X, y and Z directions can be obtained[1]:

$$B_x = \frac{\mu_0 Iz(y_2 - y_1)}{4\pi R}(\frac{D_1}{r_1} + \frac{D_2}{r_2}) \tag{3}$$

$$B_y = \frac{\mu_0 Iz(x_1 - x_2)}{4\pi R}(\frac{D_1}{r_1} + \frac{D_2}{r_2}) \tag{4}$$

$$B_z = \frac{\mu_0 I(x_1 y_2 - x_2 y_1 + x y_1 - x_1 y + x_2 y - x y_2)}{4\pi R}(\frac{D_1}{r_1} + \frac{D_2}{r_2}) \tag{5}$$

Where, R, D1 and D2 are respectively calculated by the following formula:

$$R = \left[(x_1 - x_2)^2 + (y_1 - y_2)^2\right]z^2 + [(y_1 - y_2)x - (x_1 - x_2)y + (x_1 y_2 - x_2 y_1)]^2$$

$$D_1 = \left[(x_1^2 + y_1^2) - (x_1 - x_2)x - (y_1 - y_2)y - (x_1 x_2 + y_1 y_2)\right]$$

$$D_2 = \left[(x_2^2 + y_2^2) - (x_2 - x_1)x - (y_2 - y_1)y - (x_1 x_2 + y_1 y_2)\right]$$

For the rectangular coil, as shown in Figure 4, the current carrying rectangular coil with length a and width B can be regarded as the vector superposition of the magnetic field generated by four sections of wires. The component Bz of the magnetic induction intensity generated by any point P (x, y, z) in the magnetic field space in the Z direction is expressed as[1]:

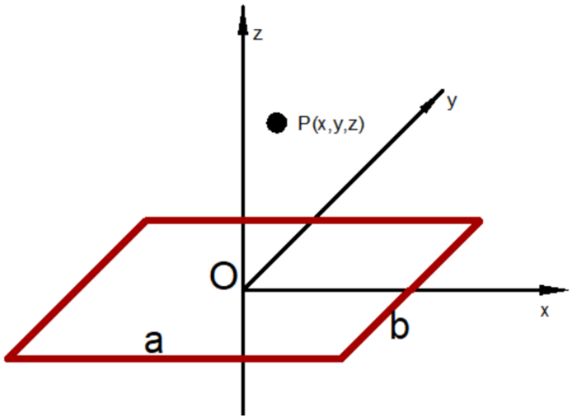

Figure 4: Schematic diagram of magnetic induction intensity of rectangular energized wire at point P in space

$$\begin{aligned} B_z = & \frac{\mu_0 I(b-y)}{4\pi\left[z^2+(b-y)^2\right]}\left(\frac{a-x}{\sqrt{(x-a)^2+(y-b)^2+z^2}}+\frac{a+x}{\sqrt{(x+a)^2+(y-b)^2+z^2}}\right) \\ & +\frac{\mu_0 I(a+x)}{\pi\left[z^2+(a+x)^2\right]}\left(\frac{b-y}{\sqrt{(x+a)^2+(y-b)^2+z^2}}+\frac{b+y}{\sqrt{(x+a)^2+(y+b)^2+z^2}}\right) \\ & +\frac{\mu_0 I(b+y)}{\pi\left[z^2+(b+y)^2\right]}\left(\frac{a+x}{\sqrt{(x+a)^2+(y+b)^2+z^2}} \frac{a-x}{\sqrt{(x-a)^2+(y+b)^2+z^2}}\right) \\ & +\frac{\mu_0 I(a-x)}{\pi\left[z^2+(a-x)^2\right]}\left(\frac{b+y}{\sqrt{(x-a)^2+(y+b)^2+z^2}}+\frac{b-y}{\sqrt{(x-a)^2+(y-b)^2+z^2}}\right) \end{aligned} \quad (6)$$

Where, μ_0 is the permeability in vacuum, $\mu_0=4\pi\times10^{-7}$, unit: T.m/A;

The permeability in the air is close to the vacuum permeability, and the vacuum permeability can often be directly used in the calculation[3];

I is the current intensity passing through the coil, unit A;

a. b is the length and width of the coil, unit M;

B_z is the magnetic induction intensity of point P in space in the Z direction, unit T;

3. Math model of magnetic field for Transmitting coil in WPT system

The electric vehicle wireless charging system studied in this paper is MCR-WPT system. The magnetic coupling resonance mechanism of the system is mainly composed of transmitting coil and receiving coil. The transmitting coil generates magnetic field under the action of exciting current, and the receiving coil generates induced electromotive force under the action of changing magnetic field.

