

Energy Efficiency Analysis of U-Coil Wireless Power Transfer System

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Abstract—In order to improve the power transfer efficiency and ensure the space cleanliness of power transfer direction in inductive coupled wireless power transfer (WPT) system, a new U-coil WPT system is proposed. Based on the mutual inductance coupling theory, a new methodology for ensuring that a U-coil system is more energy efficient than a two-coil counterpart is presented in this paper. The theoretical proof and the conditions for meeting the objective are derived and practically verified in a practical prototype. The experimental results show: 1) comparing with two-coil system, power transfer efficiency can be improved more than ten times by using U-coil system; and 2) with the same power transfer efficiency principle, the dimension of primary and load coils in U-coil system shrinks at least 66% comparing with that of two-coil system. The U-coil system not only improves power transfer efficiency but also ensures the cleanliness of the space along the energy transfer direction.

Index Terms—Energy efficiency, mutual inductance coupling, U-coil, wireless power transfer (WPT).

I. INTRODUCTION

WIRELESS power transfer (WPT) has been widely researched in recent years, since Tesla wirelessly lightened the fluorescent lamp at the World's Fair in the 1890s. Nowadays, WPT technology are widely used in the areas of electrified transportation [1]–[4], robotics [5], [6], medical implanted devices [7], [8], and service industries [9]–[11], etc.

WPT technology is usually sorted into two categories which are electromagnetic radiation way and inductive coupled way [12]. Now, inductive coupled technology, which can be based on either maximum efficiency principle or maximum power transfer principle [13], has been more widely studied and applied, and has more molded products relatively than electromagnetic radiation technology. The topologies of inductive coupled technology can be classified by two-coil system [14]–[16], four-coil system [17], [18], and more-coil system [13], [19]. For a two-coil system based on the maximum efficiency principle, the energy transfer distance is usually smaller than the geometry

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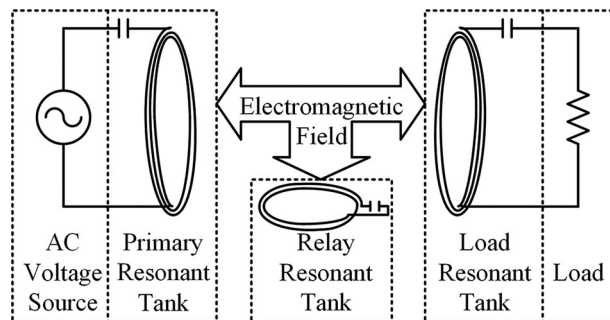


Fig. 1. Typical three-coil WPT system.

dimension of coil. Based on the maximum power transfer principle, the energy efficiency has an inherent limitation that cannot exceed 50% [20]. In order to achieve a good compromise between efficiency and transfer distance, the four-coil system and more-coil system (the domino-resonator systems) whose relay resonators are designed along the energy transfer direction have been considered. Thus, its result in the space of energy transfer direction is not clean, which is not beneficial to practical application.

According to the literature report, in order to ensure the cleanliness in the space of energy transfer direction and achieve a good compromise between efficiency and transfer distance, the three-coil system proposed in [20] is the only one. But this paper is the first one which comprehensively researched the key parameters of a relay coil in three-coil system. Meanwhile, this paper proposed a U-coil WPT system which can achieve the above two goals. From theory and experiment, the validity of U-coil system has been verified. Then, the application value of U-coil system using in the area of tridimensional storages for static wireless charging between adjacent storages has been evaluated. The theory can be applied to both low-power applications such as kitchen appliances wireless charging and high-power applications such as wireless charging of electric vehicles. In this application that primary coil and load coil are set in different cavities such as [21] and [22], the three-coil system of reference [20] is more useful than U-coil system. But under such circumstances, primary coil and load coil are set in the same cavity, and the space cleanliness of power transfer direction is needed, U-coil WPT system is very practical application.

II. THEORETICAL ANALYSIS

Fig. 1 shows the arrangement of a typical three-coil WPT system. Each coil is connected with a series capacitor to form a resonant tank. A capacitor is used to compensate the stray

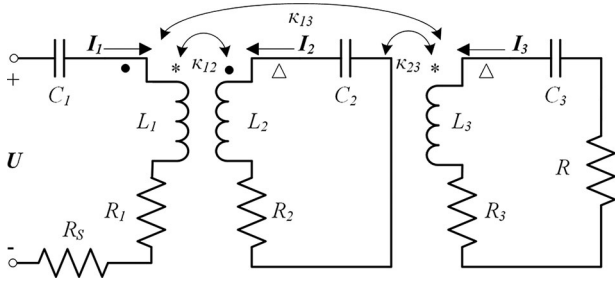


Fig. 2. Lumped circuit model of a three-resonator system.

inductance of the primary, relay, and load coils which interact with each other via electromagnetic field. For the sake of analysis, the primary, relay, load resonant tank are named Resonators 1, 2, and 3, respectively.

