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Omnidirectional Wireless Power Transfer System with Multiple Receivers and a Single Wire Wound Spiral Transmitter

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Abstract—Last decade has witnessed dramatic advancements in wireless charging distance of magnetic resonant coupling wireless power transfer (MRCWPT) for various portable electronic devices. Driven by the demand of cost-effective and compact system working for multiple receivers, a novel omnidirectional MRCWPT system with a single wire wound spiral transmitter and a single power source is proposed in this work. Besides, an equivalent circuit model is established to derive the power transfer efficiency (PTE) of this novel MRCWPT system. Finite element simulation results have shown that the magnetic field distribution for the proposed model is uniform in all directions. And the PTE of the system depending on the distance between the transmitter and receivers is demonstrated to be independent of the receiving angles. Finally, the theoretical analysis of the simulation results is verified by practical experimental results, which shows that the PTE of the system reaches 60% at the distance of 160 mm and the resonant frequency of 15.5 MHz.

1. INTRODUCTION

Since a novel technology based on magnetic resonant coupling wireless power transfer (MRCWPT) was proposed by researchers of MIT in 2007 [1], MRCWPT system has been widely applied in various fields from daily electrical products, medical equipment to aerospace fields [2–4]. MRCWPT system can solve the problems of conventional wired power transfer system, such as inadequate security, complex wiring, and frequent wire failures [5–8]. Due to the booming development of electric cars, consumer electronics, robots, portable devices, and other fields, MRCWPT technology has attracted much attention because of its great development prospect and broad market demand in the field of charging [9–13].

One conventional MRCWPT mode is one-transmitter-to-one-receiver MRCWPT, and the system can achieve high efficiency over a long distance of several meters [14, 15]. Due to the space and cost constraints, this kind of MRCWPT system is not suitable for large number of electrical devices [16, 17]. Another mode is one-to-many MRCWPT. One transmitter operates with multiple receivers, which requires less space and cost [18–20]. However, the wide application of the one-to-many MRCWPT system is limited in effective work range and direction at the receivers. To resolve this issue, an omnidirectional MRCWPT system is proposed [21–26]. In [21–23], the transmitters are made up of orthogonal coils, which require complex control methods to achieve uniform magnetic field distribution in all directions. Another omnidirectional MRCWPT system is proposed with a simple control method by connecting orthogonal coils in parallel or series [24–26], but the magnetic field distribution of the transmitter in each direction is different. Though the techniques described above ensure that the receivers can receive power in each direction, they are not highly attractive.

When multiple receivers need to be powered, there will be many problems. The one-to-one MRCWPT system requires large space and high cost, and the one-to-many MRCWPT system is limited in range and direction at the receivers. The omnidirectional MRCWPT system can overcome

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the directionality restrictions of multiple receivers. However, most omnidirectional MRCWPT systems require more than one source for orthogonal coils, which tends to increase the cost and structural complexity. In order to solve power supply problems of the system with multiple loads, this paper proposes an omnidirectional MRCWPT system with multiple receivers. Besides, the system using a cubic transmitter requires only a single power source. The cubic transmitter consists of four planar spiral coils in series, and the simple planar spiral receivers of the system are used for popular applications. The magnetic field distribution of the system is uniform in all directions, and the system can achieve relatively high efficiency.

This paper is organized as follows. The theoretical analysis is described in Section 2. An equivalent circuit model of the MRCWPT system is established to derive the power transfer efficiency (PTE) of the system. In Section 3, the omnidirectional magnetic field distribution for the MRCWPT system of the simulation is presented. The PTE of the omnidirectional MRCWPT system with different numbers of receivers is discussed. Section 4 presents the fabrication and measurement of the omnidirectional MRCWPT system. Practical experimental results are compared with the simulated ones. Finally, Section 5 draws the conclusions.

2. EQUIVALENT CIRCUIT THEORY OF THE OMNIDIRECTIONAL MRCWPT SYSTEM

The omnidirectional MRCWPT system with a novel transmitter and four receivers is shown in Figure 1. The novel transmitter is wound by a single copper wire, and the transmitter is driven by only a single power source. The power is transmitted from the transmitter to receivers through the electromagnetic field. The four identical receivers are simple plane spiral coils, which can be used for popular applications.

