A coaxial dual-receiver wireless power transfer system with bipolar coils to eliminate cross-coupling and achieve a controllable power distribution

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Abstract This paper proposes a dual-receiver wireless power transfer system that uses bipolar coils as a transmitter and receivers. Compared with a traditional dual-receiver system with unipolar coils, the proposed system can effectively and conveniently eliminate cross-coupling between the receivers, and another significant feature of the system is the ease of changing the received power of the two receiver loads by changing the relative angle of the bipolar coils. The mutual inductance of the bipolar coils is modelled by Newman’s formula. Then a system design method to eliminate the influence of cross-coupling and realize controllable power allocation is proposed.

key words: wireless power transfer, dual-receiver, bipolar coil, cross-coupling, controllable power distribution

Classification: Microwave and millimeter wave devices, circuits, and modules

1. Introduction

Wireless power transfer (WPT) has received great attention because of its safety, clean, and reliability, without the constraint of wires [1,2,3,4]. Currently, WPT technology has been widely used in various electronic devices, such as mobile phones [5,6], laptops [7,8], televisions [9,10], electric vehicles [11,12,13] and medical equipment [14].

In this paper, a coaxial dual-receiver (RX) WPT system is proposed that uses bipolar coils [15,16,17,18,19] to eliminate cross-coupling and achieve controllable power distribution. The main contributions of this paper can be summarized as follows:

1) A simulation model for the relationship between mutual inductance and the relative angle between two bipolar coils at a certain distance is established. Then propose the angle of the bipolar coils can be used as an important parameter to change the mutual inductance between the coils at the fixed position.

2) We analyze the influence of the cross-coupling on the current of the RX. Then propose a method to eliminate cross-coupling effect between the RXs in a dual-RX WPT system. Compared with other eliminating cross-coupling techniques, such as reactance compensation [20,21], bucking coil [22] and multiple resonance frequencies [23,24], the use of bipolar coils can reduce the complexity of the design of the system, and the mutual inductance between the RXs is independent of the distance.

3) A power allocation control strategy in a dual-RX WPT system is proposed. For traditional WPT systems, the power of the receiver is usually controlled by changing the phase and amplitude of the source voltage [25], or add additional control methods to the system, such as a resonant regulating rectifier [26], buck circuit [27], and impedance matching circuit [28,29]. For the proposed WPT system, the relative angle between bipolar coils is an important factor in controlling power distribution. By adjusting the relative angle between the coils, the power of the RXs can be changed.

This article is organized as follows: Section 2 carries out a theoretical analysis and numerical simulation of the mutual inductance of the bipolar coil. In Section 3, a circuit model of the dual-RX system with dipolar coils is established, and then the cross-coupling of the system and the power distribution ratio between the RXs are analyzed. In Section 4, the corresponding experimental model is constructed to verify the theory of Section 2 and Section 3. Section 5 summarizes the research results.

2. Model analysis of the coaxial bipolar coils

A schematic diagram of two coaxial horizontal circular bipolar coils in a Cartesian coordinate system is shown in Fig. 1, where the coils are parallel to the yz-plane. The coils in Fig. 1 are named $L_a$ and $L_b$, respectively. The radius of $L_a$ is $r_a$, the number of turns is $N_1$, the radius of $L_b$ is $r_b$, and the number of turns is $N_2$. The distance between the centre of $L_a$ and the centre of $L_b$ is $d$. The angle between the central axis of $L_a$ and the z-axis...
is $\theta_1$, and the angle between the central axis of $L_b$ and the z-axis is $\theta_2$.

