Progress In Electromagnetics Research M, Vol. 110, 73–82, 2022

Analysis of a Three-Coil Wireless Power Transfer System Operated under Hybrid Resonant Frequency

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Abstract—To enhance transmission performance, a novel three-coil wireless power transfer system is proposed in this work. Unlike the traditional system in which three coils are resonant, the coils in the proposed system are hybrid resonant. According to theoretical calculation, it is found that output power is dependent on resonant frequency of the transmitting coil and relay coil once the receiving coil is set to resonate at the operating frequency. Simulation work is conducted. Under various distances between transmitting coil and relay coil, resonant frequency of the two coils at which the output power is maximized is obtained. Compared with the traditional resonant system, the simulation result shows that output power of the proposed hybrid resonant system is higher especially at smaller distance. For further validation, experiments have been carried out which verify that better performance can be realized with the proposed hybrid resonant system.

1. INTRODUCTION

Attributing to the merit of energy delivery without electric wires, wireless power transfer (WPT) has drawn considerable attention [1–3]. Generally, this technique can be categorized into near-field and far-field energy transfer [4, 5]. Previous research has demonstrated that electromagnetic coupling in terms of near-field mode is more favorable due to its output performance. Especially, resonant WPT has been well known and shows its great potential in the power supply of electric vehicles [6–8], electronic devices [9–11], and biomedical implants [12–15].

Two-coil resonant WPT systems have been comprehensively investigated [16–20]. However, the transfer performance suffers from dramatic decrease once transmission distance becomes longer. To tackle this problem, three-coil resonant WPT systems have been studied. By introducing a relay coil, the power is preliminarily delivered from the transmitting side to the relay and then to the receiving side. In [21], a relay coil is adopted, and maximum efficiency transmission is realized. It has been proved that such a system tends to be more efficient than the two-coil counterpart. In [22], the simplified circuit model of a three-coil resonant WPT system is analyzed. Comparatively, higher transfer efficiency can be achieved than the two-coil system. Furthermore, by selecting optimal compensation capacitance of the relay coil, it is found that a three-coil structure is more efficient [23]. This is because the apparent self-inductance and magnetizing inductance are increased with the relay coil added. In [24], an optimal design method is proposed for efficient transmission. The relay coil is set to operate at the frequency where bifurcation phenomenon occurs. Additionally, a three-coil resonant WPT system with dual-band characteristic has been proposed [25]. A novel system with a U-coil structure is presented in [26]. It is supposed to enhance efficiency and improve spatial cleanliness of the power delivery. Simultaneously, the dimension of coils is largely reduced. In [27], frequency characteristics of a three-coil WPT system are explored. At different positions, the operating frequency which corresponds to maximum output power

Received 18 March 2022, Accepted 18 April 2022, Scheduled 29 April 2022
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and transfer efficiency is respectively calculated. It is found that the frequency varies with positions. This work offers a reference for frequency tracking of optimal transmission performance. From the state-of-art review of resonant WPT systems, it can be concluded that the three-coil resonant WPT system is preferred since its performance outperforms the two-coil system.

Generally, the transmitting coil, relay coil, and receiving coil in these previous studies have been set to resonate at the operating frequency. In this work, with the main objective of power enhancement, the output power of a three-coil system is calculated. It is found that the resonant frequency of the transmitting coil and relay coil has a direct impact on the output performance once the resonant frequency of the receiving coil is fixed at the operating frequency. Consequently, different from previous literatures, a novel three-coil WPT system operated under hybrid resonant frequency is proposed in this work. With the distance between the transmitting coil and receiving coil fixed, resonant frequency of the transmitting coil and relay coil is determined at which output power can be maximized. The performance of the proposed system is studied through simulation and experimental work. In Section 2, mathematical modeling of a three-coil WPT system is given. According to theoretical calculation, output power and input impedance are mathematically formulated. In Section 3, simulation work is performed. The optimal resonant frequencies of transmitting coil and relay coil at various distances are obtained. Besides, the output powers of the proposed and traditional systems are compared. The variation of input impedance is investigated. Experimental validation is carried out in Section 4. Section 5 draws a conclusion.