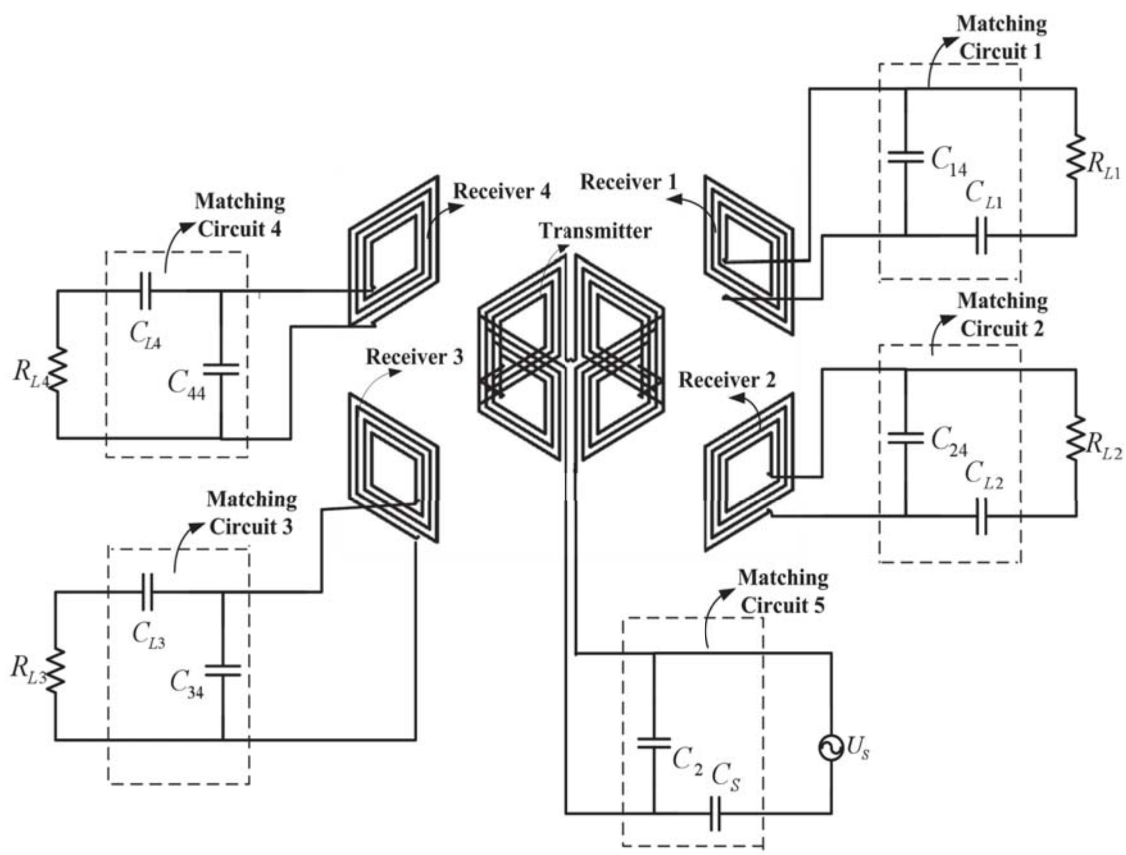

Figure 1. Omnidirectional MRCWPT system with a novel transmitter and four receivers.

In Figure 1, the matching circuit of the system consists of a parallel capacitor and a series capacitor. The matching circuits can match the termination impedance at the resonant frequency, which will provide high PTE and better stability of the system [27–29].

The omnidirectional MRCWPT system can be modeled in terms of equivalent lumped circuit elements. The equivalent schematic circuit of the system is illustrated in Figure 2.

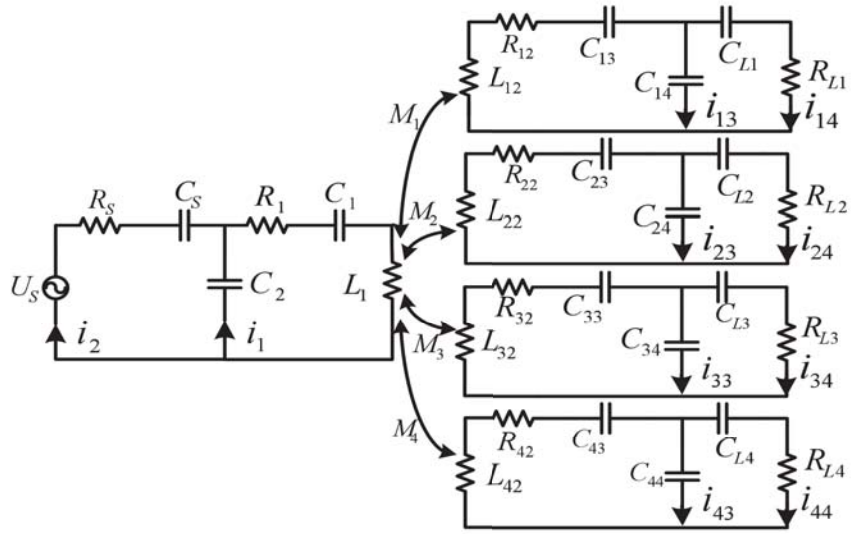

Figure 2. Equivalent schematic circuit of the omnidirectional MRCWPT system.

There are five resonant circuits in the schematic circuit corresponding to the cubic transmitter and the four receivers. L_1 and L_{n2} ($n = 1, 2, 3, 4$) are equivalent inductors of the transmitter and four receivers, respectively. Four receivers are connected by a mutual inductance M_n. In Figure 2, the sinusoidal voltage source U_S has a voltage of V_S and an impedance of R_S. C_1 and C_{n3} are parasitic capacitors. R_1 and R_{n2} are parasitic resistances. Each receiver is connected with a load impedance R_{Ln}. Series capacitors of C_S and C_{Ln} as well as parallel capacitors of C_2 and C_{n4} are added to reduce the reactance of the transmitter and receivers to match the impedance of the circuit at the resonant frequency. w is the resonance angular frequency of the system, and V_{Ln} is the voltage of R_{Ln}.

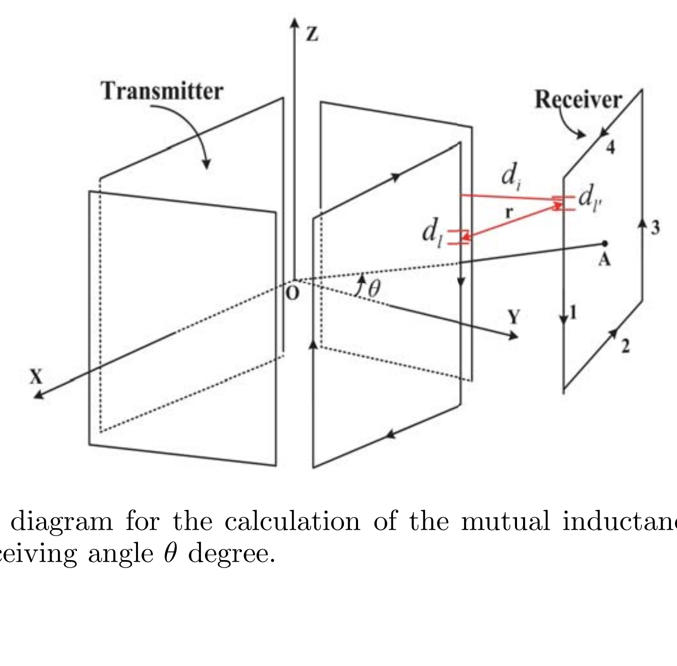

Figure 3. Schematic diagram for the calculation of the mutual inductance between the transmitter and receiver at the receiving angle θ degree.