![Fig. 1 A schematic diagram of the two horizontal circular bipolar coils](image)

As shown, a closed bipolar coil $L_a$ ($L_b$) can comprise four line segments, expressed as $l_{a1}(l_{b1})$, $l_{a2}(l_{b2})$, $l_{a3}(l_{b3})$ and $l_{a4}(l_{b4})$. The distance between the line segments $l_{a2}(l_{b2})$ and $l_{a3}(l_{b3})$ is very close; for the convenience of calculation, $l_{a2}(l_{b2})$ and $l_{a3}(l_{b3})$ can be considered to coincide. According to the Nuemann formula, the mutual inductance of the two coils can be expressed as

$$M = \frac{\mu N_1 N_2}{4\pi} \int \int_{c_1 c_2} \frac{dl_a dl_b}{R}$$

(1)

where $c_1$ and $c_2$ are the contours of the coils $L_a$ and $L_b$ structures, respectively; $dl_a$ and $dl_b$ are infinitesimal integral elements on the line segments $l_{ai}$ and $l_{bk}$ (where $i = 1, 2, 3, 4$, $k = 1, 2, 3, 4$), respectively; $R$ is the distance between the infinitesimal integral elements on the two line segments.

When the radius and the number of turns of the coil are determined, the mutual inductance of the bipolar coil can be expressed as

$$M = M(d, \Delta \theta = \theta_2 - \theta_1)$$

(2)

where $\Delta \theta$ is the relative angle of the coils.

![Fig. 2 Numerical results of the mutual inductance and relative angle $\Delta \theta$ variations of the bipolar coil.](image)

We use numerical integration to calculate the mutual inductance of the coil in MATHEMATICA software. For a comparison with experimental values, the parameters of the two coils are set to $r_a = r_b = 107.5$ mm and $N_1 = N_2 = 8$. A diagram of the mutual inductance simulation of the two coaxial bipolar coils is shown in Fig. 2. The mutual inductance of the coil decreases as the relative angle increases; when $\Delta \theta = 90^\circ$, the mutual inductance of the coil is zero and independent of the distance, this conclusion can also be obtained from the magnetic field distribution. According to the simulation results, the mutual inductance of the coil can be controlled within a certain range by adjusting the angle between the coils.

![Fig. 3 Coaxial dual-RX WPT system model diagram](image)

3.Dual-receiver WPT system model and circuit analysis

3.1 System model and parameter analysis

A diagram of the coaxial dual-RX WPT system model is shown in Fig. 3. One line segment has two arrows, indicating that two line segments coincide. To facilitate the calculation and design of the system, the coil sizes used in this paper are the same. In practical applications, the RXs may be on the same side of the transmitter (TX) or on different sides of the TX.

The equivalent circuit diagram of the system is shown in Fig. 4, where $V_s$ is the fundamental voltage amplitude of the output of the half-bridge inverter, $\omega$ is the angle frequency of the fundamental voltage, $I_1$, $I_2$, and $I_t$ are the loop currents, $L_1$, $L_2$, and $L_t$ are the equivalent inductances of the coil, $C_1$, $C_2$, and $C_t$ are the...
compensation capacitors, \( R_1, R_2, \) and \( R_t \) are the internal resistances of the coil, \( R_s \) is the internal resistance of the half-bridge inverter, and \( R_{t1} \) and \( R_{t2} \) is the resistive load of the RX. According to the mutual inductance calculation formula of the coaxial bipolar coil in Section 2, the mutual inductance of the TX and RX1 is \( M_{12} = M(d_1, \theta_1 - \theta_2) \), the mutual inductance of the TX and RX2 is \( M_{12} = M(d_2, \theta_2 - \theta_1) \), the mutual inductance of RX1 and RX2 is \( M_{12} = M(d_{12}, \theta_1 - \theta_2) \).

According to Kirchhoff’s laws of voltage and current, we have

\[
\begin{bmatrix}
V_s \\
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
Z_t & j\omega M_{t1} & j\omega M_{t2} \\
j\omega M_{t1} & Z_1 & j\omega M_{t2} \\
j\omega M_{t2} & j\omega M_{t2} & Z_2
\end{bmatrix}
\begin{bmatrix}
I_t \\
I_1 \\
I_2
\end{bmatrix}
\]  

(3)

where \( Z_t = j\omega L_t + 1/j\omega C_t + R_t + R_s, Z_i = j\omega L_i + 1/j\omega C_i + R_i + R_{li} (i = 1, 2) \), when the system is in resonance, \( j\omega L_t + 1/j\omega C_t = j\omega L_i + 1/j\omega C_i = 0 \) \((i = 1, 2)\).