Fig. 2 shows the lumped element circuit of the three-resonator system. According to mutual inductance coupling theory, its circuit equations can be expressed in

$$\begin{cases} (R_1 + R_s + jX_1) \mathbf{I}_1 + j\omega\kappa_{12}\sqrt{L_1L_2}\mathbf{I}_2 \\ \quad + j\omega\kappa_{13}\sqrt{L_1L_3}\mathbf{I}_3 = U \\ j\omega\kappa_{12}\sqrt{L_1L_2}\mathbf{I}_1 + (R_2 + jX_2) \mathbf{I}_2 \\ \quad + j\omega\kappa_{23}\sqrt{L_2L_3}\mathbf{I}_3 = 0 \\ j\omega\kappa_{13}\sqrt{L_1L_3}\mathbf{I}_1 + j\omega\kappa_{23}\sqrt{L_2L_3}\mathbf{I}_2 \\ \quad + (R_3 + R + jX_3) \mathbf{I}_3 = 0 \end{cases} \quad (1)$$

where X_i is the reactance $\omega L_i - 1/(\omega C_i)$, L_i is the inductance, C_i is the capacitance, \mathbf{I}_i is the current, and R_i is the resistance in Resonator i (where $i = 1, 2, 3$); U is the voltage source; R_s is the source resistance, and R is the load resistance; κ_{12} , κ_{23} , κ_{13} are the coupling factor between primary coil and relay coil, relay coil and load coil, primary coil and load coil, respectively; ω is the angular frequency. In this paper, bold italic letters are used to represent the phasors and italic letters are used to represent real numbers and RMS values of the phasors. For example, \mathbf{I}_1 is a current phasor and I_1 is the RMS value of \mathbf{I}_1 .

The efficiency of the three-coil system can be expressed as in [19, eq. (3)] and the coil resonators should operate in resonance mode in order to maximize the power transfer capability of the three-coil WPT system. Thus, under the resonance mode ($X_1 = X_2 = X_3 = 0$), the overall energy efficiency of the three-coil system can be expressed as

$$\eta = \frac{1}{1 + A(Q_1, Q_2, Q_3, \kappa_{12}, \kappa_{23}, \kappa_{13})} \cdot \frac{R}{R_3 + R} \quad (2)$$

where

$$A(Q_1, Q_2, Q_3, \kappa_{12}, \kappa_{23}, \kappa_{13}) = \frac{1 + 2\kappa_{23}^2 Q_2 Q_3 + (\kappa_{23}^2 Q_2 Q_3)^2 + \kappa_{13}^2 \kappa_{23}^2 Q_1 Q_2 Q_3^2 + \kappa_{12}^2 Q_1 Q_2}{1 + \frac{\kappa_{12}^2 \kappa_{23}^2 Q_2^2}{\kappa_{13}^2}} \quad (3)$$

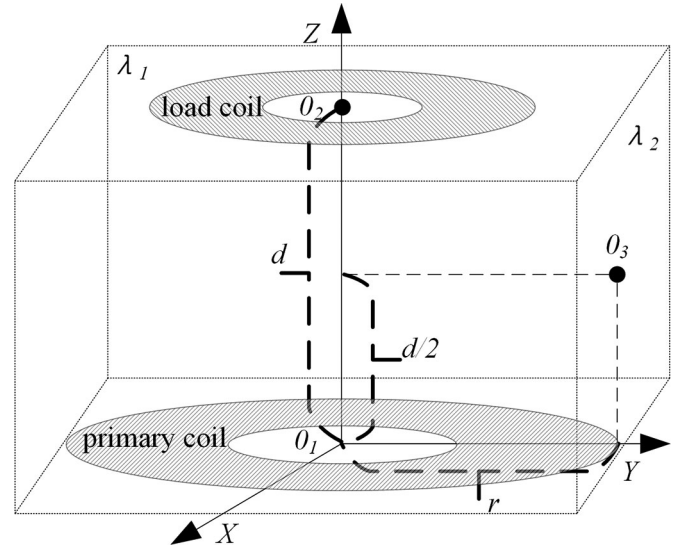


Fig. 3. Schematic drawing of two flat-helix coils system.

is the discriminant of power transfer efficiency improvement (hereinafter referred to as discriminant A) while Q_i is the quality factor of Resonator i (where $i = 1, 2, 3$). For example, $Q_1 = \omega L_1 / (R_1 + R_s)$, $Q_2 = \omega L_2 / R_2$, $Q_3 = \omega L_3 / (R_3 + R)$.