The induced electromotive force in the receiving coil is directly proportional to the excitation frequency of the transmitting coil signal source, inversely proportional to the square of the distance between the two coils, and directly proportional to the effective magnetic induction acting on the receiving coil[4]

The transmitting coil is installed on the ground and the receiving coil is installed under the vehicle chassis. When working, the two are approximately parallel; According to the principle of induced electromotive force generation, only the component Bz perpendicular to the plane of the receiving coil can form the effective magnetic flux。

The shape of the coil is similar to that of the rectangular coilFigure 5[1], which is designed by the circumference of the coil 8, as shown in the reference figure 650×500mm, inner space size is about

350 × 200mm, the average width of each week is about 37.5mm (0.0375m). It is equivalent to the magnetic field formed by vector superposition in space of 8 rectangular coils of different sizes passing through the same current. The coil is wound in two wires, and the two wires jointly undertake the current intensity. In order to facilitate calculation, it can be regarded as a single wire and calculated by taking the total current intensity.

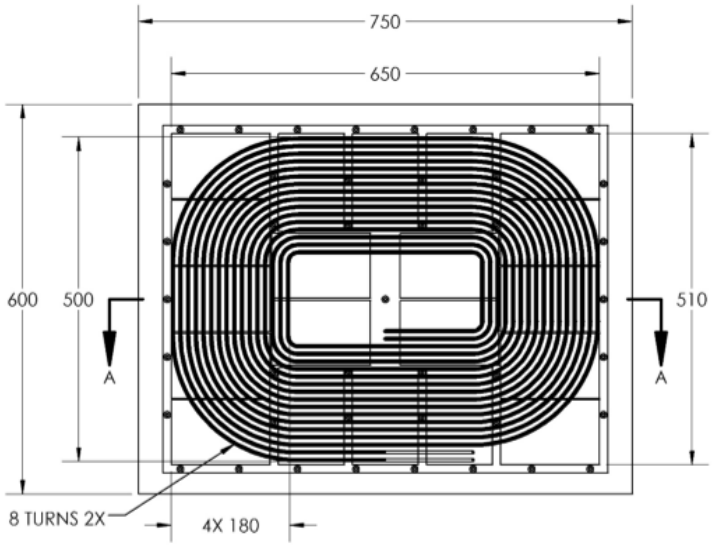

Figure 5: Planar graph of transmitting coil

According to the calculation method of the magnetic induction intensity of the rectangular coil described in the previous section, the calculation formula of the magnetic induction intensity component Bz generated in space by the WPT transmitting coil wound with 8 turns in the above figure is as follows:

$$\begin{aligned} B_z = \sum_{i=0}^{7}\{ & \frac{\mu_0 I((b-gi)-y)}{4\pi\left[z^2+((b-gi)-y)^2\right]}\left(\frac{(a-gi)-x}{\sqrt{(x-(a-gi))^2+(y-(b-gi))^2+z^2}}+\frac{a-gi+x}{\sqrt{(x+(a-gi))^2+(y-(b-gi))^2+z^2}}\right) \\ & +\frac{\mu_0 I(a-gi+x)}{\pi\left[z^2+(a-gi+x)^2\right]}\left(\frac{b-gi-y}{\sqrt{(x+a-gi)^2+(y-(b-gi))^2+z^2}}+\frac{b-gi+y}{\sqrt{(x+a-gi)^2+(y+b-gi)^2+z^2}}\right) \\ & +\frac{\mu_0 I(b-gi+y)}{\pi\left[z^2+(b-gi+y)^2\right]}\left(\frac{a-gi+x}{\sqrt{(x+a-gi)^2+(y+b-gi)^2+z^2}}\frac{a-gi-x}{\sqrt{(x-(a-gi))^2+(y+b-gi)^2+z^2}}\right) \\ & +\frac{\mu_0 I(a-gi-x)}{\pi\left[z^2+(a-gi-x)^2\right]}\left(\frac{b-gi+y}{\sqrt{(x-(a-gi))^2+(y+b-gi)^2+z^2}}+\frac{b-gi-y}{\sqrt{(x-(a-gi))^2+(y-(b-gi))^2+z^2}}\right)\} \end{aligned} \tag{7}$$

