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A Novel Planar Wireless Power Transfer System with Distance-Insensitive Characteristics

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Abstract—Unlike conventional systems in which two identical resonant loops are employed, a pair of novel planar loops is developed for wireless power transfer. The proposed transmitting and receiving coils have different distances between turns while the wire length is the same. The effect of mutual inductance on transfer efficiency is analyzed. The mutual inductance of the proposed loops is more uniform than the conventional one, which is helpful for suppressing frequency splitting at closer transfer distance. Moreover, the power transfer performance is enhanced at longer distance. Additionally, an experimental prototype is fabricated to verify the distance insensitive characteristic of the proposed system.

1. INTRODUCTION

In recent years, wireless power transfer (WPT) has attracted a lot of attention as the power is transferred without electric wire which is safer and more convenient [1–3]. It has been applied in a variety of applications such as electrical vehicles, portable electronic products and implanted medical devices [4–6]. Generally, near-field WPT technology can be classified into inductive WPT (IWPT) and magnetic coupling resonant WPT (MCR-WPT) [7–9]. Compared with IWPT, the transfer distance is longer, and efficiency of MCR-WPT is higher. However, frequency splitting exists in MCR-WPT leading to an abrupt decrease of the transfer efficiency at the original resonant frequency when the distance is smaller than a certain value [10–13]. To address the issue of frequency splitting, maximum efficiency tracking control and impedance matching network have been commonly used [14–16]. However, these approaches complicate the system as extra circuits are required. In addition, changing configuration of resonant coils provides another solution without requiring complex circuits [17, 18]. Nevertheless, multiple turns for the receiving coil is required in [17], and the mutual inductance at longer distance is reduced, which shortens the transfer distance in [18].

In this work, a novel configuration of planar resonant coils is proposed for MCR-WPT system to solve the problem mentioned above. Simulation and experiment have been carried out to validate its performance. Frequency splitting is inhibited, and the power transfer ability is improved.

2. ANALYSIS OF THE PROPOSED MCR-WPT SYSTEM

The equivalent circuit of a typical two-coil MCR-WPT system is shown in Figure 1. The coils can be modeled by resistance and inductance connected in series. An AC power source supplies power to the transmitting coil. Both the transmitting coil and receiving coil are designed to resonate at the same frequency by a compensated capacitance, which ensures that the magnetic interaction between coils is sufficiently strong, and the interaction with non-resonant objects is minimal. As a result, the power transfer ability could be largely improved.

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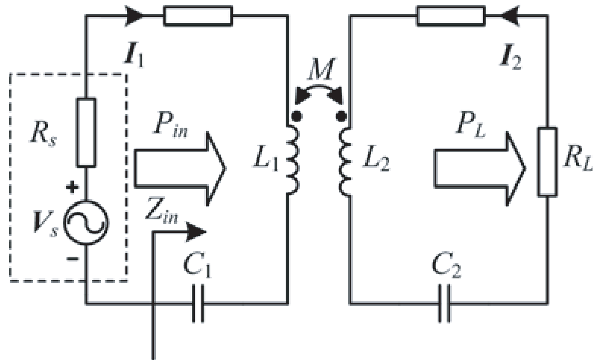

Figure 1. Equivalent circuit of the MCR-WPT system.

As shown in Figure 1, V_s and R_s are the voltage and internal resistance of the source; I_m is the current flowing in the loops; L_m and R_m are the self-inductance and resistance of the coils; C_m is the compensation capacitor (where $m = 1$ denotes the transmitting coil, and $m = 2$ denotes the receiving coil); R_L is the load resistance; M is the mutual inductance between the two coils; P_{in} and P_L are the input and output powers, respectively; Z_{in} is the input impedance.

The equivalent circuit model of the MCR-WPT system can be calculated as

$$\begin{pmatrix} \mathbf{V}_S \\ 0 \end{pmatrix} = \begin{pmatrix} R_S + R_1 + j\omega L_1 + \dfrac{1}{j\omega C_1} & j\omega M \\ j\omega M & R_2 + j\omega L_2 + \dfrac{1}{j\omega C_2} + R_L \end{pmatrix} \begin{pmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \end{pmatrix} \tag{1}$$

where ω is the angular frequency of the source.