A traditional two-coil WPT system is the system which put the relay resonator away in three-coil system. Its energy efficiency can be expressed as (see [20, eq. (3)])

$$\hat{\eta} = \frac{1}{1 + \frac{1}{\kappa_{13}^2 Q_1 Q_3}} \cdot \frac{R}{R_3 + R} \quad (4)$$

Comparing (2) with (4), for the energy efficiency of the three-coil system to be higher than that of the two-coil system, the following inequality equation should be met:

$$A < 1. \quad (5)$$

When R_s and κ_{13} are negligible, inequality equation (5) is equivalent to inequality equation (11) $\omega M_{a1} > (R_{P1} + R_{E1})(1 + R_{Pa}/R_s)^{0.5}$ in [20]. But inequality equation (5) has the wider meaning that the energy efficiency is higher when A is closer to zero. So, (6) can be used as the objective function to optimize the key parameters (position and turns of relay coil) of the three-coil system

$$\text{Min} : A. \quad (6)$$

From discriminant (3), the simplified mathematical derivation can be expressed in (7). If $B > 1$, then $A > 1$, otherwise $A \leq 1$. So, B is important to improve power transfer efficiency

$$B = \frac{\kappa_{13}^2}{\kappa_{12}^2} \left(\frac{2Q_3}{Q_2} + \kappa_{23}^2 Q_3^2 + \kappa_{13}^2 \frac{Q_1}{Q_2} Q_3^2 \right) + \frac{\kappa_{13}^2}{\kappa_{23}^2} \frac{Q_1}{Q_2}. \quad (7)$$

III. RELAY POSITION ANALYSIS

Fig. 3 shows the schematic drawing of two flat-helix coils system, where the center of the primary coil corresponds with the origin $O_1(0, 0, 0)$ of plane XO_1Y , and where the coil's axis corresponds to the z -axis. The load coil, whose axis corresponds

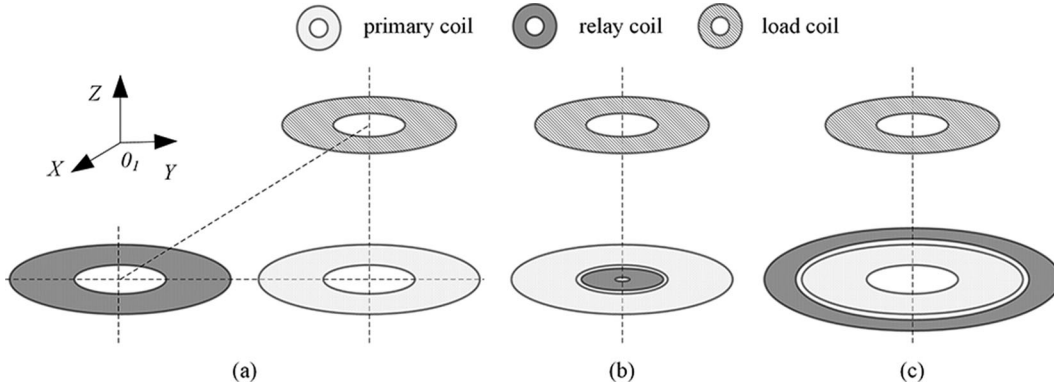


Fig. 4. Setting patterns of relay coil. (a) Outside pattern. (b) Inner pattern. (c). Outer pattern.

to the z -axis and the center is $O_2(0, 0, d)$ is located in plane λ_1 whose general equation is given by

$$\lambda_1 \equiv z - d = 0. \quad (8)$$

We also define the following plane and point:

1) Plane λ_2 , the plane of relay flat-helix coil, general equation is given by

$$\lambda_2 \equiv y - r = 0. \quad (9)$$

2) Point $O_3(0, r, d/2)$, in plane λ_2

where r is the larger outer radius between primary coil and load coil.

Using Maxwell equations, the self-inductance of a one-turn circular conductive loop L_i , M_{ij} between a pair of parallel single-turn circular coils, the self-inductance L_{Self} of a coil and the quality factor Q of a coil can be found from equations in [23, eqs. (30), (31), (33), (38)]

$$L_i = 0.5\mu_0\mu_r \frac{r_i}{2} \ln\left(\frac{r_i}{2W_r}\right) \quad (10)$$

$$M_{ij} = \frac{2\mu_0}{\alpha} \sqrt{r_i \cdot r_j} \left[\left(1 - \frac{\alpha^2}{2}\right) K(\alpha) - E(\alpha) \right] \quad (11)$$

$$L_{\text{Self}} = \sum_{i,j} M_{ij} + \sum_i L_i \quad (12)$$

$$Q = \frac{\omega L_{\text{Self}} [\pi \delta r^2 (r/2 - \delta)]}{8nW_r^2 \rho_c^2} \quad (13)$$

where

$$\alpha = 2\sqrt{\frac{r_i \cdot r_j}{(r_i + r_j)^2 + d_{ij}^2}}, \quad \delta = \sqrt{\frac{2\rho_c}{\mu_0\omega}}. \quad (14)$$

The coupling coefficient κ is defined as in [24, eq. (3)]

$$\kappa_{ij} = \frac{M_{ij}}{\sqrt{L_i L_j}}. \quad (15)$$

All of the equations are closely related to the parameters of a coil, such as the radii (r, r_i, r_j) and turns n of a coil, the diameter of wire W_r , the coupling distance between the two coils d_{ij} , the resistivity of the conductive material ρ_c . With ruly wrap-mode,

the greater the number of coil's turns, the greater the coupling coefficient and quality factor.