Where, μ_0 is the permeability in vacuum, $\mu_0=4\pi\times10^{-7}$, unit: T.m/A;

The permeability in air is close to vacuum permeability, so vacuum permeability can be directly used in calculation;

I is the current intensity passing through the coil, unit A;

a, b is the length and width of the coil, unit metre; In this paper, 0.65m and 0.50m are taken respectively;

g is the average line width of each cycle of the coil, taken as 0.0375m in this paper;

i is the cumulative ordinal number; Initial value i=0,i=i+1<=7;

B_z is the magnetic induction intensity of point P in space in the Z direction, unit T;

4. Magnetic field distribution diagram for Transmitting coil in WPT system

For the positioning research of WPT, we focus on the spatial distribution of the effective magnetic induction component Bz of the magnetic field generated by the transmitting coil.

If 20A current is applied to the coil, according to Figure 5, a specific value can be calculated for the magnetic induction intensity of any point P in the magnetic field space. In order to easily estimate the magnetic field distribution generated by the transmitting coil and better find the best position of the receiving coil, in this paper, the distribution of magnetic induction intensity in several planes parallel to the transmitting coil is drawn by using the computer programming language Python and referring to Figure 5.

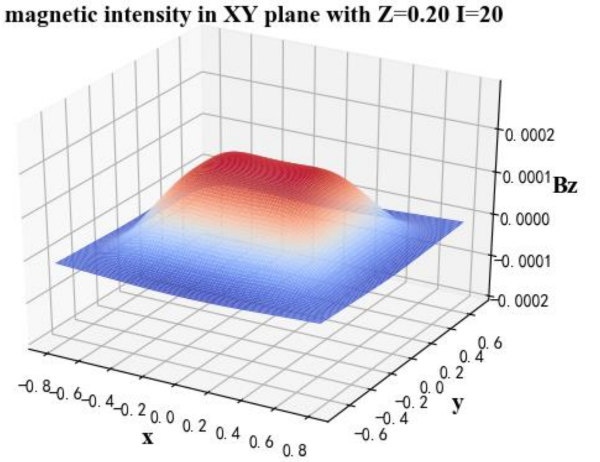

Figure 6: Scatter diagram for magnetic intensity in XYplane with Z=0.20 I=20

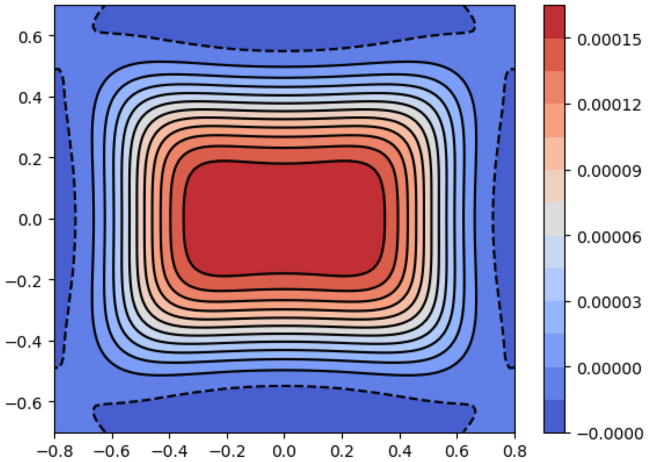

Figure 7: Figure 6 corresponding contour map

