Omnidirectional wireless power transfer system with a multidirectional receiver inside a cubic transmitter

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Abstract Dramatic advancements have been witnessed for the magnetic resonant coupling wireless power transfer technology used in various portable electronic devices. A novel omnidirectional wireless power transfer system was proposed in this paper. Instead of conventional planar coils, a multidirectional receiver inside the transmitter was designed to receive the electromagnetic energy from all the directions. As expected, the finite element simulation results show that the distribution of magnetic field is uniform at different positions inside the transmitter. And the power transfer efficiency (PTE) of the newly designed system with the multidirectional receiver is obviously greater than that of the conventional system with the planar coil. Effects of the different receiver structural sizes on the system performance were discussed. PTE of the system becomes higher when the receiver is larger. Furthermore, PTE is insensitive to position and angular misalignment of the multidirectional receiver. The experimental measurements show that PTE of the system with the multidirectional receiver is 26% at the frequency of 6.78 MHz. The newly designed magnetic resonant coupling wireless power transfer system will be significative for the electronic devices indoor.

key words: wireless power transfer, multidirectional receiver, magnetic resonant coupling, power transfer efficiency

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

1. Introduction

Since an epoch-making technology based on the magnetic resonant coupling wireless power transfer (MRCWPT) incredibly realized the energy migration by a cordless way in 2007 [1], the seemingly magic MRCWPT systems have been widely applied in various fields, such as portable electronic devices, medical equipment, electric vehicles, integrated circuits, and so forth [2,3,4,5,6]. For its remarkable virtues of movability, flexibility, and convenience, the MRCWPT technology is also an ideal technical solution to develop the smart home engineering in the near future [7,8,9,10]. The MRCWPT technique has attracted more and more attention from the researchers of the charging field [11,12,13,14,15].

The conventional transmitter and receiver are placed in unidirectional coaxial positions. Thus, the receiver is limited by both range and direction in this case [16,17,18,19,20,21,22]. Furthermore, power transfer efficiency (PTE) will decrease dramatically when there is a little angular misalignment for the planar receiver. The omnidirectional MRCWPT systems were proposed in the recent researches to overcome the restrictions to the receivers [23,24,25,26,27,28]. A planar receiver coil with almost the same size as the transmitter was placed outside the transmitter to catch power in each direction. But the orthogonal coils of the system requires more than one power source. The systems need complex control methods to maintain uniform distribution of magnetic field, and it is bound to increase structural complexity and cost for the system [23,24,25]. In order to solve this problem, orthogonal coils connected in series for the omnidirectional MRCWPT systems were presented in [26,27,28], but the distribution of magnetic field is not uniform in different directions. Though the omnidirectional MRCWPT technique can overcome limitations in range and direction for the receiving terminals, angular misalignment of the planar receiver is not discussed.

In this paper, we reported the proposed omnidirectional wireless power transfer system with a multidirectional receiver inside a cubic transmitter. The transmitter consisted of four planar spiral coils in series supplied only by a single power source. Instead of using conventional planar coils, a novel multidirectional receiver was designed and placed inside the transmitter to receive the energy from all the directions. The magnetic field distribution inside the transmitter is uniform at different positions. Furthermore, PTE is insensitive to the position and angular misalignment of the multidirectional receiver.

2. Design of the Omnidirectional MRCWPT System

The proposed omnidirectional MRCWPT system with a novel multidirectional receiver inside the cubic transmitter is illustrated in Fig. 1. The cubic transmitter and the multidirectional receiver were both wound by a single wire, and the transmitter was driven by a power
source. The energy was transmitted from the cubic transmitter to the multidirectional receiver through the magnetic field. The matching circuits consisted of a serial capacitor and a parallel capacitor. The matching circuits in Fig. 1 can match the system termination impedance at the resonant frequency, which is beneficial to PTE and stability of the system [29,30].

![Image](image1)

Fig. 1. The designed structure of the omnidirectional system.