As shown in Fig. 3, using axial symmetry principle, the relay coil in the six positions can be set for ensuring the cleanliness in the space of energy transfer direction: 1) plane XO_1Y ; 2) plane λ_1 ; 3) plane λ_2 ; 4) area $z < 0$; 5) area $z > d$; 6) area $y > r$. Then, we can assume the conditions in actual system: 1) the same litz wire is used to make primary coil, relay coil, and load coil; 2) primary coil's dimension is not smaller than that of load coil; 3) source impedance is negligible (because the normal driving circuit is most likely a power electronic inverter). The power transfer efficiency of three-coil system with relay coil in different positions can be analyzed as follows.

A. In Plane XO_1Y

Assume that the parameters of primary and relay coil are the same and are set at the same position, $\kappa_{13} = \kappa_{23}$ and $Q_1 = Q_2$ can be obtained. But in the actual system, as shown in Fig. 4(a), primary coil is set at the optimal position coaxial with load coil, while relay coil is set at the position noncoaxial with load coil, which led to $\kappa_{13} > \kappa_{23}$. Otherwise, from (7), $B > (\kappa_{13}/\kappa_{23})^2(Q_1/Q_2)$ can be obtained. So, inequality $B > 1$ does always stand up in this case, we cannot improve power transfer efficiency using this relay coil for the reason that inequality (5) is not met. In Fig. 4(a), when relay coil's turns decrease, we have $\kappa_{13} > \kappa_{23}$ and $Q_1 > Q_2$, thus $B > 1$, power transfer efficiency cannot be improved, and when the turns of relay coil are more than that of primary coil, $\kappa_{23} > \kappa_{13}$ if the position of relay coil is set at that of primary coil, and $Q_2 > Q_1$, higher efficiency can be obtained to swap the primary coil and relay coil (do not set the relay coil).

As shown in Fig. 4(b), relay coil is set in the area of primary coil's inner diameter which is so small in actual system that $\kappa_{13} > \kappa_{23}$ and $Q_1 > Q_2$ can be obtained; thus, the energy efficiency of the three-coil system is less than that of the two-coil system.

In Fig. 4(c), if the turns of relay coil is few which results in $\kappa_{23} < \kappa_{13}$ and $Q_2 < Q_1$, the energy efficiency may decrease when relay coil is set at this position. To meet the condition $\kappa_{23} > \kappa_{13}$ and $Q_2 > Q_1$, the turns of relay coil should be

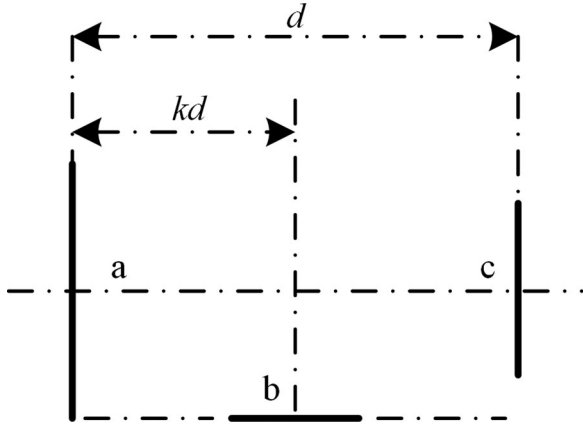


Fig. 5. Typical U-coil WPT system.

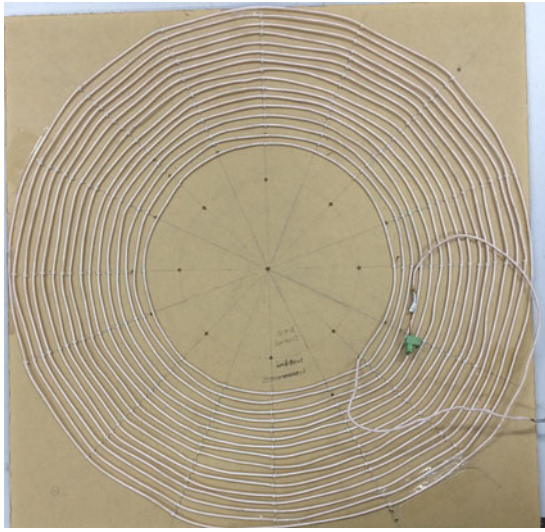


Fig. 6. Photograph of the practical coil.

increase, but higher efficiency can be obtained to swap the primary coil and relay coil as before.

Therefore, setting relay coil in plane XO_1Y is not valid.