2. MATHEMATICAL MODELING

For a three-coil WPT system, its equivalent schematic diagram is shown in Fig. 1. The coils are respectively represented by serially connected inductance L_i and resistance R_i ($i = 1, 2, 3$); C_i stands for compensation capacitor in each loop; $\mathbf{V}_S$ is the power source; ω is the operating frequency; R_S is the internal resistance of power source; R_L is the load; $\mathbf{I}_i$ denotes the current in each loop; $M_{i,j}$ represents the mutual inductance between loops.

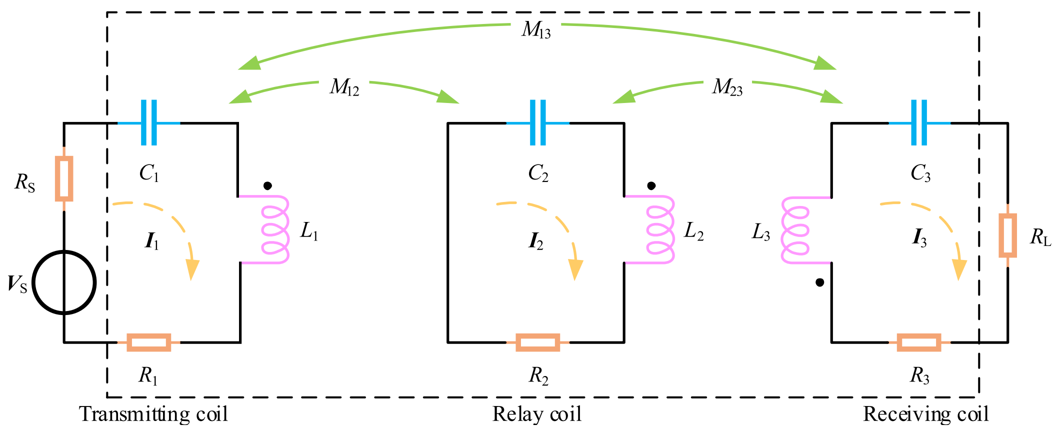

Figure 1. Equivalent schematic diagram.

For a helix coil, its resistance mainly includes loss resistance $R_{i\text{loss}}$ and radiation resistance $R_{i\text{rad}}$ which is written as [28]

$$R_i = R_{i\text{loss}} + R_{i\text{rad}} = \frac{r_i}{r_{ci}}\sqrt{\pi\mu_0\rho f} + 320\pi^6\left(\frac{r_i f}{c}\right)^4 \tag{1}$$

where r_i is the radius of coils; r_{ci} is radius of wire; μ_0 is the permeability in free space; ρ and c are respectively the resistivity of material and speed of light; f is the operating frequency.

The self-inductance of the coil is computed by [29]

$$L_i = \mu_0 r_i\left[\ln\left(\frac{8r_i}{r_{ci}}\right) - 2\right] \tag{2}$$

To make the three-coil WPT system resonate, the capacitance should be

$$C_i = \frac{1}{(2\pi f_i)^2 L_i} \tag{3}$$

where f_i denotes the resonant frequency of the ith loop.

The mutual inductance M between two coils can be computed by

$$\begin{cases} M = \sum_{p=1}^{n1} \sum_{q=1}^{n2} M_{pq}\left(r_p, r_q, D\right) \\ M_{pq}\left(r_p, r_q, D\right) = \frac{2\mu_0}{k} \sqrt{r_p r_q} \left[\left(1 - \frac{k^2}{2}\right) K\left(k\right) - E(k) \right] \\ k(r_p, r_q, D) = \sqrt{\frac{4 r_p r_q}{\left(r_p + r_q\right)^2 + D^2}} \end{cases} \tag{4}$$

where n_1 and n_2 represent turns of coils; r_p and r_q denote radius of the pth turn and the qth turn of coils; D is the transfer distance; $K(k)$ and $E(k)$ are respectively the first kind and second kind of ellipse integral.