2.1. Simulation of the Omnidirectional Magnetic Field Distribution

The model of the MRCWPT system was built by the simulation software HFSS. The simulation model is illustrated in Fig. 2. The cubic transmitter is powered by the driven current to generate the magnetic field. The multidirectional receiver placed inside the cubic transmitter catches the energy from all directions. The matching circuits can match the impedance of the system. $\theta$ is the rotation angle of the receiver.

![Image](image2)

Fig. 2. The simulation model of the omnidirectional system.

| Parameters          | Value | Parameters          | Value |
|---------------------|-------|---------------------|-------|
| Wire Diameter       | 2 mm  | Wire Diameter       | 2 mm  |
| Wire Spacing        | 8 mm  | Wire Spacing        | 4 mm  |
| Turns               | 4     | Turn                | 1     |
| Coil Diameter       | 120 mm| Coil Diameter       | 40 mm |

Table 1. Parameters of the transmitter and receiver

The gap between the adjacent planar coils of the cubic transmitter is 15 mm. And the main parameters of the cubic transmitter and multidirectional receiver are listed in Table 1. Reflection coefficient $S_{11}$ at different frequencies for the system are shown in Fig. 3. It is obvious that the resonant frequency of the system is 6.78 MHz.

![Image](image3)

Fig. 3. Parameters of the transmitter and receiver

The energy is transmitted from the transmitter to the receiver through the electromagnetic field. Fig. 4 presents the distribution of magnetic field inside the cubic transmitter along with the multidirectional receiver. At the frequency of 6.78 MHz, the magnetic field values at different positions inside the cubic transmitter are shown in Fig. 5. It is clear that the magnetic field values are all near 22.5 A/m at different positions. Obviously, the distribution of magnetic field inside the cubic transmitter is omnidirectional and homogeneous, and the magnetic coupling between the cubic transmitter and the receiver is strong almost equally in each direction, suggesting that the receiver can catch the energy from all the directions.

![Image](image4)

Fig. 4. The distribution of magnetic field inside the transmitter along with the receiver.
2.2. PTE of the Proposed Omnidirectional MRCWPT System

The conventional unidirectional planar receiver can only receive the power from the transmitter in limited directions. The newly designed multidirectional receiver in this paper and the conventional unidirectional planar receiver are compared in Fig. 6(a), (b), respectively. As shown in Fig. 6(a), the coils formed along 1-2-3-4-5-6-7, 7-8-9-10-11, and 11-12-13-14-15-16 are placed on the YOZ, ZOX, and XOY planes, respectively. Finally, point 16th placed on the ZOX plane returns to point 1st through point 17th, 18th, and 19th. Thus, the receiver coil requires only a single port and can omnidirectionally receive power from the transmitter. The multidirectional receiver with such a symmetrical structure will overcome the issue that PTE drops dramatically when there is an angular misalignment.

The MRCWPT system is equivalent to a general two-port network, as illustrated in Fig. 7. \( S_{11} \) and \( S_{22} \) are incident waves, and \( S_{1} \) and \( S_{2} \) are reflected waves. \( S_{11} \) and \( S_{22} \) are defined in formula (1) and (2), respectively. \( Z_0 = Z_t = 50 \Omega \).

The scattering parameter \( S_{21} \) is defined as follow:

\[
S_{21} = \frac{S_{2} - S_{1} Z_0}{S_{11} Z_0} = \frac{2\sqrt{Z_0}}{V_1 + I_1 Z_0} \frac{V_2 - (V_2)}{V_S} = \frac{2V_2}{V_S} \quad (3)
\]

According to the maximum power transfer theorem, the maximum available power (\( P_t \)) at port one of the two-port network is given by

\[
P_R = \left( \frac{1}{2} V_S \right)^2 / Z_0 \quad (4)
\]

The PTE of the two-port network is

\[
\text{PTE} = \frac{P_L}{P_R} = \frac{V_2^2 / Z_L}{(1/2) V_S^2 / Z_0} = (2V_2 / V_S)^2 = S_{21}^2 \quad (5)
\]