The input impedance could be computed by

$$Z_{in} = R_1 + \frac{(\omega M)^2}{R_2 + R_L} \tag{2}$$

The compensation capacitance can be calculated as

$$\begin{cases} C_1 = \dfrac{1}{\omega^2 L_1} \\ C_2 = \dfrac{1}{\omega^2 L_2} \end{cases} \tag{3}$$

Therefore, the transfer efficiency of the two-coil system is

$$\eta = \frac{P_L}{P_{in}} = \frac{(\omega M)^2 R_L}{(R_2 + R_L)\left[(\omega M)^2 + R_1 (R_2 + R_L)\right]} \tag{4}$$

It can be observed from Eq. (4) that the power transfer ability is mainly dependent on the mutual inductance between loops. For spiral resonant coils with multiple turns, the mutual inductance M between loops can be obtained as [17, 18]

$$\begin{cases} M = \displaystyle\sum_{i=1}^{n_1} \sum_{j=1}^{n_2} M_{ij}(r_i, r_j, d) \\ M_{ij}(r_i, r_j, d) = \dfrac{2\mu_0}{k} \sqrt{r_i r_j} \left[\left(1 - \dfrac{k^2}{2}\right) K(k) - E(k) \right] \\ k(r_i, r_j, d) = \sqrt{\dfrac{4 r_i r_j}{(r_i + r_j)^2 + d^2}} \end{cases} \tag{5}$$

where n_1 and n_2 are the numbers of turns for the transmitting coil and receiving coil; $r_i(r_i = r_o-(i-1)p_1)$ and $r_j(r_j = r_o-(j-1)p_2)$ are the radii of the ith and jth turns of the transmitting and receiving coils; r_o is the outer radius of the coils; p_1 and p_2 are the distance between turns; M_{ij} is the mutual inductance between two coils with single-turn; $K(k)$ and $E(k)$ are complete elliptic integrals of the first and second kinds, respectively; d is the distance between the coils.

In a traditional MCR-WPT system, the transmitting and receiving coils are identical. Parameter k tends to 1 as the transfer distance is close to 0, which makes $K(k)$ infinitely large and $E(k)$ to 1. Dramatic increase of mutual inductance between coils exists, and frequency splitting occurs when transfer distance is too small, deteriorating the power transfer efficiency of the system. To improve the power transfer performance, it is critical to control the mutual inductance in a more uniform variation. As a result, frequency splitting can be suppressed as the receiving coil moves close to the transmitting coil.

Based on Eq. (5), it can be found that the mutual inductance can be modified by changing the distance between turns. Figure 2 illustrates the configuration of the proposed novel resonant loops for MCR-WPT system, where r_o is the outer radius of the coils; p_1 and p_2 are the distance between turns; n_1 and n_2 are the numbers of turns of the transmitting and receiving coils, respectively. It should be noted that the copper wire length of the transmitting coil is identical to that of the receiving coil. Besides, the coils are fabricated with the same outer radius. However, the distances between turns in the transmitting and receiving coils are different.

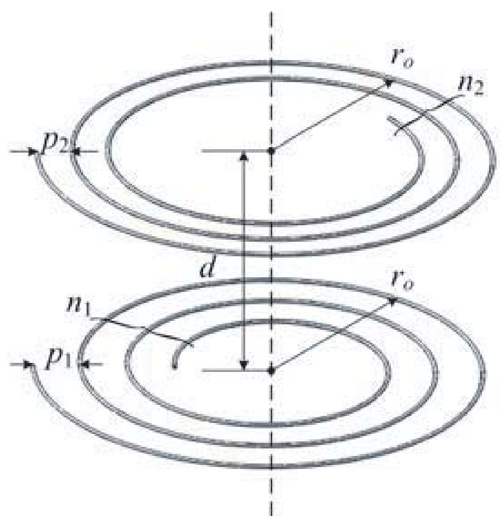

Figure 2. Configuration of coils in the conventional system.