From Kirchhoff's law, the three-coil WPT system can be mathematically modeled by

$$\begin{pmatrix} Z_{11} & j\omega M_{12} & j\omega M_{13} \\ j\omega M_{12} & Z_{22} & j\omega M_{23} \\ j\omega M_{13} & j\omega M_{23} & Z_{33} \end{pmatrix} \begin{pmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \mathbf{I}_3 \end{pmatrix} = \begin{pmatrix} \mathbf{V}_S \\ 0 \\ 0 \end{pmatrix} \tag{5}$$

where $Z_{11} = R_S + R_1 + j(\omega L_1 - 1/(\omega C_1))$, $Z_{22} = R_2 + j(\omega L_2 - 1/(\omega C_2))$, $Z_{33} = R_L + R_3 + j(\omega L_3 - 1/(\omega C_3))$.

By solving Eq. (5), it can be obtained that

$$\frac{\mathbf{I}_1}{\mathbf{I}_3} = -\frac{Z_{22} Z_{33} + \omega^2 M_{23}^2}{j\omega M_{13} Z_{22} + \omega^2 M_{12} M_{23}} \tag{6}$$

$$\frac{\mathbf{I}_2}{\mathbf{I}_3} = \frac{M_{12} Z_{33} - j\omega M_{13} M_{23}}{M_{13} Z_{22} - j\omega M_{12} M_{23}} \tag{7}$$

$$\mathbf{I}_3 = \frac{\mathbf{V}_S}{Z_{11} \frac{\mathbf{I}_1}{\mathbf{I}_3} + j\omega M_{12} \frac{\mathbf{I}_2}{\mathbf{I}_3} + j\omega M_{13}} \tag{8}$$

For the three-coil WPT system, the active power delivered to the load can be expressed by

$$P_{out} = I_3^2 R_L \tag{9}$$

where I_3 denotes the effective value of the current flowing through the receiving coil.

The transmission efficiency can be expressed by the ratio between load power and total power. Therefore, the transmission efficiency can be calculated as

$$\eta = \frac{I_3^2 R_L}{I_1^2 (R_S + R_1) + I_2^2 R_2 + I_3^2 (R_L + R_3)} \tag{10}$$

For a certain load, it can be found from Eq. (6) to Eq. (9) that the power delivered to the load is closely related to the impedances of loops (Z_{11}, Z_{22}, Z_{33}) once the distance between coils is fixed. Generally, the impedance is supposed to be resistance in a traditional three-coil resonant WPT system where the coils are set to resonate at the operating frequency by matching suitable capacitor. It is known that the impedances of loops can be modified by adjusting the resonance frequency. In this work, the performance of a three-coil hybrid resonant WPT system in which transmitting coil and relay coil are not resonant at the operating frequency is studied. Under such a condition, Z_{11} and Z_{22} will be complex values instead of real values.

Additionally, the input impedance can be used as an alternative to evaluate the power transfer performance. Combined with the input voltage $\mathbf{V}_{in} = \mathbf{V}_S - R_S \mathbf{I}_1$, the input impedance Z_{in} is derived as

$$Z_{in} = Z_{11} - R_S + j\omega M_{12} \frac{\mathbf{I}_2}{\mathbf{I}_3} \cdot \frac{\mathbf{I}_3}{\mathbf{I}_1} + j\omega M_{13} \cdot \frac{\mathbf{I}_3}{\mathbf{I}_1} \tag{11}$$

3. PERFORMANCE EVALUATION OF THE PROPOSED WPT SYSTEM

The configuration of a three-coil hybrid resonant WPT system is depicted in Fig. 2. As shown in Fig. 2, the transmitting coil and receiving coil are respectively linked to a power source and a load. All the three coils are helical winded with 5 turns. The radius of coils is 8 cm, and the cross-sectional radius of copper wire is 1.1 mm. In the simulation study, the receiving coil is set to be resonant at the operating frequency. Different from this, the resonance frequency of the transmitting coil and relay coil is set to vary in a certain range. Correspondingly, the impedance of the loops at the operating frequency would change. The resonant frequencies of transmitting coil and relay coil are respectively denoted as f_T and f_R. The transfer distance between transmitting and receiving coils is fixed at 16 cm. The distance between transmitting and relay coils is denoted as d.