PTE of the omnidirectional system with the multidirectional receiver and the unidirectional receiver was calculated in HFSS, respectively. PTE is related to \( S_{21} \) by \( \text{PTE}=S_{21}^2 \). When the receiver is placed in the middle of the transmitter, the PTE results of the multidirectional receiver and the unidirectional receiver with different sizes are shown in Fig. 8. Obviously, PTE of the system with the multidirectional receiver is higher than that of the system with the unidirectional receiver. Also, PTE increases with the structure size of the multidirectional receiver and the unidirectional receiver. And PTE with the multidirectional receiver increases faster than the unidirectional receiver. The proposed multidirectional receiver can catch more power inside the transmitter than the conventional unidirectional receiver, and PTE can also be significantly improved by the multidirectional receiver inside the cubic transmitter.
3. Experimental Results of the MRCWPT System

To verify the simulated results, the cubic transmitter and the novel multidirectional receiver were both fabricated by using the parameters listed in Table 1. The side length of the multidirectional receiver is 40 mm. The experimental platform for the proposed omnidirectional system is shown in Fig. 9. The cubic transmitter was driven by only a single power source generated by a signal generator (Tektronix AFG1062). The sinusoidal voltage source has voltage of $V_S$ and impedance of $R_S$. The oscilloscope (Tektronix MDO3012) was used to measure the signal in the multidirectional receiver. The receiver was connected with load impedance $R_L$, and $V_L$ was the voltage of $R_L$. The matching circuits were designed to match the impedance of the MRCWPT system. The serial capacitor $C_1$ and the parallel capacitor $C_2$ were adopted to match the impedance of the cubic transmitter. The serial capacitor $C_3$ and the parallel capacitor $C_4$ were used to match the impedance of the receiver. The cubic transmitter was fixed in a certain position, and the multidirectional receiver was placed inside the cubic transmitter. Parameters of the system described above were listed in Table 2. PTE of the system was determined by $\text{PTE} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = \frac{V_L^2}{R_L} \times \frac{V_S^2}{R_S} \times 100\%$.

| Transmitter | Value |
|-------------|-------|
| $R_S$       | 50 $\Omega$ |
| $C_1$       | 25 pF   |
| $C_2$       | 54.5 pF |

| Receiver    | Value   |
|-------------|---------|
| $R_L$       | 50 $\Omega$ |
| $C_3$       | 116 pF  |
| $C_4$       | 2370 pF |

When the receiver was shifted to different positions, the simulated PTE and the measured PTE were compared as shown in Fig. 10. The measured values are slightly lower than the simulated results, mainly due to the fabrication tolerance. PTE of the system can be higher than 26% no matter how the position changes. Thus, it is concluded that the receiver can effectively catch the energy at different positions for the uniformly distributed magnetic field.

In order to verify whether the system is sensitive to angular misalignment of the multidirectional receiver, PTE was measured at different rotation angles of the receiver localized in position 5. The simulated and measured PTE results were compared in Fig. 11. PTE of the system can also maintain higher than 26% at different rotation angles. Thus, PTE is insensitive to the angular misalignment of the receiver, which is positive to actual application.
Fig. 11. PTE of the system with the receiver at different rotation angles.

4. Conclusion

An omnidirectional MRCWPT system with the multidirectional receiver inside the cubic transmitter was proposed. The magnetic field distribution inside the cubic transmitter was omnidirectionally uniform, and the coupling between the cubic transmitter and the receiver is efficient. When the multidirectional receiver is used in the cubic transmitter instead of the unidirectional planar receiver, PTE is significantly improved. PTE of the designed system is high as 26% at the resonant frequency of 6.78 MHz. Furthermore, PTE is insensitive to the position and angular misalignment of the multidirectional receiver. The proposed MRCWPT technology will be valuable for smart home applications.

Acknowledgments

This research was funded by the National Key Research and Development Program of China (Grant No. 2017YFA0204600), and the National Natural Science Foundation of China (Grant No. 51802352).

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