Three-dimensional multidirectional inductance coil owning environmental conformal feature for wireless power transfer

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Abstract: For wireless power transfer (WPT) application with multi-load or multi-repeater, the system must need some inductance coil possessing the characteristic of transmitting power to multiple directions. This paper proposes a novel three-dimensional hexagon coil with simple structure, which is fabricated conveniently and easy to conformal with surrounding environment. The formula to calculate self- and mutual-inductances for the coil are given with the direction feature also introduced. Furthermore, numerical simulations and experimental results show mutual inductance is very stable in a wide scope of direction angle, to be applied in WPT with multidirectional transmission characteristics.

Keywords: wireless power transfer, multi-directional, environmental conformal, mutual inductance

Classification: Electron devices, circuits, and systems

References

1 Introduction

Magnetically-coupled resonant wireless power transfer (referred to MCR-WPT as below) has attracted a great attention because it’s safe, clean and convenient; it has been applied broadly in variety of applications such as wireless sensor networks [1], human implantable medical devices [2, 3], RFID tag [4], no-tail TV [5], mobile phone [6] and electric vehicle [7, 8]. In recent years, MCR-WPT applications with multiple loads [9, 10] have gradually become a new research hotspot. The inductive coil, usually a plane round or square hollow structure, presents strong directivity so that the transmission efficiency is sensitive to the relative position and direction between transmitting and receiving coils. A multi-directional or omni-directional WPT system can simultaneously supply power to multiple loads in different directions, which requires the coil with the almost same magnetic strength in a plurality of different directions. In [11], the system transmission performance is almost irrelevant to direction by utilizing three mutually orthogonal circular coils and power supplies of the same frequency source with 90 degrees of phase difference. However, the composite coil is required to be wrapped around a spherical structure, which is hard to be conformal with surrounding environment with occupying additional room, and the power circuit is complex because of two or three sources with accurate 90 degrees of phase difference required. However, in most WPT applications with multi-load, it is not essential for the omni-directional coil but the coil irrelevant to most directions to be utilized. This paper proposes a three-dimensional inductance coil with the virtues of simple structure and easy to implement [12], this patent-pending structure is easy to be conformal with surrounding environment (such as the table angles, the wall corners in a room), and its mutual inductance with plane circular or square coil varies little in a large range of the azimuth angle. The structure and the formula to calculate the self-inductance of the 3D coil are presented, and then the directional characteristic is illuminated. Finally, the directional characteristics of the 3D coil are verified by numerical calculations and experiments, and the results of numerical calculation are in good agreement with the experimental results.
2 The structure and self-inductance of the proposed 3D coil

The structure of the proposed two-turn 3D coil is shown in Fig. 1, which is fabricated by enameled copper wire wrapped along the six edges of a cube of side length \( l \). For an N-turn 3D coil, the self-inductance can be derived by Neumann [13] formula as Eq. (1):

\[
L = \frac{3N^2\mu_0}{\pi} \left[ \ln\left(\frac{2l}{a}\right) - 1.341 \right]
\] (1)

where \( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \), \( l \) is the side length of the 3D coil and \( a \) is the radius of the copper wire as well.

![Fig. 1. The structure of the proposed 3D coil](image1)

![Fig. 2. The 3D coil can be regarded as the superposition of six plane square coils](image2)

![Fig. 3. The simulated magnetic strength distribution](image3)
Taking the 3D coil of one turn as an example, the magnetic field around the 3D coil with a current \( i \) flowing on the coil can be regarded as the superposition of the magnetic fields generated by the six plane square coils of side length \( l \) with the currents \( 0.5i \) as shown in Fig. 2. The magnetic strength distribution for the 3D coil is simulated by Maxwell3D software and shown in Fig. 3.

### 3 Transmission characteristics of the 3D coil

A testing square coil of one turn is placed coaxially in parallel with some face of the 3D coil of one turn, as shown in Fig. 4. According to the equivalence illuminated in Fig. 2, it is easy to discern the mutual inductance between the square coil and loop 1 as well as that between the square coil and loop 2 are of the same values and the contrary signs, as well as the square coil with loop 3 and 4, thus \( M \) the mutual inductance of the square coil and the proposed 3D coil is equivalent to a half of the sum of the mutual inductances of the square coil with loop 5 and 6. Therefore, when the square coil and the 3D coil are placed equidistantly, the mutual inductances in the six directions (above, below, left, right, front and back) are essentially the same and can be derived according to [14] as Eq. (2):