B. In Plane λ_1

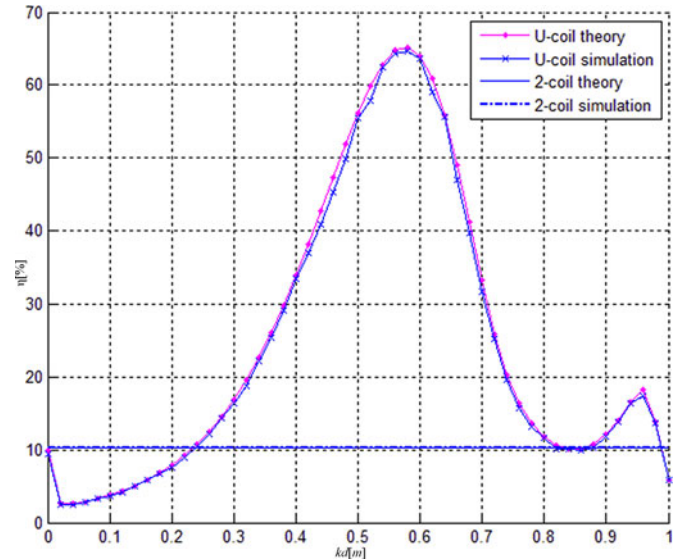
In this case, we can swap the positions of primary coil and load coil as shown in Fig. 4. It is impractical to set relay coil as shown in Fig. 4(a) and (c) in actual system by large area of load. The inner diameter of load coil is so small that $\kappa_{13} > \kappa_{12}$ and $Q_1 > Q_2$, and the condition $Q_3 > 1$ is always true in actual system. So, inequality $B > 1$ does always stand up with this relay coil. Therefore, for improving energy efficiency, we cannot set relay coil in plane λ_1 .

C. In Plane λ_2

With different positions for relay coil in plane λ_2 , κ_{12} and κ_{23} are different. There are some coefficients κ_{12} and κ_{23} that make inequality (5) established. It means that there are some positions to set relay coil for improving power transfer efficiency. For this

TABLE I
PARAMETERS OF A PRACTICAL COIL

Parameters	Symbol	Value
Inner diameter	d_i	280 mm
Coil width	W_r	2.5 mm
Distance of turns	d_c	10 mm
Number of turns per layer	–	16
Number of layers	–	1

Fig. 7. Energy efficiency versus the distance kd .

condition, the objective is to minimize discriminant A , with the position and turns of relay coil as constraints and optimized variables. This optimization problem will be included later.

D. In Area $z < 0$

As analysis A, the system using relay coil setting in this area is not suitable for high-efficiency power transfer.

E. In Area $z > d$

According to the results of analysis B, it is invalid when place relay coil in the area $z > d$.

F. In Area $y > r$

In this case, power transfer efficiency will increase with right position of relay coil as shown in analysis C.

IV. COMPUTER-AIDED ANALYSIS

The specified operating conditions defined by (5) can be implemented in a three-coil system with relay coil setting in plane λ_2 or in area $y > r$, namely the primary coil (Coil a), the relay coil (Coil b), and the load coil (Coil c). This WPT system is named U-coil WPT system as shown in Fig. 5, where d is used to represent the power transfer distance, where k (ranged from