Figure 3 shows how the mutual inductance and transfer efficiency vary with the distance when using the novel resonant loops and using the conventional one. In the electromagnetic simulation, the geometrical parameters are listed as follows. For the traditional resonant loops: $r_o = 100\,\text{mm}$, $p_1 = p_2 = 15\,\text{mm}$, $n_1 = n_2 = 6$ while for the proposed resonant loops: $r_o = 100\,\text{mm}$, $p_1 = 15\,\text{mm}$, $p_2 = 5\,\text{mm}$, $n_1 = 6$, $n_2 = 3.6$. The wire lengths in both resonant loops are equal to 2.073 m. From Figure 3(b), it can be seen that the MCR-WPT system with the proposed resonant loops shows a better performance than that using conventional loops. The transfer efficiency is improved at a closer distance and the longer distance due to uniform variation of the mutual inductance. However, the transfer efficiency of the conventional system drops dramatically when the receiving coil moves close to the transmitting coil due to frequency splitting caused by sudden increase of the mutual inductance as shown in Figure 3(a). Besides, its transfer efficiency at longer transfer distance is also smaller as a result of weak magnetic coupling. It can be drawn that the mutual inductance of the proposed resonant loops is more uniform. Frequency splitting is eliminated for closer distance, and magnetic coupling is strengthened for longer distance with enhanced power transfer ability for MCR-WPT system.

Figure 4 shows the distribution of magnetic field when the transfer distance varies in the over-

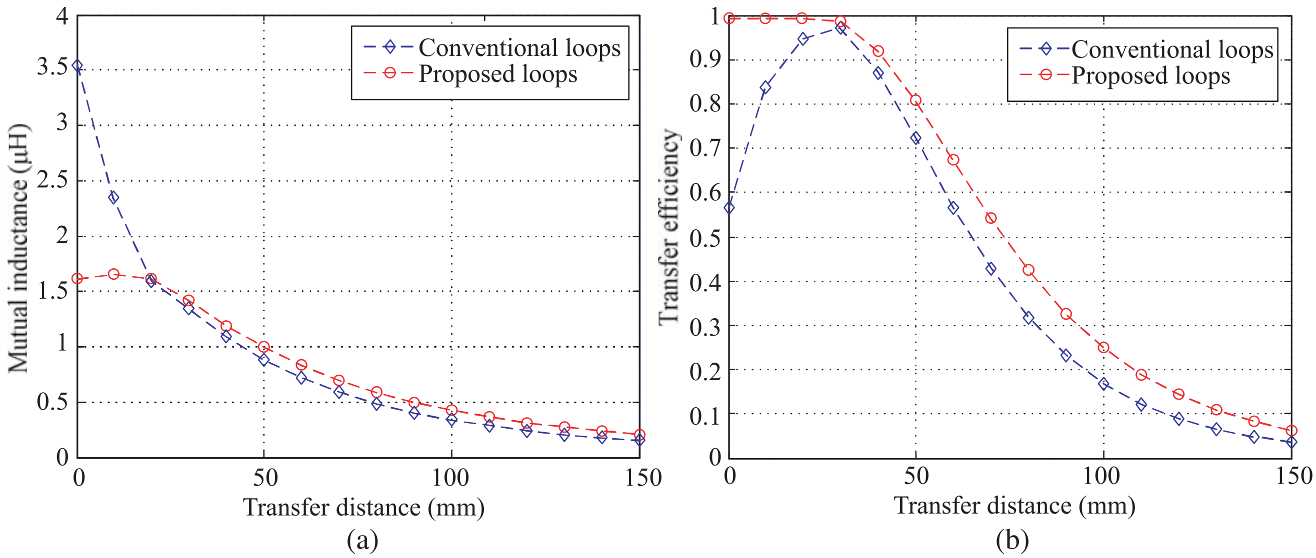

Figure 3. Comparisons of (a) mutual inductance, (b) transfer efficiency.