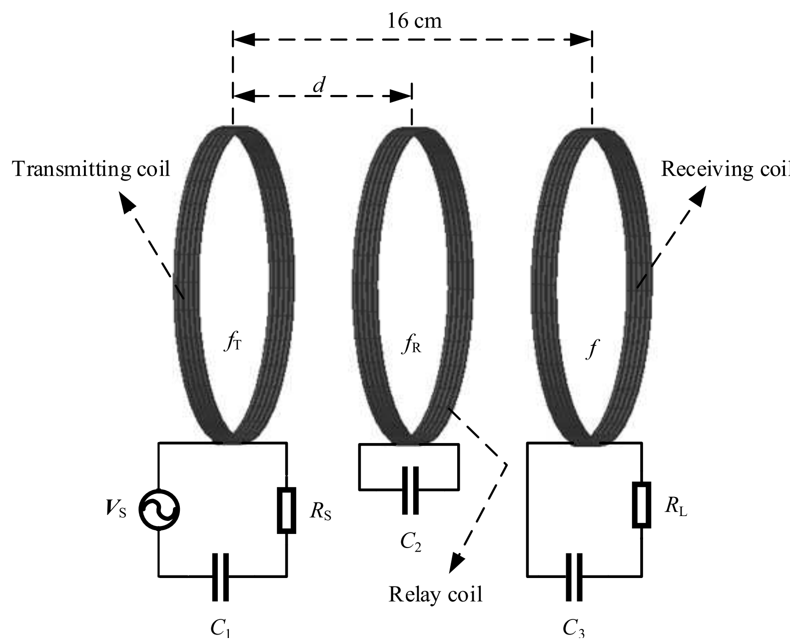

Figure 2. Configuration of a three-coil hybrid resonant WPT system.

The frequency and voltage of the power source are 6.78 MHz and 10 Vpp. Besides, the receiving coil is resonant at 6.78 MHz, and the load resistance is 50 Ω. Based on Eq. (8) and Eq. (9), output power versus resonant frequencies of transmitting coil and relay coil when $d = 5$ cm is depicted in Fig. 3. It can be observed that maximum output power is 62 mW. The corresponding resonant frequencies of transmission coil and relay coil are respectively $f_T = 7.3$ MHz and $f_R = 7.1$ MHz. In Fig. 4, magnetic field distributions at $f_T = 7.3$ MHz and $f_R = 7.1$ MHz are compared with the traditional system where three coils are set to resonate at 6.78 MHz. Obviously, stronger magnetic coupling is observed for the proposed hybrid system where the coils are not simultaneously resonant. The result indicates that more energy will be transferred.

Similarly, resonant frequencies of transmitting coil and relay coil at which the output power is maximized can be found when the distance between transmitting coil and receiving coil varies from 1 cm to 12 cm with a step of 1 cm. The results are listed in Table 1. With the variation of distance between transmitting coil and relay coil, it can be seen that resonant frequencies of the two coils change.

According to the resonant frequencies of transmitting and relay coils listed in Table 1, output power of hybrid resonant WPT system is calculated and compared with that of a traditional resonant WPT system, as shown in Fig. 5. Obviously, the output power of a hybrid resonant system tends to be higher than its counterpart. At a smaller distance, there is a large difference between the two systems. The output power remains high and constant for the proposed hybrid resonant WPT system while a dramatic variation is observed for the traditional resonant WPT system. Once the distance

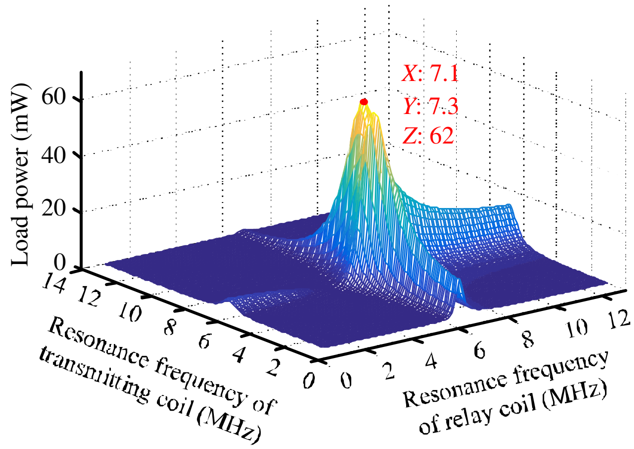

Figure 3. Output power versus resonant frequency of transmitting coil and relay coil.