The power transfer efficiency (PTE) can be expressed as

\[
\eta = \frac{V_s^2 R_{t1} + V_s^2 R_{t2} + V_1^2 (R_{1t} + R_s) + V_2^2 (R_{2t} + R_s)}{V_s^2 (R_{1t} + R_s) + V_1^2 (R_{1t} + R_s) + V_2^2 (R_{2t} + R_s)}
\]  

(4)

3.2 Cross-coupling effects and elimination methods

This paper analyses the influence of cross-coupling between RXs on the system from the current of the RXs. Because the internal resistance of the component is much smaller than the load resistance, so we can assume that \( Z_t = 0, Z_1 = R_{t1}, Z_2 = R_{t2} \) at the resonance frequency. Therefore, solve (3), the loop current of the RX1 would be:

\[
I_t = \frac{V_s (j\omega M_{t1} R_{t2} + \omega M_{t2} M_{t2})}{\omega(M^2 R_{t1}^2 + M^2 R_{t2}^2 - 2 j\omega M_{t1} M_{t2})}
\]  

(5)

To simplify the analysis, we can assume that

\[
R_{t2} = aR_{t1}, \quad M_{t2} = bM_{t1}
\]  

(6)

So, (5) can be express as:

\[
I_t = \frac{V_s (j\omega R_{t1} + \omega b M_{t2})}{\omega M_{t1} (aR_{t1} + b^2 R_{t1} - 2 j\omega b M_{t1})}
\]  

(7)

For comparison purposes, the normalized current is used to indicate the effect of cross-coupling on current, where the normalized current is expressed as

\[
I_{1,nor} = \frac{I_1}{I_t(M_{t2} = 0)} = \frac{(a^2 + ab^2) R_{t1} - j\omega (ab + b^2) M_{t2}}{(a^2 + ab^2) R_{t1} - j\omega (2ab) M_{t2}}
\]  

(8)

As can be seen from (8), The value of \( I_{1,nor} \) is related to \( a \) and \( b \), it can be derived as follows:

\[
\begin{align*}
 b^2 > a & \implies I_{1,nor} < 1 \\
 b^2 = a & \implies I_{1,nor} = 1 \\
 b^2 < a & \implies I_{1,nor} > 1
\end{align*}
\]  

(9)

As can be seen from (8) and (9), There are two ways to eliminate the effects of cross-coupling on the current of RXs:

(1) Let \( a = b^2 \). Although this method can eliminate the influence of cross-coupling on the RXs current, but it cannot eliminate the system efficiency degradation caused by cross-coupling [20,21,30].

(2) Let \( M_{12} = 0 \mu H \). For the unipolar coil coaxial multi-RX WPT system, it is difficult to eliminate the cross-coupling between the RXs, but for the bipolar coil WPT system proposed in this paper, as shown in Fig.3, we can make \( \theta_1 - \theta_2 = 90^\circ \) to eliminate the coupling of the RXs.

3.3 Power allocation control strategy

The power of the load can be calculated according to the loop current at the RX side.

\[
P_1 = \frac{1}{2} |I_1|^2 R_{t1}, P_2 = \frac{1}{2} |I_2|^2 R_{t2}
\]  

(10)

where \( P_1 \) is the load power of RX1, \( P_2 \) is the load power of RX2, and the RX's load power ratio is

\[
P_1 : P_2 = \frac{\omega^2 M_{t1}^2 R_{t1} + j\omega M_{t1}(R_{t2} + R_s)}{\omega^2 M_{t2}^2 R_{t2} + j\omega M_{t2}(R_{t1} + R_s)} R_{t1} R_{t2}
\]  

(11)

It can be seen from (11) that the RX's load power allocation calculation is very complicated, because RX1 and RX2 not only receive power from the TX but also have power transfer between RX1 and RX2. When \( M_{12} = 0 \mu H \), the power transmission path is the TX to RX1 and RX2, and the RX's load power ratio can be calculated as

\[
P_1 : P_2 = \frac{\omega^2 M_{t1}^2 R_{t1}}{(R_{t1} + R_{t1})^2} : \frac{\omega^2 M_{t2}^2 R_{t2}}{(R_{t2} + R_{t2})^2}
\]  

(12)