Figure 3 shows the schematic diagram of the transmitter and the receiver at the receiving angle θ degrees for calculating mutual inductance. The mutual inductance between two parallel wires can be derived by solving Neumann's formula

$$M_1|_i = \frac{\mu_0}{4\pi} \iint \frac{d_l d_{l'}}{r} \tag{1}$$

where d_l and $d_{l'}$ define the infinitesimal of l of the transmitter and receiver, respectively. r is the distance between d_l and $d_{l'}$, and μ_0 is the magnetic permeability of free space. With two wires of same length l, Eq. (1) can be reduced by

$$M_1|_i = \frac{\mu_0 l}{2\pi}\left[\ln\left(\frac{l}{d_{1i}} + \sqrt{1+\frac{l^2}{d_{1i}^2}}\right) - \sqrt{1+\frac{d_{1i}^2}{l^2}} + \frac{d_{1i}}{l}\right] \tag{2}$$

where d_{1i} is the distance between the first wire of the receiver and the considered parallel wire of the transmitter. The total mutual inductance between the transmitter and receiver at the receiving angle θ degree is given by

$$M_\theta = \sum_{k=1}^{4} M_k|_i = \sum_{k=1}^{4}\sum_{i=1}^{N_1} M_k|_i - \sum_{k=1}^{4}\sum_{j=1}^{N_2} M_k|_j \tag{3}$$

where N_1 and N_2 are the numbers of transmitter wires in which the current flows in the same and opposite directions with the current in the receiver wire, respectively. From Eq. (3), the mutual inductance between the transmitter and receiver can be calculated at each receiving angle.

The coupling coefficient k_n between the transmitter and receivers is related to M_n through the formula

$$k_n = \frac{M_n}{\sqrt{L_1 L_{n2}}} \tag{4}$$

According to Kirchhoff's voltage law (KVL), the voltage equations of the system are obtained.

$$(i_1 + i_2)Z_1 + jwM_n(i_{n3} + i_{n4}) + i_2 Z_S = V_S \tag{5}$$

$$(i_{n3} + i_{n4})Z_{n2} + jwM_n(i_1 + i_2) + i_{n4} Z_{Ln} = 0 \tag{6}$$

$$V_S = i_2 R_S + i_2 \frac{1}{jwC_S} - i_1 \frac{1}{jwC_2} \tag{7}$$

$$V_{Ln} = -i_{n4} R_{Ln} = i_{n4} \frac{1}{jwC_{Ln}} - i_{n3} \frac{1}{jwC_{n4}} \tag{8}$$

where

$$\begin{aligned} Z_1 &= R_1 + jwL_1 + \frac{1}{jwC_1} \\ Z_{n2} &= R_{n2} + jwL_{n2} + \frac{1}{jwC_{n3}} \\ Z_S &= R_S + \frac{1}{jwC_S} \\ Z_{Ln} &= R_{Ln} + \frac{1}{jwC_{Ln}} \end{aligned}$$

Solving the above equations yields V_{Ln}/V_S which can be expressed as follows,

$$\frac{V_{Ln}}{V_S} = \frac{jwk_n\sqrt{L_1 L_{n2}} R_{Ln} Z_S}{\begin{pmatrix} w^4 k_n^2 L_1 L_{n2} C_2 C_{n4} R_S Z_S Z_{Ln} - jw^3 k_n^2 L_1 L_{n2} R_S (C_2 Z_S + C_{n4} Z_{Ln}) - R_S (Z_S + Z_1)(Z_{Ln} + Z_{n2}) \\ -jwR_S[C_2 Z_S Z_1 (Z_{Ln} + Z_{n2}) + C_{n4} Z_{Ln} Z_{n2} (Z_S + Z_1)] - w^2 R_S (k_n^4 L_1 L_{n2} - C_2 C_{n4} Z_S Z_{Ln} Z_1 Z_{n2}) \end{pmatrix}} \tag{9}$$

The PTE is calculated in terms of scattering parameter $|S_{21}|$ by $\mathrm{PTE}_n = |S_{21}|^2$ [27]

$$S_{21} = 2\frac{V_{Ln}}{V_S}\sqrt{\frac{R_S}{R_{Ln}}} \tag{10}$$

Therefore, the total PTE of the system is calculated by $\mathrm{PTE} = \Sigma \mathrm{PTE}_n$.

3. SIMULATION OF THE OMNIDIRECTIONAL MRCWPT SYSTEM

The simulation model of the omnidirectional MRCWPT system with a transmitter and four receivers is established in the electromagnetic simulation software HFSS. The system simulation model is illustrated in Figure 4. d shown in Figure 4 is the distance value between the transmitter and receiver. The transmitter is powered by the driven current to generate magnetic field. The four identical receivers are placed around the transmitter to obtain power, and the adjacent receivers are orthogonal. The matching circuits are used to match the system impedance and improve the stability of the system.

3.1. Simulation of Omnidirectional Magnetic Field Distribution

The currents flow in opposite directions in the closely coupled wires, which is beneficial to magnetic field emission. The gap value between the adjacent plane coils for the transmitter is 15 mm. The concrete parameters and values of the transmitter and receivers are shown in Table 1. The system reflection coefficient S_{11} at different frequencies is shown in Figure 5. It is obvious that the system resonant frequency is 15.5 MHz. With this frequency, the circuit dimension is much smaller than the wavelength of the current, so we can assume that the current in each side coil of the transmitter is identical.