\[
M = \frac{\mu_0}{4\pi} \left[ 2\sqrt{2b^2 + 4d^2} - 4bl - 4dl + 3l^2 + 2\sqrt{2b^2 + 4d^2} + 4bl - 4dl + 3l^2 \
+ 2\sqrt{2b^2 + 4d^2} - 4bl + 4dl + 3l^2 + 2\sqrt{2b^2 + 4d^2} + 4bl + 4dl + 3l^2 \
- 4\sqrt{2b^2 + 4d^2} - 4dl + 3l^2 - 4\sqrt{2b^2 + 4d^2} + 4dl + 3l^2 \
+ (b + l)\ln \left( \frac{\sqrt{2b^2 + 4d^2} - 4dl + 3l^2 + b + l}{\sqrt{2b^2 + 4d^2} - 4dl + 3l^2 - b - l} \right) + (b - l)\ln \left( \frac{\sqrt{2b^2 + 4d^2} + 4bl + 3l^2 + b + l}{\sqrt{2b^2 + 4d^2} + 4bl + 3l^2 - b - l} \right) \
+ (b + l)\ln \left( \frac{\sqrt{2b^2 + 4d^2} + 4bl - 4dl + 3l^2 + b - l}{\sqrt{2b^2 + 4d^2} + 4bl - 4dl + 3l^2 - b + l} \right) + (b - l)\ln \left( \frac{\sqrt{2b^2 + 4d^2} - 4bl - 4dl + 3l^2 + b - l}{\sqrt{2b^2 + 4d^2} - 4bl - 4dl + 3l^2 - b + l} \right) \
+ (b + l)\ln \left( \frac{\sqrt{2b^2 + 4d^2} + 4dl + 3l^2 - b + l}{\sqrt{2b^2 + 4d^2} + 4dl + 3l^2 - b - l} \right) + (b - l)\ln \left( \frac{\sqrt{2b^2 + 4d^2} - 4bl - 4dl + 3l^2 - b - l}{\sqrt{2b^2 + 4d^2} - 4bl - 4dl + 3l^2 + b + l} \right) \right]
\]

where \( b, d, l \) represent the side length of the square coil, the distance between the 3D coil and the square coil and the side length of the 3D coil respectively.

![Fig. 4. The equivalent calculation of mutual inductance for the 3D coil with a plane square coil due to Fig. 2](image)

Besides, the directional characteristic of the proposed coil is not limited in just the abovementioned six directions. The proposed 3D coil is placed as shown in Fig. 5, where O is the origin of coordinate and overlaps the cube center, the square
coil (it can be receiving coil or transmitter coil depending on the application) placed vertically with xy plane and Line OP (Point P is the center of the square coil) is perpendicular to the square coil.

When the azimuth angle $\phi$ between OP and x axis is increased from 0° to 360°, i.e. the square coil rotates around the z axis for a cycle, the mutual inductance varies very little in the range of $-20^\circ$ to $110^\circ$ and $160^\circ$ to $290^\circ$. Fig. 6 shows the simulation results for $l = 20$ cm and the number of turns for the proposed coil and the square coil are both one, where $b$ and $d$ are set as several different data. In a large azimuth angle range ($-20^\circ$ to $110^\circ$) and ($160^\circ$ to $290^\circ$), the variation of the amplitude of $M$ is less than 10%. The value of $M$ at $135^\circ$ or $315^\circ$ is near zero which indicates the 3D coil and the square coil are orthogonal each other at these angles, thus in the relevant application users should arrange to evade approaching $135^\circ$ or $315^\circ$.

Furthermore, if the square coil is replaced with a circular one of the same area, i.e. The radius $r$ of circular coil is equal to $\sqrt{S/\pi}$, and $S$ represents the same area, the curves are almost overlapped as shown in Fig. 6. It indicates that the concrete shape of the planer coil has little impact on the mutual inductance if the areas of two planar coils are the same.

The mutual inductance between the 3D coil and the square coil is relative to the azimuth angle $\phi$ and the inclination angle $\theta$, where the configurations of the angles...
are displayed in Fig. 7 and the simulated curves of $M$ versus azimuth angle $\phi$ in different inclination angle $\theta$ is shown in Fig. 8.