Contrasting (11) and (12), in order to more conveniently control the power distribution of the RXs and reduce the design complexity of the system, the mutual inductance between the RXs should be zero. Therefore, for the dual-RX WPT system shown in Fig. 3, the relative angle of the RXs coils should be set to \( \theta_1 - \theta_2 = 90^\circ \).
In practical applications, \( R_{L1} \gg R_1 \) and \( R_{L2} \gg R_2 \), so (12) can be simplified as:

\[
P_1, P_2 = \frac{M_{12}^2}{R_{L1}} + \frac{M_{12}^2}{R_{L2}} + \frac{M_t^4(d_1, \theta_1 - \theta_2)}{R_{L1}} + \frac{M_t^4(d_2, \theta_1 - \theta_2 - 90^\circ)}{R_{L2}}
\]  \( (13) \)

It can be seen from (13) that the load power ratio of the RXs is related to the load value and the mutual inductance of the RX and the TX. For a traditional multi-RX WPT with a unipolar coil, the mutual inductance of the RX and the TX is a function of the distance. When bipolar coils are used as magnetic couplers in a multi-RX WPT system, the mutual inductance of the TX and RX is a function of the distance and relative angle. When the distance of the coil is fixed, the mutual inductance between the coils can be changed by adjusting the relative angles, thereby controlling the power distribution ratio of the receiver, which increases the flexibility of the system design. It is worth noting that when \( \theta_1 - \theta_2 = 90^\circ \) or \( 0^\circ \), the mutual inductance between one of the RXs and the TX is zero, and then only one RX can obtain power, which means the power of the TX can be selectively transmitted to the RXs.

### Table 1 Experimental parameters

|                | TX  | RX1 | RX2 |
|----------------|-----|-----|-----|
| Inductance(\( \mu \)H) | 49.48 | 49.32 | 48.91 |
| Compensation capacitor (nF) | 70.79 | 71.07 | 71.52 |
| Loss resistance(\( \Omega \)) | 0.51 | 0.52 | 0.51 |
| Load resistance(\( \Omega \)) | 5 | 5 | 5 |

Fig. 5 The experimental prototype of a dual-RX WPT system

![Fig. 6 Experimental model and experimental results of the influence of mutual inductance of two RXs on the system](image)

(a) The experimental setup model  
(b) The mutual inductance of the coils varies with \( \theta_1 \)  
(c) The current of RXs and PTE varies with \( \theta_2 \)  
(d) The current of RXs when \( M_{12} = 0 \) \( \mu \)H and \( M_{12} = 12.8 \mu \)H

![Fig. 7 Model and experiment results of experiment setup 1](image)

(a) The experimental setup model  
(b) The mutual inductance of the coils varies with \( \theta_1 \)  
(c) The load power of RXs and the PTE varies with \( \theta_2 \)

![Fig. 8 Model and experiment results of experiment setup 2](image)

(a) The experimental setup model  
(b) The mutual inductance of the coils varies with \( \theta_1 \)  
(c) The load power of RXs and the PTE varies with \( \theta_2 \)
4. System implementation and experiment

4.1 Experimental device

Three identical planar circular bipolar coils are fabricated as shown in Fig. 5, the radius of the coil is 107.5 mm, and the number of turns is 8. The experimental prototype of a dual-RX WPT system is shown in Fig. 5. A half-bridge inverter consisting of an IRF540 MOSFET is connected to a 12 V DC voltage source to supply power to the system as an AC power source. The on-resistance of the MOSFET is 0.035-0.117 Ω [30], and the on-resistance stands for the internal resistance $R_s$ of the power supply. In general, a frequency below several hundred kHz is more convenient to make the inverter, so the resonance frequency of this paper is set to 85 kHz. The two measurement ports of the oscilloscope are connected to two loads to measure the voltage. Another oscilloscope is used to measure the output voltage and current of the half-bridge inverter to calculate the system input power, and the current of the TX is measured by Tektronix oscilloscope AC current probe P6021. The system parameters are shown in Table 1.