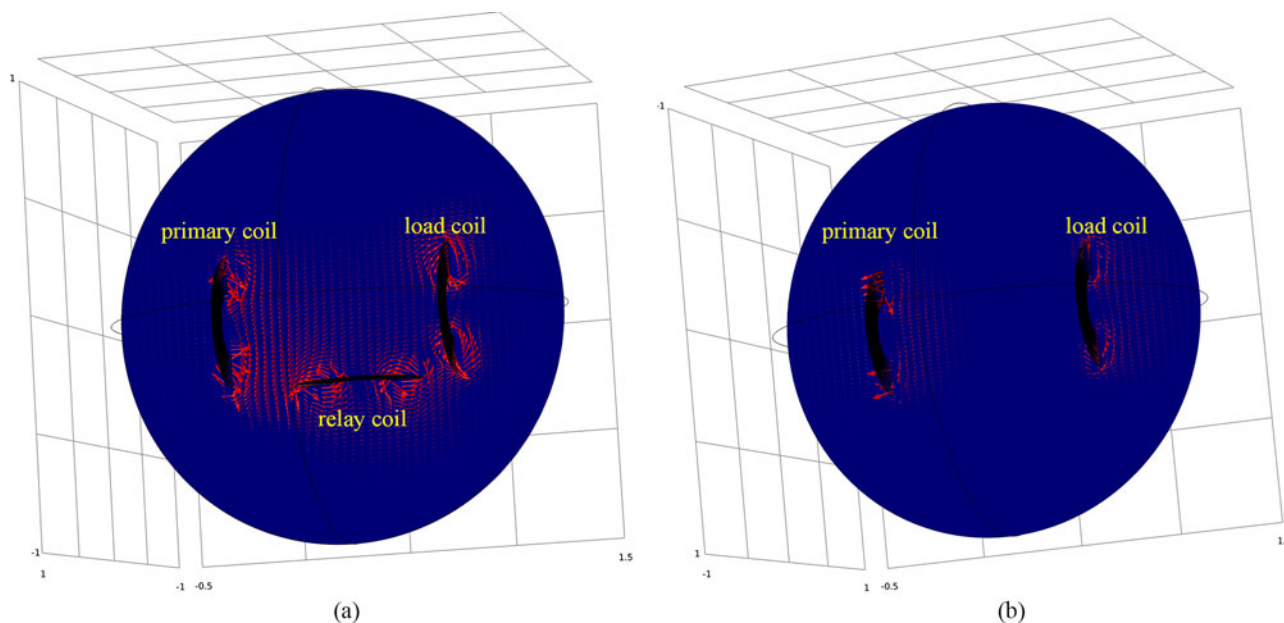


Fig. 8. COMSOL simulation results. (a) U-coil system with $k = 0.58$. (b) two-coil system.

0 to 1) represents distance ratio from center of Coil b to plane of Coil a.

A. Positions of Coil b

In this example, practical coil’s parameters are used in COMSOL simulation environment. The actual coil picture is shown in Fig. 6 and the parameters are shown in Table I. All of the three coils are the same and are made of litz wire which has 300 strands of no. 38 AWG (0.1 mm diameter). The distance from Coil a to Coil c is set at 1m for the application in the area of tridimensional storages, and the load resistance for the simulation study is set at 10Ω . For tests on power transfer efficiency, the distance ratio k is increased from 0 to 1. In the COMSOL simulation environment, solid copper wire which cross-sectional area is 2.356 mm^2 (calculated by $300 * \pi * 0.05^2$) is used, skin and proximity effects are ignored because 0.1 mm diameter is much less than skin depth of copper working at 85 kHz operating frequency.

As can be seen from Fig. 7, the simulated results agree with the theoretical equations (2) and (4), and the energy efficiency can be improved significantly by increasing the distance ratio at this operating frequency. The increasing value of k implies a changing discriminant A . However, there is a diminishing return when k becomes larger. When k is set at 0.58, the COMSOL simulation is shown in Fig. 8, and the highest power transfer efficiency (about 65%) can be obtained.

As shown in Fig. 8, the energy received in load coil is much more than that of two-coil system, that is because the electromagnetic energy can be transferred even more to load coil from primary coil in optimized relay coil system than that of nonrelay system in the conditions of same input energy and transmission distance.

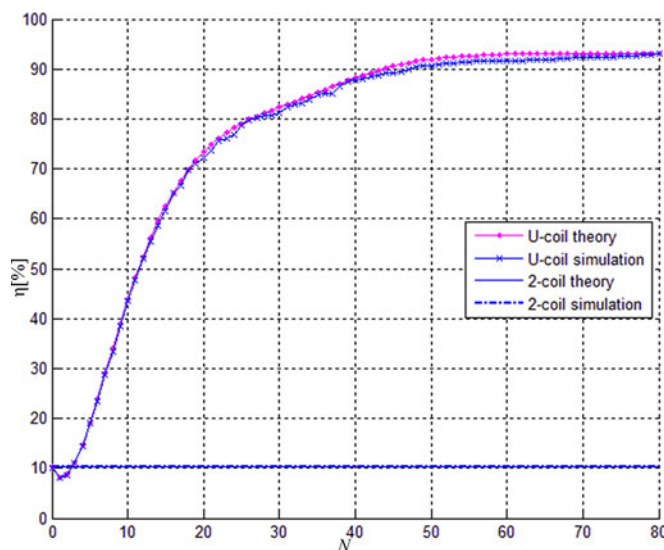


Fig. 9. Efficiency curve with different turns of relay coil in U-coil system and efficiency curve in two-coil system.

B. Turns of Coil b

If the relay coil is considered as a coil with different turns, the values of discriminant A are different. What is the rule of energy efficiency in U-coil system with different turns of relay coil? It has been answered in this example. k is set at 0.58, set other parameters to the same as example A. Then, changing the turns N of Coil b from 1 to 28 (because the outer diameter of Coil b should be smaller than d in actual system), we can obtain the efficiency curve with different N as shown in Fig. 9.

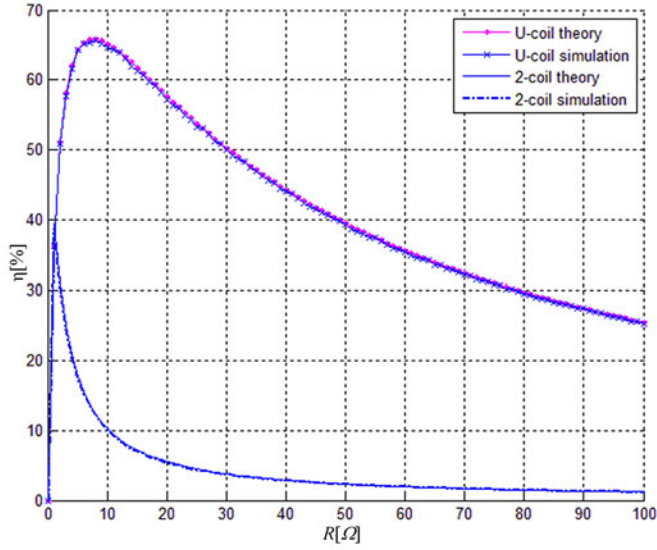


Fig. 10. Efficiency comparison between U-coil and two-coil system under different loading conditions.