![Fig. 7. Top view of the 3D coil and the square coil](image)

According to Figs. 6 and 8, within the range from $-20^\circ$ to $110^\circ$ and from $160^\circ$ to $290^\circ$ for the azimuth angle $\phi$, $M$ alters very little and is not much sensitive to the inclination angle $\theta$. Moreover, the above conclusions still hold if replacing the square coil with a circular one. As shown in Figs. 6 and 8, when the area of the square coil is equal to the area of the circular coil, the mutual inductances almost remain unchanged [14].

4 Experimental verification

As shown in Fig. 9, the experimental platform is established with a GDS-2202 digital storage oscilloscope, a GPD-3303 DC power source, a half bridge inverter, a transmitter composed of the 3D coil and a compensated capacitor and a receiver composed of a plane circular coil, a compensated capacitor and a resistive load. The DC power supply outputs 5 V voltage in the whole experiment.

![Fig. 9. Experimental platform](image)
In Fig. 10, $C_S$ and $R_1$ represent the resonant capacitance and the loss resistance in the transmitter; $R_L$, $C_L$ and $R_2$ represent the power resistance, the resonant capacitance, the loss resistance in the receiver respectively. $V_S$ is the amplitude of the voltage source and $\omega_0$ represents the operating angular frequency. According to circuit analysis in [13], the load voltage amplitude $V_L$ and the mutual inductance $M_{12}$ satisfy Eq. (3):

$$V_L = \left| \frac{V_S \omega_0 M_{12} R_L}{\omega_0^2 M_{12}^2 + R_1 (R_L + R_2)} \right|$$

As shown in Fig. 9, the 3D coil is fabricated by 1 mm diameter enameled copper wire wrapped for 5 turns. The measured inductance of the 3D coil is about 27.3 $\mu$H, and the compensatory capacitance of 3D coil in the platform is about 100.1 nF. The testing coil is a plane circular coil (as we have pointed out in section 3, the shape of the testing coil is of little effect on $M_{12}$), which fabricated by 1.5 mm diameter enameled copper wire wrapped for 10 turns and the inner radius of the coil is 8 cm and the outer radius of the coil is 9.5 cm. The inductance of the testing coil is about 43.7 $\mu$H, while its compensatory capacitance is about 62.9 nF. The load resistance $R_L = 50 \Omega$ and the operating frequency is set as 96 kHz.

The distance between the center of the 3D coil and the receiving coil is set as 20 cm, the position of the test coil remains unchanged and the inclination angle $\theta$ is kept as 0°. With the 3D coil rotated counterclockwise, the voltage waveforms of the load in different azimuth angle $\phi$ are measured by the digital oscilloscope GDS-2202 and compared with the numerical solutions as shown in Fig. 11.
According to (3) and Fig. 11, the experiments show the load voltage varies very little at the range of azimuth angle $\phi$ from $-10^\circ$ to $100^\circ$ and from $170^\circ$ to $280^\circ$, as well as the mutual inductance between the 3D coil and the plane circle coil due to (2). Moreover, when $d = 20$ cm, the measured load voltage versus $\phi$ in some different inclination angle such as $\theta = 0^\circ$, $15^\circ$ and $30^\circ$, compared with the numerical results, are shown in Fig. 12.

Figs. 11 and 12 indicate that when the plane circle coil for testing rotates around z axis and evades from the restricted zone near $135^\circ$ or $315^\circ$, $M$ is almost not varied and not sensitive to the inclination angle $\theta$ in the large azimuth angle range ($-10^\circ$ to $100^\circ$) and ($170^\circ$ to $280^\circ$), which may be suited to the applications conformal with the environment such as a room corner to naturally evade the restricted zone, as shown in Fig. 13, in which a 3D coil conformal with the room corner power multiple LEDs simultaneously.

5 Conclusion

In this paper, a three-dimensional multidirectional inductance coil (3D coil) is proposed, the mutual inductance between the proposed coil and a plane square or
circle coil change smoothly in the large azimuth angle range, which is of the virtues such as simple structure, conveniently fabricated and easy to be conformal with surrounding environment (such as the edges and corners of furniture or walls) to avoid the restricted zone and not to occupy additional space. Compared with the planar coil, the mutual inductance between the 3D coil and the test coil varies very little in the scope of a large sphere (angle). Besides, the 3D coil is easy to be conformal with the edges and corners of furniture or walls as shown in Fig. 13. The 3D coil is suitable to play the role of the transmitter coil or the relay coil in the WPT system with multi-load.

Acknowledgments

This work is supported by National Natural Science Foundation of China (61461031, 61261006).