Figure 6 demonstrates the magnetic field distribution of the omnidirectional cubic transmitter in different planes. The simulation results of the omnidirectional magnetic field distributions in XOY, YOZ, and ZOX planes are shown in Figures 6(a), (b), and (c), respectively. Figure 6(d) demonstrates the simulation result of magnetic field distribution in a plane where its normal vector at an angle of 45 degrees to the positive axis of X and Y. It is obvious that the magnetic field distribution around the transmitter is homogeneous and omnidirectional.

Furthermore, Figure 7 presents the magnetic field distribution of the transmitter along with different numbers of receivers to better understand the coupling between the transmitter and multiple receivers. The magnetic field distributions of the transmitter with one, two, three, and four receivers in the XOY plane are shown in Figures 7(a), (b), (c), and (d) respectively. Obviously, the magnetic field distribution around the transmitter is omnidirectional regardless of the number of receivers, and the coupling between the transmitter and different numbers of receivers is good enough through the homogeneous magnetic field between the transmitter and receivers.

The magnetic field magnitudes at different receiving angles are illustrated in Figure 8 at points with a resonant frequency of 15.5 MHz and at a distance of 160 mm between the transmitter and receivers. Apparently, the magnetic field magnitude is about 0.5 A/m at different receiving angles. It is further proved that the magnetic field of the transmitter is uniformly distributed in all directions. The transmitter can transmit power to receivers in different directions.

Table 1. The parameters and values of the transmitter and receivers.

Transmitter		Four Receivers	
Parameter	Value	Parameter	Value
Structure	Cubic	Structure	Plane
Material	Copper	Material	Copper
Wire Diameter	2 mm	Wire Diameter	2 mm
Wire Spacing	8 mm	Wire Spacing	8 mm
Turn	4	Turn	4
Coil Diameter	120 mm	Coil Diameter	120 mm

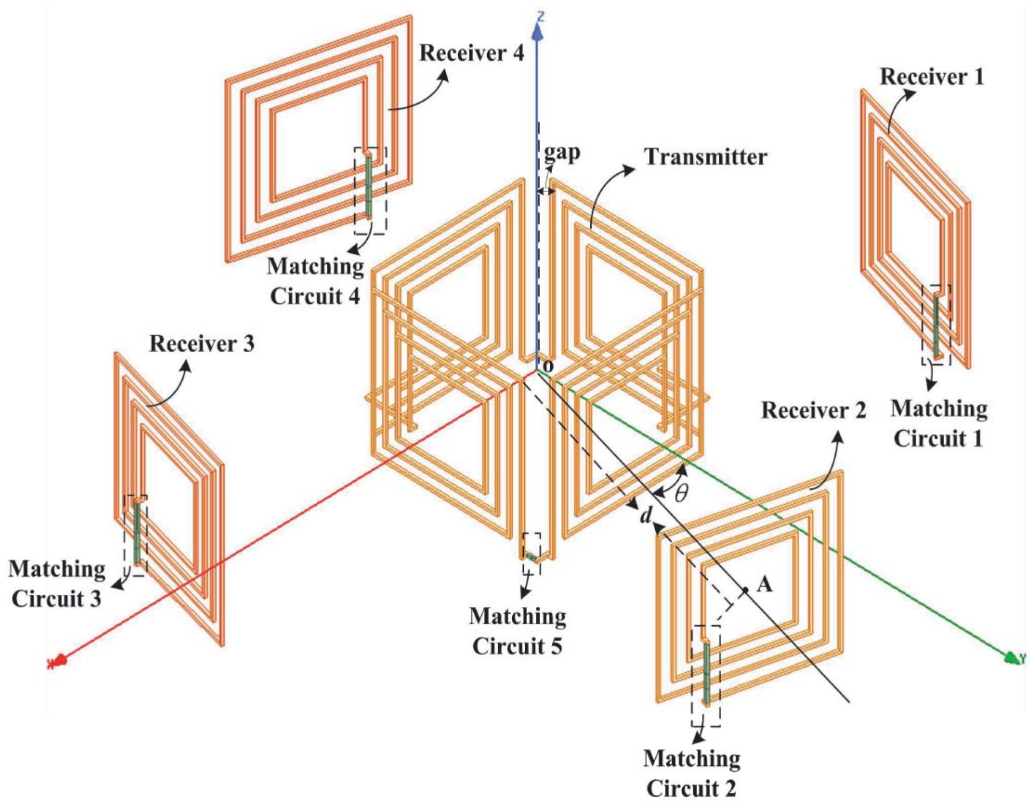

Figure 4. The simulation model of the MRCWPT system with a transmitter and four receivers.

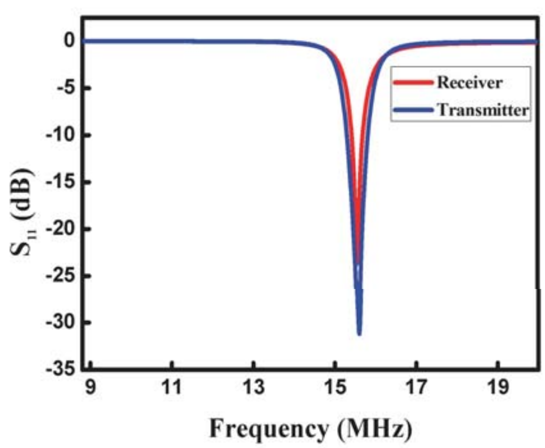

Figure 5. The system reflection coefficient S_{11} at different frequencies.