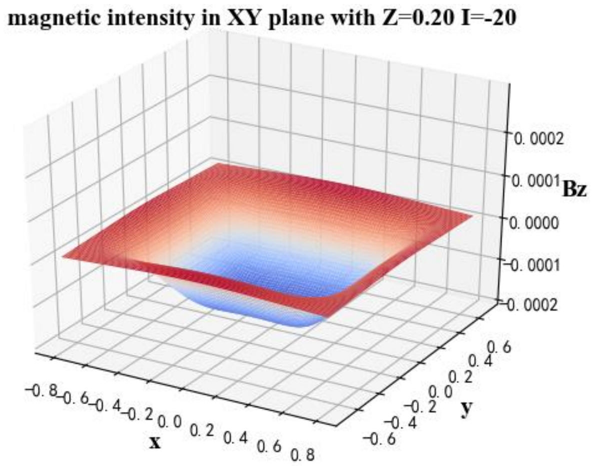

Figure 8: Scatter diagram for magnetic intensity in XYplane with Z=0.20 I=-20

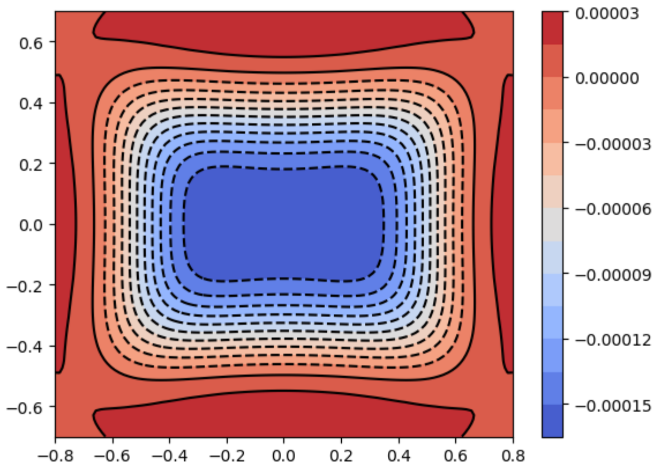

Figure 9: Figure 8 corresponding contour map

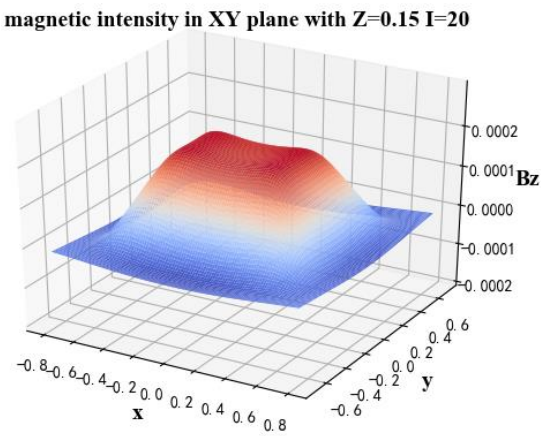

Figure 10: Scatter diagram for magnetic intensity in XYplane with Z=0.15 I=20

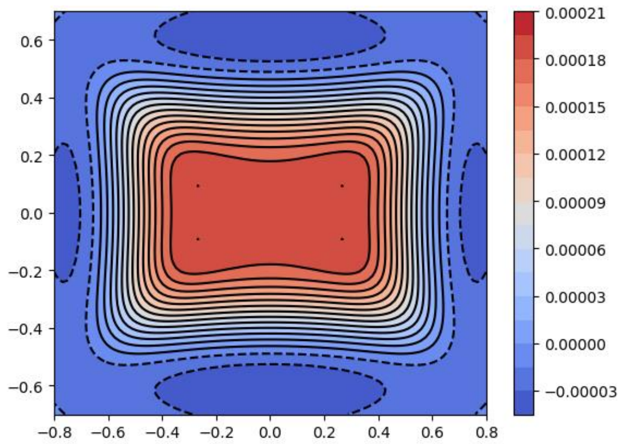

Figure 11: Figure 10 corresponding contour map

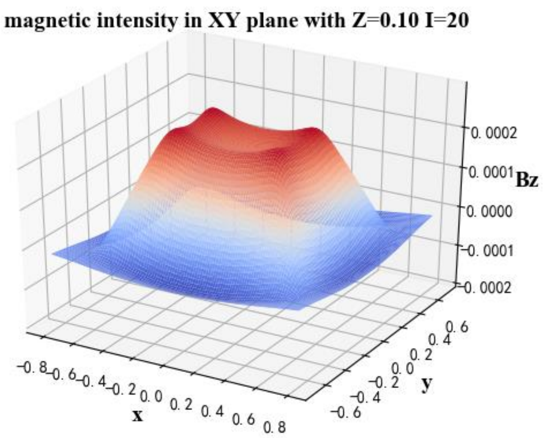

Figure 12: Scatter diagram for magnetic intensity in XYplane with Z=0.10 I=20

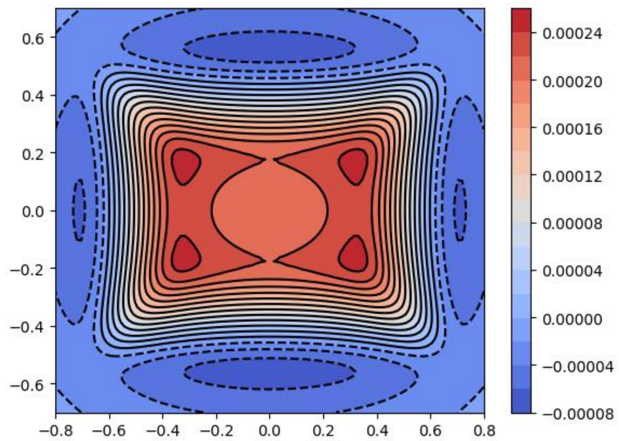

Figure13: Figure 12 corresponding contour map

As shown in Figure 6, Figure 7 is the distribution diagram of the effective magnetic induction intensity Bz in the XY plane directly above 20cm from the transmitting coil and parallel to the transmitting coil when the transmitting coil is led to 20A forward current;

As shown in Figure 8, Figure 9 is the distribution diagram of the effective magnetic induction intensity Bz in the XY plane directly above 20cm from the transmitting coil and parallel to the transmitting coil when the transmitting coil is led to - 20A reverse current;

As shown inFigure 10, Figure 11 is the distribution diagram of the effective magnetic induction intensity Bz in the XY plane directly above and parallel to the transmitting coil when the transmitting coil is connected to 20A forward current;

As shown in Figure 12, Figure13 is the distribution diagram of the effective magnetic induction intensity Bz in the XY plane directly above and parallel to the transmitting coil when the transmitting coil is connected to 20A forward current;

5. Conclusions

From the analysis of the above figures, it can be seen that the effective magnetic induction intensity Bz is mainly distributed directly above the transmitting coil, and Bz decreases rapidly outside the area deviated from the upper part of the opening; When a reverse current is applied to the transmitting coil, the direction of Bz is also opposite; When the distance between the receiving coil and the transmitting coil approaches from 20cm to 15cm and 10cm, the size of Bz increases rapidly, but the uniformity of effective magnetic induction intensity distribution on the same plane decreases.

By analyzing the distribution of effective magnetic induction Bz in space, it can be estimated that the receiving coil of WPT system should be positioned directly above the transmitting coil and coaxial with the center line of the transmitting coil, so as to receive the maximum effective magnetic flux; At the same time, the closer the receiving coil is to the transmitting coil, the greater the effective magnetic induction Bz is. The research on the spatial distribution of effective magnetic induction intensity Bz provides a theoretical basis for the design of WPT system positioning.

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Research project

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(2) Research results of the high-level innovation team of new energy automotive electronics technology in Guangxi Electrical Polytechnic Institute, No. GEPI [2020] 268

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