Fig. 9 shows the power transfer efficiency of U-coil system is higher than that of two-coil system when turns of Coil b is bigger than two and the more turns, the higher the power transfer efficiency of U-coil system. However, there is a negligible increase when N is larger than 50. If N is larger than 28, the outer edge of relay coil will enter into the area of load coil, and it is invaluable in actual system. In other words, under certain conditions, larger coupling between primary coil and load coil can be get with more turns of relay coil, so higher power transfer efficiency can be obtained. In this example, when N is set at 28, the highest power transfer efficiency (about 82%) can be obtained.

C. Effects of Load Resistance

According to discriminant A , load resistance is one of the critical factor. Meanwhile it may have different values in different power transfer systems. So, let us set k to 0.58, set N to 28, set the values of load resistance from 0 to 100 Ω (particular interest in actual system) and set other parameters to the same as example A in this simulations. The efficiency comparison between U-coil and two-coil system under different loading conditions is shown in Fig. 10.

Fig. 10 shows that the power transfer efficiency of U-coil system is higher than that of two-coil system when the value of load resistance is bigger than 1 Ω . U-coil system has the highest energy efficiency (about 66%) when R is 8 Ω . The energy efficiency of the two-coil system deteriorates faster when the load resistance increases from 1 to 8 Ω , but that of the U-coil system increases much faster. When the value of load resistance is bigger than 8 Ω , the efficiencies of U-coil and two-coil system decrease gradually, but the former is always much higher than the latter.

TABLE II
OPTIMAL RESULTS

Parameters	Symbol	Value
Distance ratio	k	0.5
Number of turns per layer	N	36
Power transfer efficiency	η	90.3%

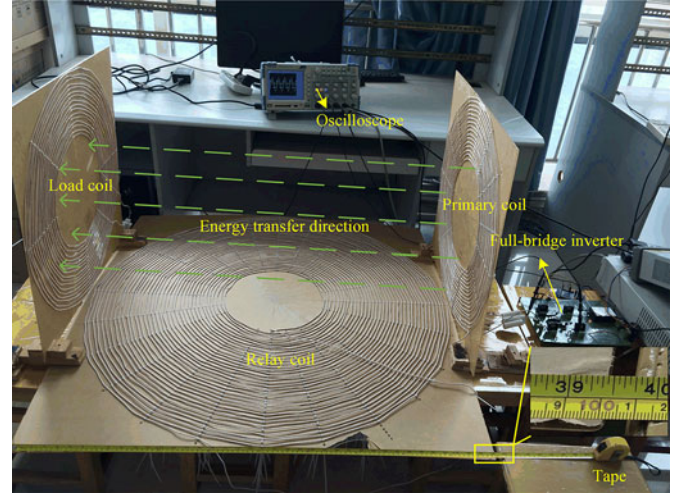


Fig. 11. Practical setup of U-coil WPT system.

D. Optimization of Coil b

Figs. 7 and 9 indicate positions and turns of relay coil are two of the key parameters impacting power transfer efficiency in U-coil system, and Fig. 10 shows energy efficiencies are different under various load conditions. Under given conditions, such as parameters of primary coils and load coils (shown in example A), energy transfer distance (1m), load resistance (8 Ω), and resonance frequency (85 kHz), positions and turns of a relay coil can be optimized by using objective function (6) and the constraints as follows:

$$\begin{cases} 0 \leq k \leq 1 \\ \frac{d_i}{2} + d_c(N-1) \leq \min[kd, (1-k)d] \\ N \geq 1. \end{cases} \quad (16)$$

In this example, the optimal results are shown in Table II.

V. PRACTICAL VERIFICATION

Experiment has been carried out to verify the optimal results. A practical setup of U-coil wireless power transfer system is shown in Fig. 11. The practical parameters of primary coil (Coil a) and load coil (Coil c) are listed in Table I, and the practical parameters of relay coil (Coil b) are listed in Table III. The electrical parameters of the coils are measured by using the LCR digital electric bridge (ZX8526A) and are listed in Table IV. Full-bridge inverter and resistive load are used to do the measurement. The compensating capacitances of Coil a, Coil b, and Coil c are calculated by $C = 1/(\omega^2 L)$, and the measured

TABLE III
 PARAMETERS OF A RELAY COIL

Parameters	Symbol	Value
Inner diameter	d_i	280 mm
Coil width	W_r	2.5 mm
Distance of turns	d_c	10 mm
Number of turns per layer	N	36
Number of layers	–	1