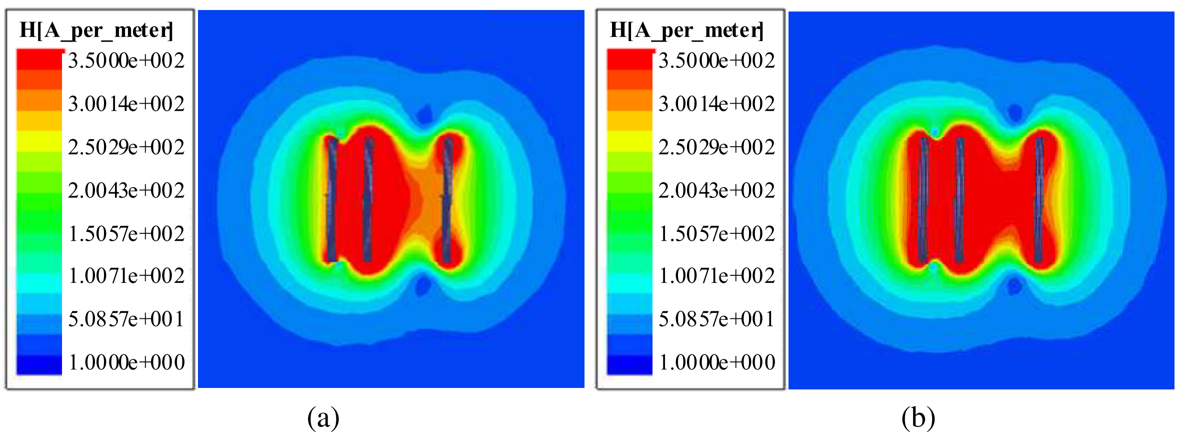

Figure 4. Electromagnetic coupling at $d = 5\,\text{cm}$. (a) Three coils are simultaneously resonant. (b) Three coils are not simultaneously resonant.

Table 1. Resonant frequency of transmitting coil and relay coil for hybrid resonant WPT system.

d (cm)	f_T (MHz)	f_R (MHz)
1	9.2	7.3
2	8.6	7.2
3	7.9	7.2
4	7.5	7.2
5	7.3	7.1
6	7.0	7.0
7	6.7	6.9
8	6.7	7.0
9	6.7	7.2
10	6.8	7.8
11	6.8	9.0
12	6.8	11.8

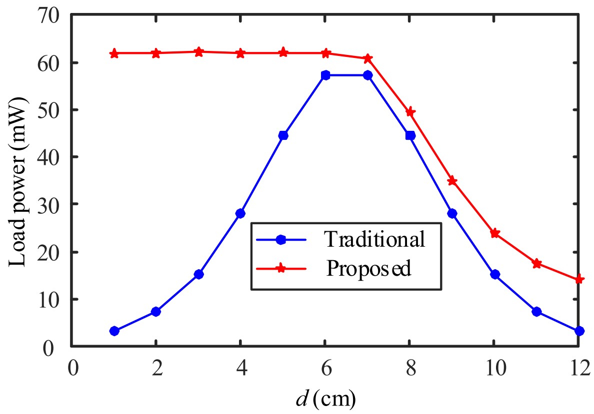

Figure 5. Comparison of output power against distance between transmission and the relay coils.

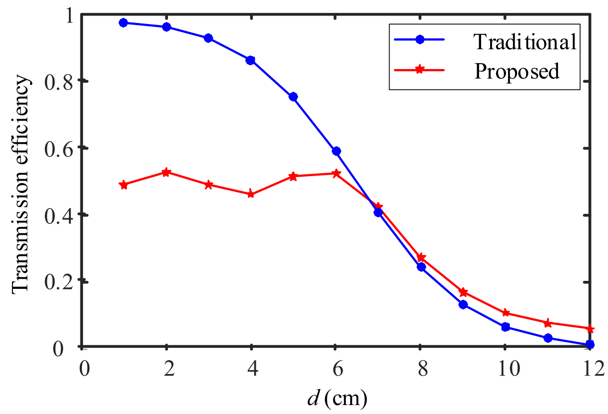

Figure 6. Transmission efficiency versus the distance between the transmission coil and the relay coil.

between transmission coil and relay coil is beyond a certain value, output power is reduced for both of the systems. Nevertheless, the performance of the proposed system still outperforms the traditional system.