3.2. The PTE of the Omnidirectional MRCWPT System with Different Number of Receivers

According to the theoretical analysis described in Section 2, the PTE of the omnidirectional MRCWPT system is derived by the equivalent circuit model of the system. Also, the total PTE of the system is equal to the sum of the PTE of each receiver. In order to discuss if the total PTE will be influenced by different numbers of receivers, the PTE of the omnidirectional MRCWPT system with different numbers of receivers has been simulated in the electromagnetic simulation software HFSS. The finite

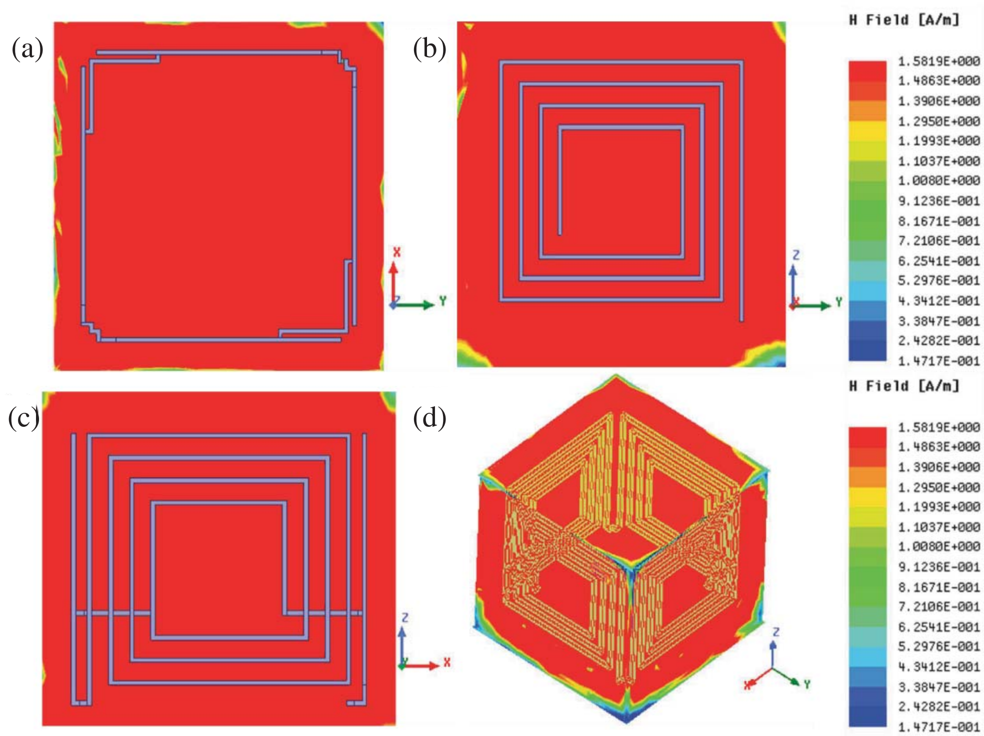

Figure 6. The magnetic field distribution of the transmitter.

element simulation results of the PTE with one, two, three, and four receivers are shown in Figure 9. The results of the total PTE of the system with different numbers of receivers show that the total PTE increases slightly with the number of receivers. Also, the PTE of each receiver decreases as the number of receivers increases due to the law of conservation of energy. As a result, the increase in the number of receivers is beneficial to the total PTE of the proposed omnidirectional MRCWPT system. And the PTE on a single receiver varies little as the number of receivers increases, which has also shown that the magnetic field between the transmitter and different numbers of receivers shown in Figure 8 is homogeneous.

4. EXPERIMENTAL VERIFICATION OF THE MRCWPT SYSTEM

To verify the correctness of theoretical analysis of the system, the transmitter and four receivers are fabricated by using a copper wire with the parameters given in Table 1. The practical volume of the transmitter is 120 mm $\times$ 120 mm $\times$ 120 mm. The experimental platform of the system is shown in Figure 10. The transmitter is driven by a single source which is generated by a signal generator (Tektronix AFG1062). The oscilloscope (Tektronix MDO3012) is used to measure the signal of the receivers. The matching circuits are used to match the impedance of the system. The transmitter coil is fixed in one position, and four receivers are placed around the transmitter at different angles. The angles value θ is shown in Figure 3. The MRCWPT system circuit parameters are illustrated in Table 2. In Table 2, the equivalent parameters R_1, C_1, and L_1 of the transmitter as well as the equivalent parameters R_2, C_2, and L_2 of the receiver are measured by the impedance analyzer (KEYSIGHT E4990A). The measuring instrument of the impedance analyzer is shown in Figure 11. The measurement procedure of the parameters includes four steps in general. Firstly, the impedance analyzer should be calibrated with a resistor of 50 Ω. Secondly, the transmitter or receiver is connected with the impedance analyzer by a terminal adapter (KEYSIGHT 42942A) and spring clip fixture (KEYSIGHT 16092A). Thirdly, select the format of the equivalent circuit. Finally, take measurements and get results. Other circuit parameters such as the source impedance of R_S, load impedance R_L, series impedance matching capacitors of C_S