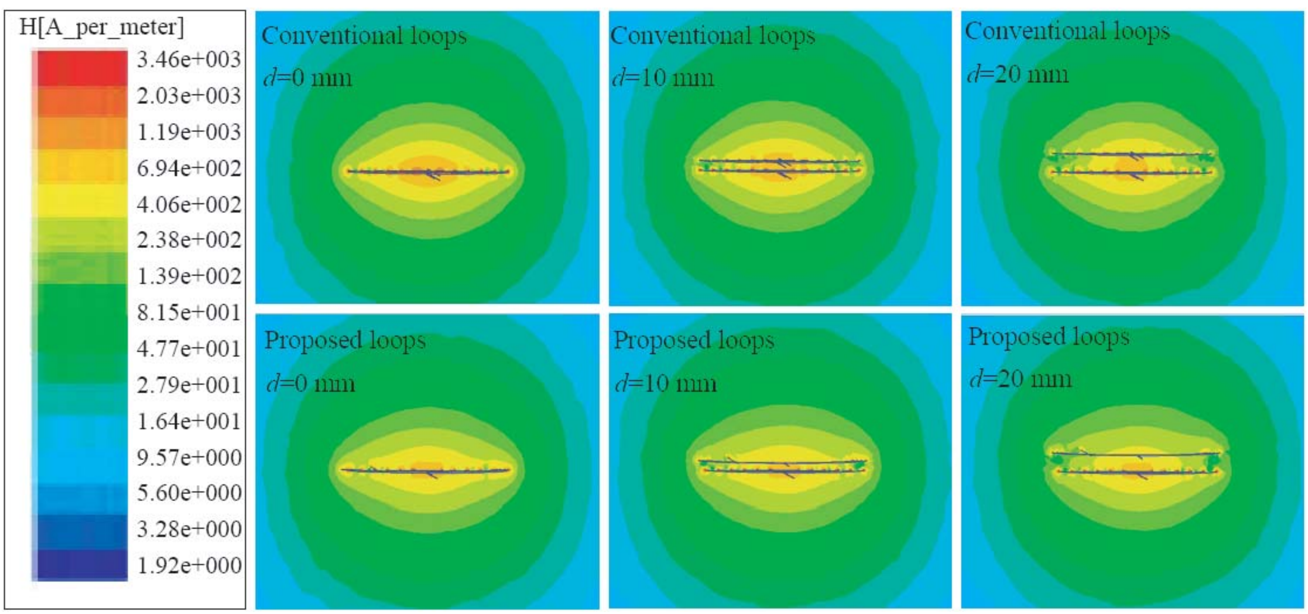

Figure 4. Comparisons of magnetic field distribution.

coupled region. From Figure 4, it can be found that the magnetic field of conventional coils is strongly coupled at short distance which causes frequency splitting while the magnetic field of the proposed structure is uniformly distributed which avoids frequency splitting.

3. EXPERIMENTAL VERIFICATION

To verify the performance of the proposed resonant coils, a prototype of the proposed two-coil MCR-WPT system is built as shown in Figure 5. The transmitting coil is connected to a pure sinusoidal signal generator via a power amplifier, and the receiving coil is linked to a load. The wire length of the transmitting and receiving coils are the same while the distances between turns of the two coils are different.

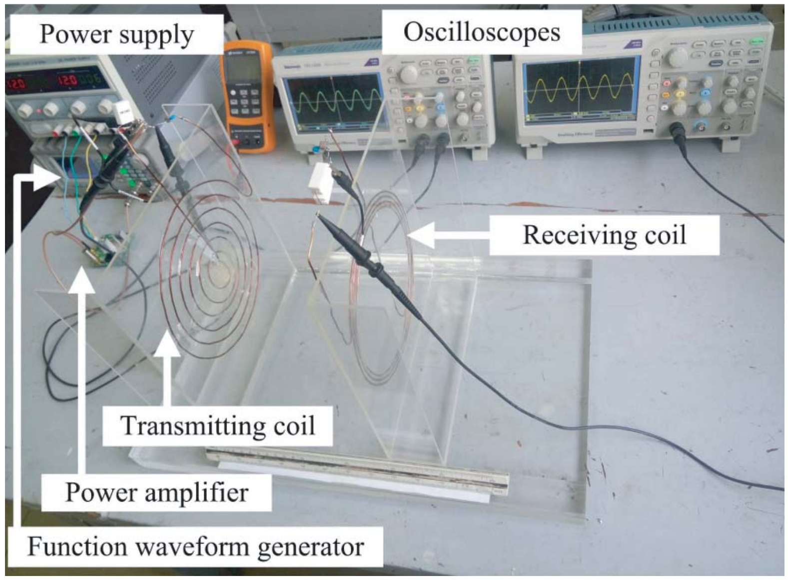

Figure 5. Prototype of the MCR-WPT system.