Figure 6 compares the transmission efficiencies of the traditional system and the proposed system. It can be noted that the efficiency rapidly decreases for the traditional system. Comparatively, the efficiency of the proposed system keeps relatively stable and is smaller when the distance between the transmission coil and relay coil is smaller than 7 cm. For the distance larger than 7 cm, the transmission efficiency of the proposed system is a little higher.

Impedance matching may offer an explanation why the proposed hybrid system outperforms the traditional resonant system. According to Eq. (11), input impedance is calculated and compared to evaluate power transfer ability. Little power would be delivered if argument of the input impedance approximates 90° or −90° which indicates pure inductive or capacitive impedance. The output power is higher when amplitude of the input impedance is matched to internal resistance of the power source and when the absolute value of the argument is small. In Fig. 7, the amplitude and argument of the input impedance against the distance are depicted respectively in Fig. 7(a) and Fig. 7(b). It can be seen that amplitude of the input impedance for the proposed hybrid resonant WPT system is about 50 Ω, and the argument is close to 0° when the transmission distance between transmitting coil and relay coil is smaller than 7 cm. Even for larger distance, a better impedance matching is observed. Therefore, the output power tends to be higher.

4. EXPERIMENTAL VALIDATION

The experimental setup of a three-coil hybrid resonant WPT system is shown in Fig. 8. Parameters of the coils are the same as those in Section 3. The power source has the amplitude of 10 Vpp and is set to operate at the frequency of 6.78 MHz. The distance between transmitting coil and receiving coil is fixed at 16 cm. During the experiment, the distance between transmitting coil and relay varies. By selecting appropriate capacitors, the resonance frequencies of transmitting coil and relay coil at different distances are set according to the simulation results shown in Table 1. The receiving coil is resonant at the operating frequency. The load is 50 Ω. With an oscilloscope, the load voltage can be measured.

In Fig. 9, the load voltage measured from the proposed WPT system is compared with that of a resonant WPT system when the distance varies. As shown in Fig. 9(a), the output voltage of the traditional system increases when the distance changes from 3 cm to 6 cm. With a further increase of the distance, the output voltage decreases. Comparatively, it can be observed from Fig. 9(b) that the output voltage of the proposed system is larger than its counterpart which almost remains constant for small distance. Also, the decrease of the voltage tends to be smaller when the distance increases.

Based on the measured output voltage, the output power at different distances is calculated