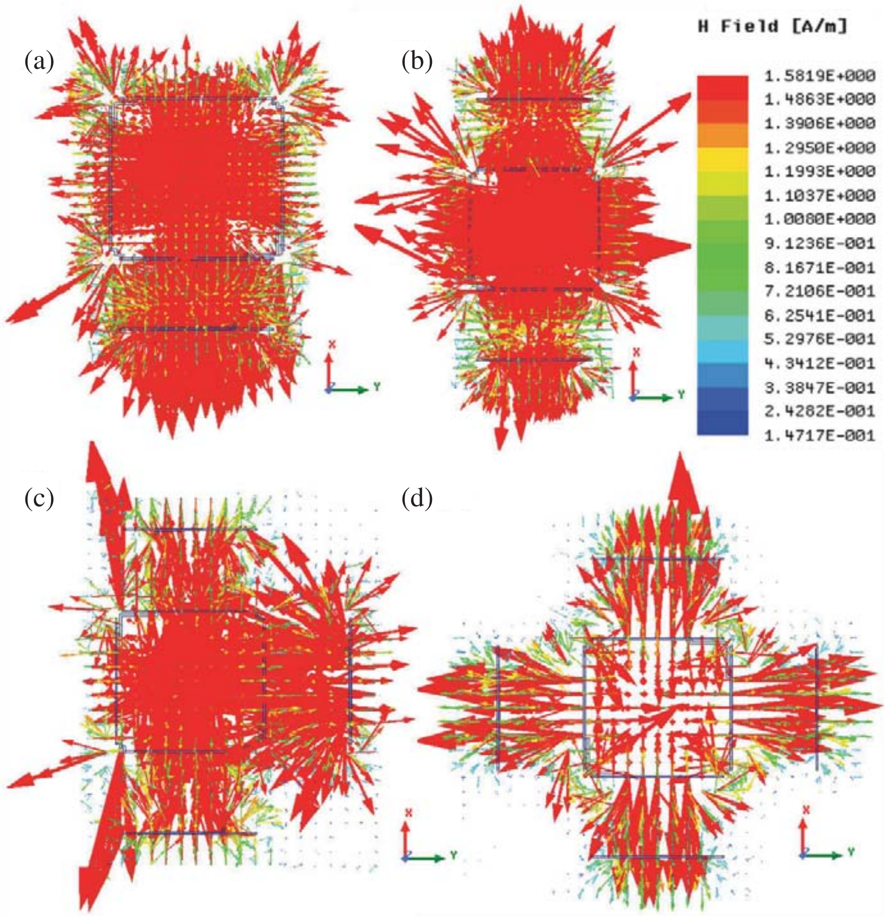

Figure 7. The magnetic field distribution of the transmitter along with different number of receivers.

Table 2. The circuit parameters of the MRCWPT system.

Transmitter		Receivers	
Parameter	Value	Parameter	Value
R_S	$50\,\Omega$	R_L	$50\,\Omega$
R_1	$1.39\,\Omega$	R_2	$0.76\,\Omega$
C_1	6.1 pF	C_3	12.3 pF
C_2	3 pF	C_4	32 pF
C_S	12 pF	C_L	15.5 pF
L_1	28.9 µH	L_2	12.6 µH

and C_L, as well as parallel impedance matching capacitors of C_2 and C_4 in Table 2, are all known in advance.

The mutual inductances between the transmitter and receiver are measured at the receiving angles and a distance of 160 mm from the origin of the coordinate system. A comparison of mutual inductance between simulation and measurement results is shown in Figure 12. There is a good agreement between the simulated and measured results that are obtained using Eq. (3) to describe mutual inductance of the transmitter and receiver. Measured results are slightly lower than the simulated ones, and there is an average relative error about 4.8% between the experimental and simulated results.

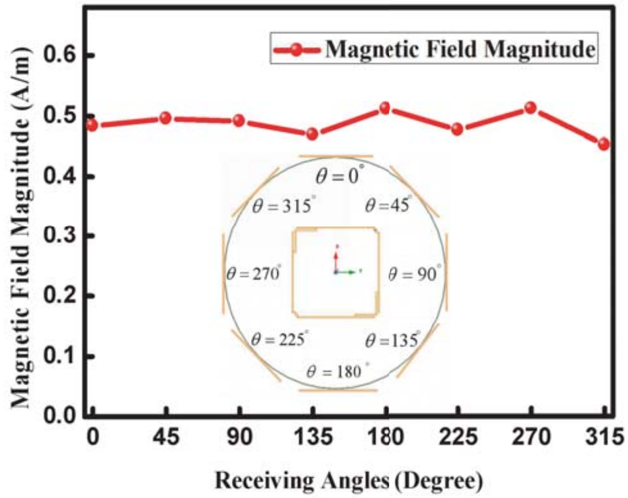

Figure 8. The magnetic field magnitude at different receiving angles.

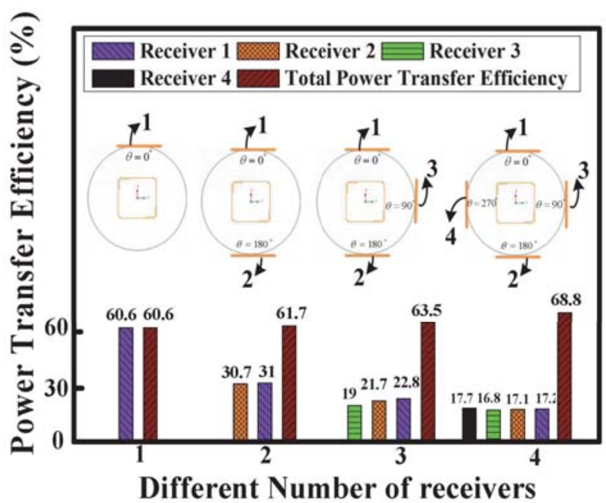

Figure 9. The PTE of the omnidirectional MRCWPT system with different number of receivers.

Table 3. Comparison of this research with other previous researches.