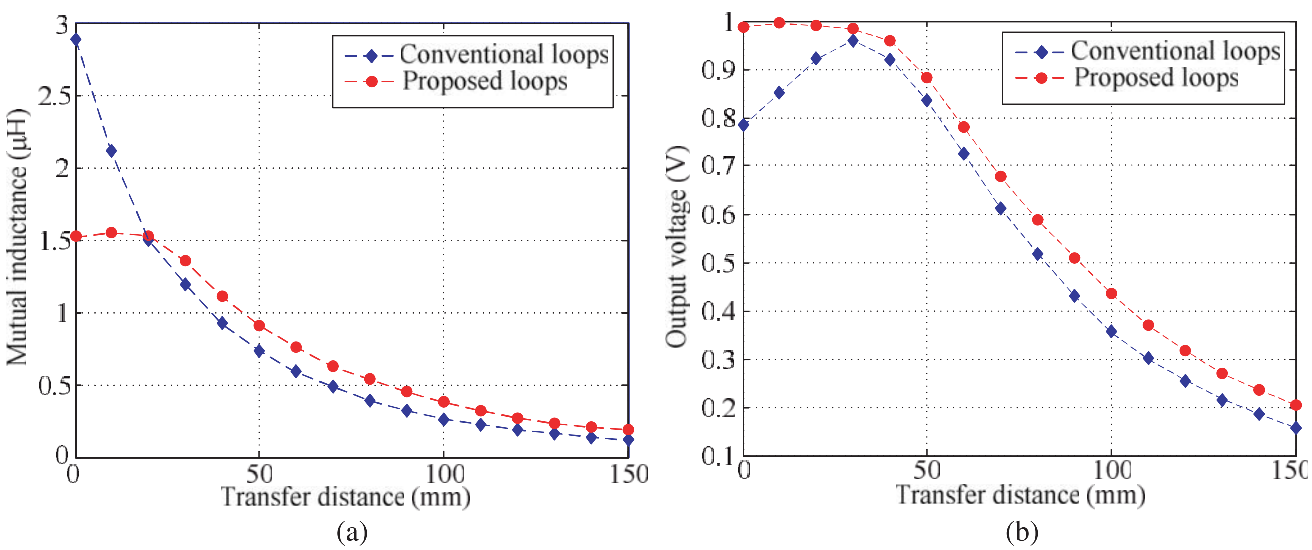

Figure 6. Comparisons of measured (a) mutual inductance, (b) output voltage.

The resonant frequency is set to 5 MHz. The geometrical parameters of the coils in the experiment are the same as that in the simulation. The wire diameter of the coils is 1.4 mm. The load resistance is set to 25 Ω. Compensated capacitance is used for magnetic resonance for efficient power transfer.

Figure 6 presents the variation of mutual inductance and measured output voltage between the proposed and conventional resonant loops. The mutual inductance is calculated by measuring the inductive voltage across the receiving coil and the current flowing in the transmitting coil. It can be seen from Figure 6(a) that the mutual inductance of the conventional loops decreases with the increase of transfer distance while the mutual inductance of the proposed loops presents a relatively small variation. The mutual inductance at the closer distance is lower than that of the conventional loops, which avoids frequency splitting, and the mutual inductance at longer distance is higher which extends the transfer distance. In addition, the measured results are a bit smaller than the simulated mutual inductance because the distance in the experiment cannot be controlled exactly the same as that in the simulation.

It can be seen from Figure 6(b) that the MCR-WPT system with the proposed resonant loops shows better performance and outperforms that with the conventional resonant loops.

4. CONCLUSION

In this letter, a pair of novel planar spiral coils is proposed for wireless power transfer. A transmitting coil and a receiving coil are designed with different distances between turns while the total wire lengths are identical. The mutual inductance of the proposed structure is relatively more uniform than that of the conventional identical loops. Frequency splitting in the conventional loops at the closer distance is eliminated by using the proposed scheme. Besides, the transfer efficiency at the longer distance is enhanced due to the increase of mutual inductance. The simulated and experimental results are in good agreement and indicate the feasibility of the proposed method in improving the performance of the MCR-WPT system.

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