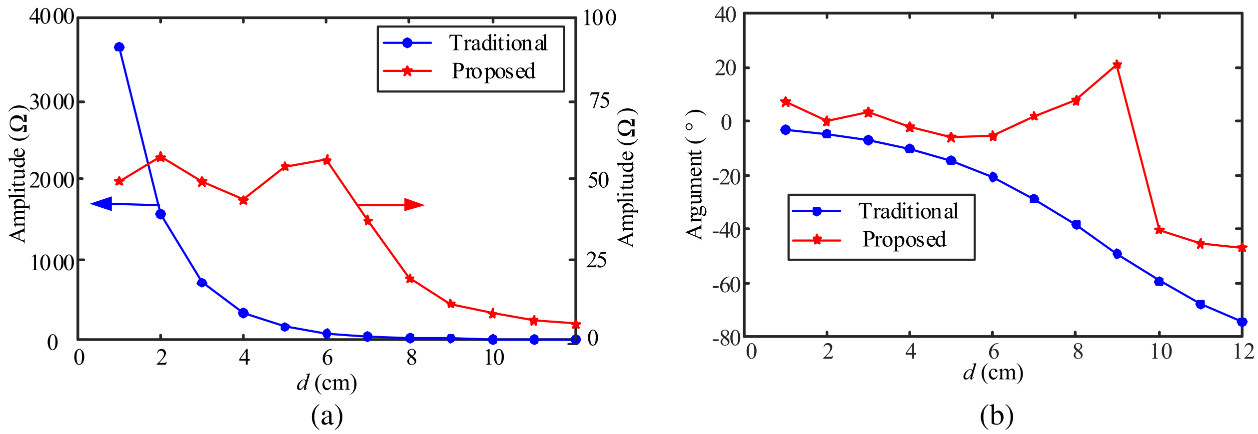

Figure 7. Input impedance against distance between transmission and relay coils. (a) Amplitude of input impedance. (b) Argument of input impedance.

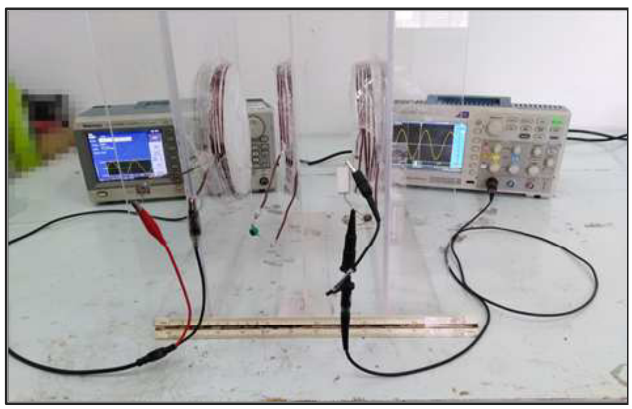

Figure 8. Experimental setup of a hybrid resonant three-coil MRC-WPT system.

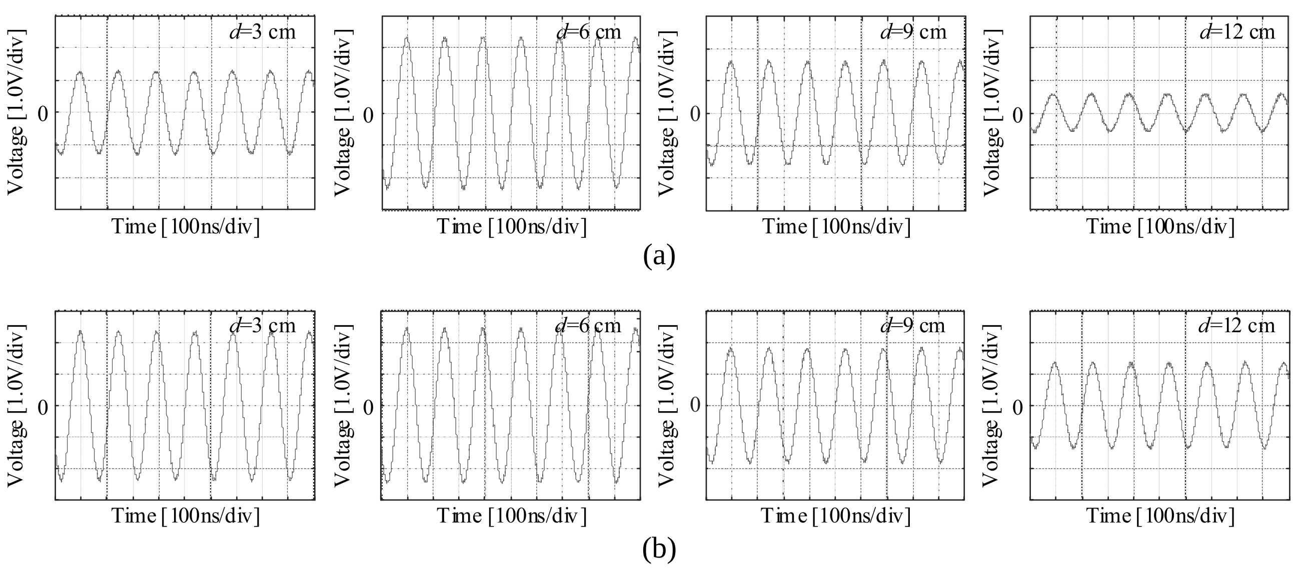

Figure 9. Output voltage of three-coil systems at different distance. (a) Traditional resonant system. (b) Proposed hybrid resonant system.