WPT Type	Transmitter Structure	Frequency	PTE	Reference
Unidirectional, multiple receivers	Spiral coil with a single source	22.5 MHz	29%	[15]
Omnidirectional, one receiver	Orthogonal coils with current control methods	550 kHz	69%	[17]
Omnidirectional, multiple receivers	Orthogonal coils with a single source	640 kHz	Not mention	[21]
Omnidirectional, multiple receivers	Cubic Transmitter with a single source	15.5 MHz	60%	This work

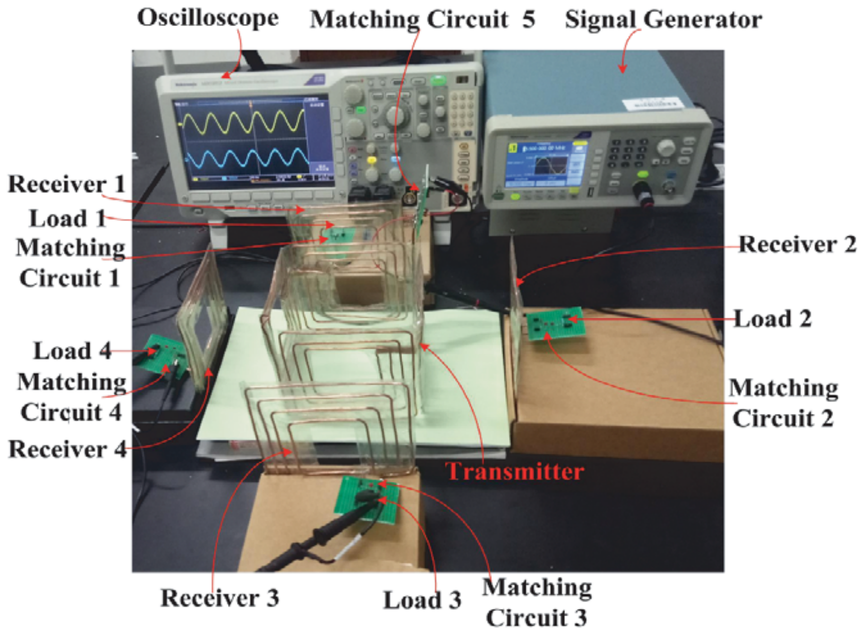

Figure 10. The experimental platform of the MRCWPT system.

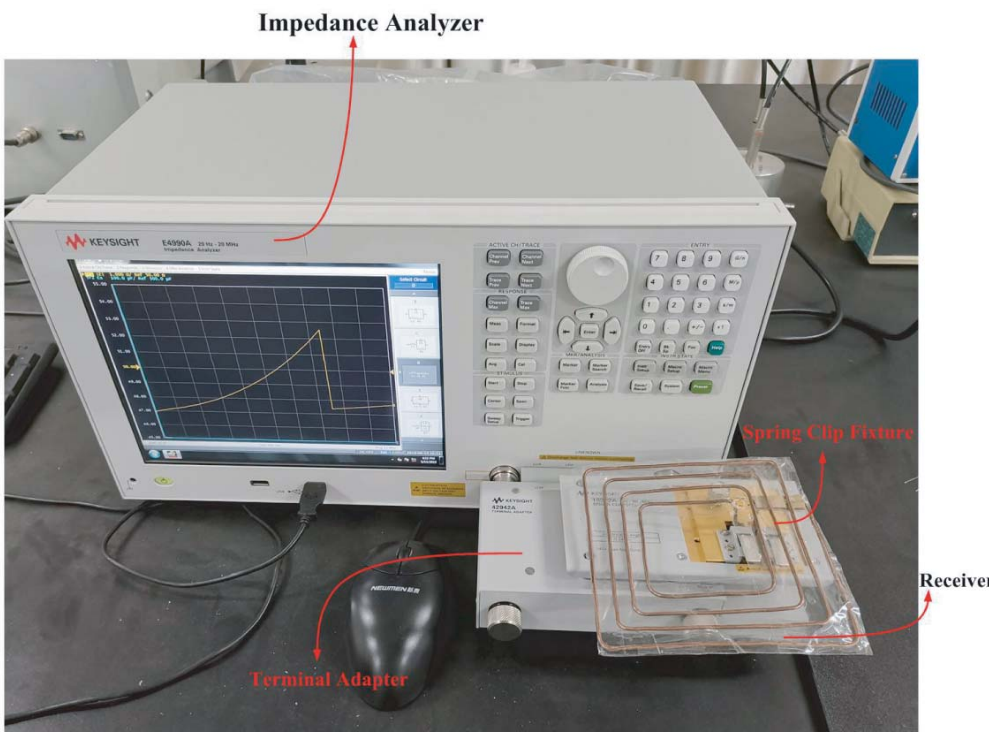

Figure 11. The measuring instrument of impedance analyzer (KEYSIGHT E4990A).

The PTE of the receivers and the total PTE of the system are measured by using Eq. (10) at different angles and a distance of 160 mm. The distance value d is shown in Figure 4, and the system works at the resonant frequency of 15.5 MHz. Comparison of the PTE between the simulation and measurement results at different receiving angles is plotted in Figure 13. Figure 13(a) demonstrates the PTE of the receivers and the system in the case that four receivers are placed around the transmitter

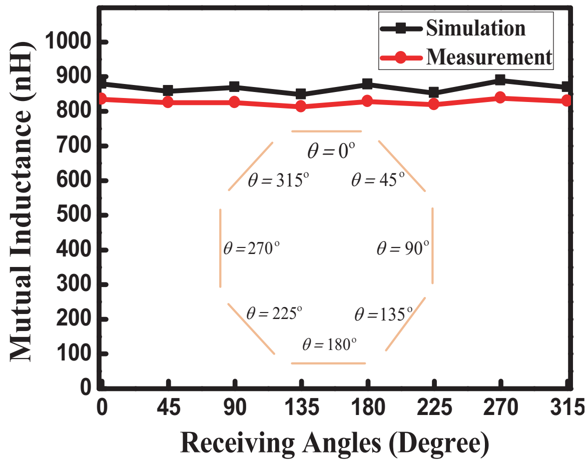

Figure 12. Comparison of simulated and measured mutual inductance values at different angles.