4.2 The effects of the coupling between the RXs on the system

To investigate the effects of cross-coupling on PTE and the current of RXs, the established WPT system model is shown in Fig. 6(a), where $\theta_1 = 45^\circ$, $\theta_2 = 90^\circ$, the angle $\theta_2$ of RX2 is changed from 0° to 90°, and the measured values and calculated values of the mutual inductance of the coil are shown in Fig. 6(b). When $\theta_2$ increases, the measured $M_{12}$ increased from 0.17µH to 24.9µH, and $M_{t1}$ and $M_{t2}$ change little and close to each other.

The measured value and calculated value of the system PTE and current are shown in Fig. 6(c). The small error between the calculated and measured values is caused by the error of the circuit modelling due to device error and line loss (the following errors are the same). The system PTE decreases with an increase in $M_{12}$, and $I_1$ and $I_2$ have little change.

In order to prove that when $a = b^2$, cross-coupling has little effect on the current of RXs, we set $\theta_2 = 45^\circ$, $\theta_1 = 90^\circ$, $R_{L1} = 5\Omega$, and then adjust $\theta_1$ and $R_{L2}$ so that $a = b^2$. The experimental results are shown in Fig. 6(d), the measured and calculated values of $I_1$ and $I_2$ when $M_{12} = 12.8\mu H$ are almost equal to the calculated values of $I_1$ and $I_2$ when $M_{12} = 0 \mu H$.

4.3 Power distribution of RX1 and RX2

We designed two sets of experiments with RXs coils in different positions to investigate the relationship between the angle of the TX coil and the power distribution of the RXs.

Experiment setup 1: The system model is shown in Fig. 7(a), where RX1 and RX2 are on different sides of the TX, the distance from the TX is 40 mm, and the relative angle of RX1 and RX2 is set to 90° to eliminate cross-coupling between the RXs. The angle $\theta_1$ of the TX is changed from 0° to 90°, and the measured and calculated values of the mutual inductance of the coils are shown in Fig. 7(b). Because the distance of the two RXs to the TX are the same, the mutual inductance changes of the RXs are symmetrical, the measured mutual inductance $M_{t1}$ varies from 0.15 µH to 8.63 µH, and $M_{t1} = M_{t2}$ when $\theta_1 = 45^\circ$. Fig. 7(c) shows that the load power and system PTE vary with $\theta_1$. The PTE of the system remains essentially the same when $\theta_1$ changes. The three dotted lines marked in Fig. 7(c) are the angles of the corresponding TX when the measured load power ratio is $P_1: P_2 = 2:1$, $P_1: P_2 = 1:1$, and $P_1: P_2 = 1:2$.

Experiment setup 2: When RX1 and RX2 are on the same side of the TX and the distances from the TX are 40 mm and 60 mm, respectively, the system model is as shown in Fig. 8(a). Fig. 8(b) shows the measured and calculated values of the mutual inductance with $\theta_1$; the measured mutual inductances $M_{t1}$ and $M_{t2}$ vary from 8.63 µH to 0.15 µH and 0.09 µH to 5.02 µH, respectively, when $\theta_2 = 60^\circ$, and $M_{t1}$ is almost equal to $M_{t2}$. The load power and system PTE vary with $\theta_1$ is shown in Fig. 8(c). The measured PTE changes from 69.1% to 51%. The three dotted lines in Fig. 8(c) indicate the three different measured load power ratios.

Therefore, the above experimental results show that the proposed dual-RX WPT system can realize a controllable load power distribution ratio by simply adjusting the angle of the TX coil without changing the position of the coils, and for some specific angles of the TX, the power of the TX can be selectively transferred to RXs or uniformly transferred to RXs.

5. Conclusion

This paper proposes a coaxial dual-RX WPT system using bipolar coils. Theoretical analysis and experimental results verify the effectiveness of the proposed system in eliminating cross-coupling and achieving controllable power allocation. For the dual-RX WPT system proposed in this paper, the relative angle between the RXs should be set to 90° to eliminate cross-coupling between the RXs, and the angle of the TX is an important parameter to control the load power distribution.
ratio between the RXs. In addition, compared to unipolar coils, bipolar coils have greater potential for applications in WPT systems. In future work, the application of bipolar coils in multi-transmitter, multi-receiver and multi-repeater WPT systems will be further studied.

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