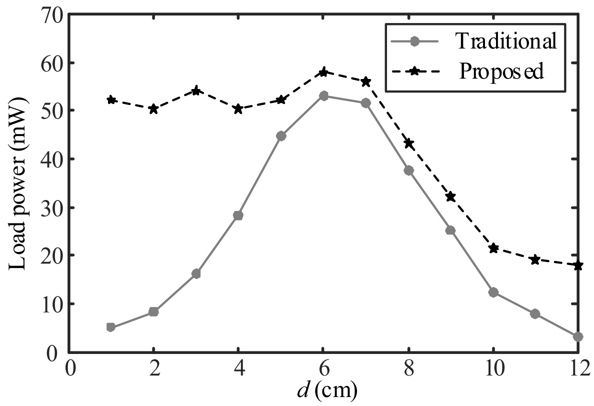

Figure 10. Variation of output power against distance.

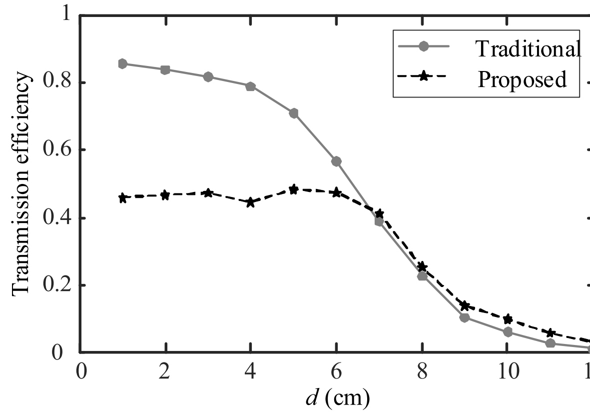

Figure 11. Transmission efficiency versus the distance.

as shown in Fig. 10. The traditional three-coil WPT system is sensitive to the distance between transmitting coil and relay coil. The performance is the most excellent only at a specific point. Once the distance deviates, dramatic decrease is observed. Comparatively, the proposed system shows much better performance. It can be seen that output power of the hybrid resonant system is higher than that of the traditional resonant system. Especially, an excellent performance is observed when the distance is smaller than 7 cm. Even when relay coil is kept in a farer distance from transmitting coil, the performance of the proposed system is more advantageous over the tradition one.

Figure 11 shows how the transmission efficiency varies. From Fig. 11, it can be seen that the experimental results are generally consistent with the simulation. The transmission efficiency of the traditional system gradually decreases. For the proposed system, it is more stable when the distance is smaller than 7 cm.

5. CONCLUSION

In this paper, a three-coil WPT system in which three coils are not simultaneously resonant is proposed and investigated. To enhance the output power, the resonant frequencies of transmitting coil and relay coil are respectively calculated. In comparison to the traditional resonant system, the simulation result shows that the input impedance of the proposed hybrid resonant system is better matched with the internal resistance of the power source. Therefore, the output power is observed to be higher than that of the traditional system. Although the transmission efficiency is lower when the distance between transmitting coil and relay coil is small, it is much more stable. Experiments are carried out for validation. The results validate that the output power of the hybrid resonant WPT system has been improved. To conclude, this work proposes a hybrid resonant three-coil WPT system with a general helix coil structure which improves the performance of the traditional three-coil WPT system. The proposed idea can be used in a specific application such as in the wireless charging of electric vehicles, electronic devices, or biomedical implants. Note that the performance of the proposed system is mainly validated by simulation and experimental work in this study. In the future research, in-depth theoretical analysis will be conducted for further and better understanding.

ACKNOWLEDGMENT

This work was supported in part by the National Natural Science Foundation of China under Grants U1904182 and 52177004, in part by Natural Science Foundation of Henan Province of China under Grants 212300410055, in part by Science and Technology Project of Henan Province of China under Grants 212102210012, in part by Foundation for University Key Young Teacher by Henan Province of China under Grants 2020GGJS061 and in part by Scientific and Technological Innovation Program for Universities in Henan Province of China under Grant 21HASTIT018.

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