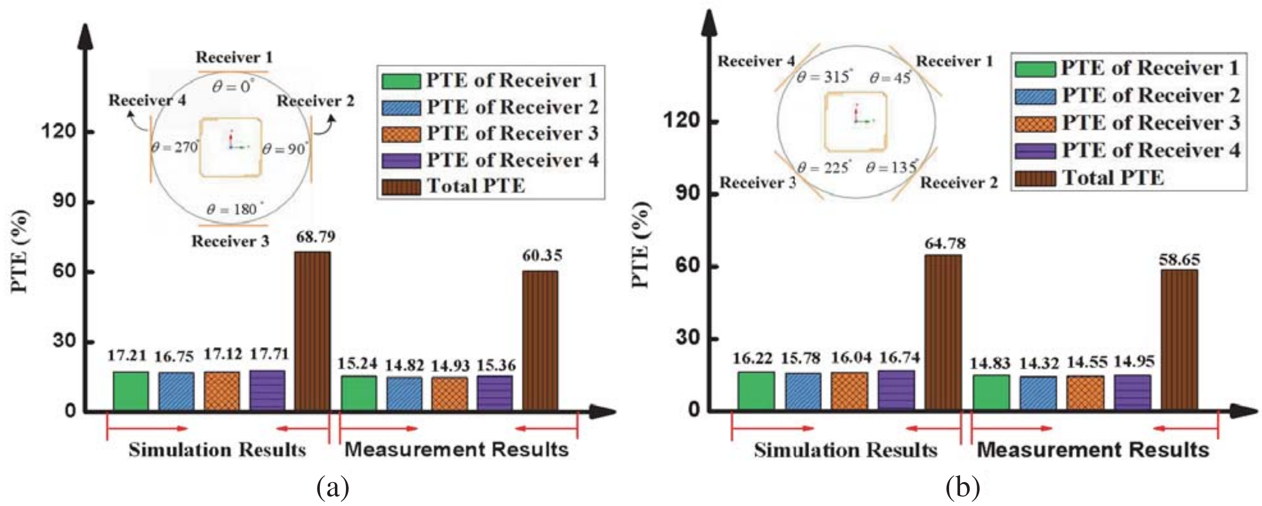

Figure 13. Comparison of the PTE between the simulation and measurement results at different angles.

at the angles of 0°, 90°, 180°, and 270°. When four receivers are placed around the transmitter at the angles of 45°, 135°, 225°, and 315°, the PTE of the receivers and the system in this case is provided in Figure 13(b). In general, the measured PTE is 12.3% lower than simulated results due to the fabrication tolerance. It is obvious that the PTE of the system keeps around 60%, and the PTE of each receiver is relatively close in each case. Therefore, it is concluded that the magnetic field distribution around the practical transmitter is uniform, which is consistent with the simulation results. The theoretical analysis of the system is verified by the experiment.

The experimental results of evolution of the PTE with increasing in the distance are shown in Figure 14 as well as the simulation results. It is obvious that the PTE decreases when the distance value increases. The measurement results are relatively lower than the simulation ones, which have relative error about 7% because of practical fabrication tolerance. At the distance of 160 mm, the PTE of the system reaches 60%.

Similar studies on omnidirectional system as well as novel omnidirectional system for multiple receivers in this work are summarized in Table 3. Clearly, an omnidirectional MRCWPT system with multiple receivers is proposed, which requires only a single power source. And the PTE of the system reaches 60% at the working frequency of 15.5 MHz.

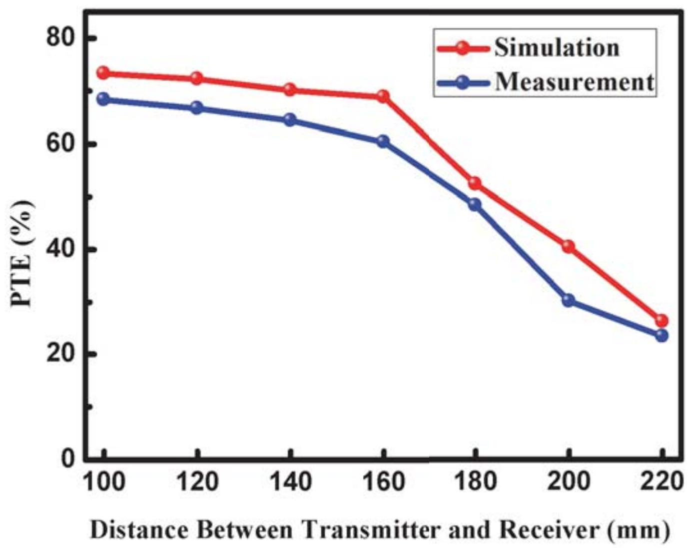

Figure 14. Comparison of the system PTE between the simulation and measurement results at different distance values.

5. CONCLUSION

In this paper, an omnidirectional MRCWPT system with multiple receivers is proposed. An equivalent circuit model of the system is established to derive the PTE. The magnetic field distribution around the transmitter is uniform, and the magnetic field magnitude is about 0.5 A/m in each direction. The increase in the number of receivers is beneficial to the total PTE of the proposed omnidirectional MRCWPT system. In addition, practical experiment of the MRCWPT system verifies the correctness of theoretical analysis. It is shown that the PTE of the system is about 60% at the resonant frequency of 15.5 MHz and a distance of 160 mm. The system with multiple receivers requires only a single power source without complex control methods, which will greatly facilitate its use.

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