 TABLE IV
 PARAMETERS OF THE COILS OBTAINED FROM ZX8526A AT 85 KHZ

Symbol	Value
L_a	135.8 μ H
R_a	0.25 Ω
L_b	772.8 μ H
R_b	0.92 W
L_c	135.1 μ H
R_c	0.24 W
κ_{ab}	0.0716
κ_{bc}	0.0709
κ_{ac}	0.0074

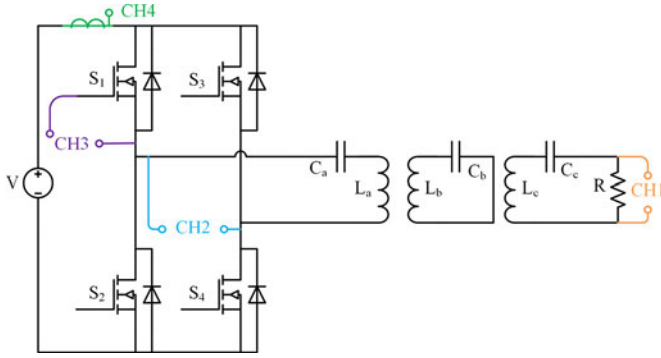


Fig. 12. Circuit schematic of the practical measurement.

values of practical capacitances are 25 nF, 4.4 nF, and 26 nF, respectively.

A. Practical Measurements

A high-speed digital oscilloscope (TPS2024B, 200 MHz bandwidth) is used to record the output voltage and input current waveforms of the full-bridge inverter, the load voltage, and the driven pulse of MOSFET in the full-bridge inverter. The circuit schematic of the practical measurement and the measured waveforms are shown in Figs. 12 and 13, respectively. As shown in Fig. 12, V is ac Voltage Source, S_1 , S_2 , S_3 , and S_4 are the MOSFETs of full-bridge inverter, CH1, CH2, CH3, and CH4 are the channels of oscilloscope. As shown in Fig. 13, the measurements of CH1, CH2, CH3, and CH4 represent load voltage waveform, output voltage, MOSFET's driven pulse, and input current waveforms of the full-bridge inverter, respectively. The output power and transfer efficiency of the U-coil system are 118 W and 87.8% with transfer distance of 1 m and operating frequency of 86.2 kHz. Comparing with two-coil system, the

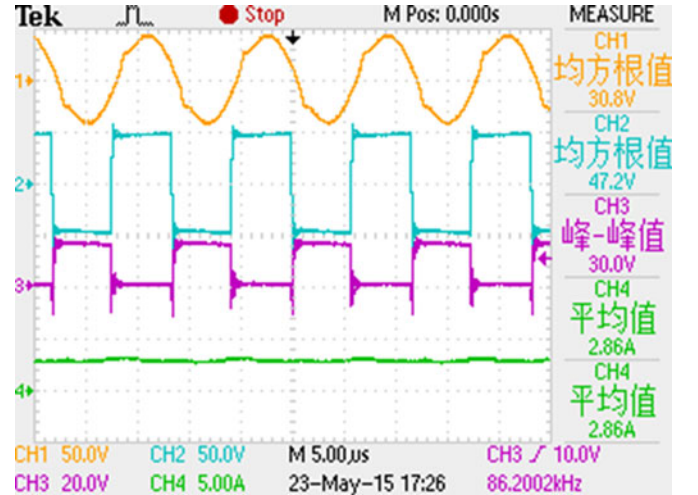


Fig. 13. Practical measurements of the U-coil WPT system.

power transfer efficiency is improved 13.7 times (from 6.4% to 87.8%).

From the measured and simulated results, the measured efficiency (87.8%) calculated by $\eta = (U_{CH1}^2/R)/(U_{CH2} * I_{CH4})$ is smaller than the simulated efficiency (90.3%), and the measured operating frequency (86.2 kHz) is bigger than the simulated operating frequency (85 kHz). These deviations are caused by the parameters of practical coils and emulational coils.

B. Coil's Dimension Evaluation

An effective way to highlight the advantage of the proposed theory is to check the dimensions of the primary and load coils of the U-coil and two-coil systems for the same energy transfer efficiency. It is envisaged that turns of primary coil and load coil are the same, energy transfer distance is 1 m, load resistance is 10 Ω , and resonance frequency is 85 kHz. The efficiency comparison between U-coil and two-coil system under different turns of coil conditions is shown in Fig. 14.

Fig. 14(a) and (b) shows that energy efficiencies are improving when the turns of primary and load coils are increasing, energy efficiency of two-coil system cannot go over 90% in these conditions. Achieving the same power transfer efficiency, the dimensions of primary and load coils in U-coil system shrink at least 66% comparing with that of two-coil system as shown in Fig. 14(c).

VI. CONCLUSION

This paper describes a method for ensuring that a U-coil WPT system being more energy efficient than a two-coil counterpart and being more space cleanliness than a domino-resonator counterpart in medium-distance (energy transfer distance bigger than coil's dimension) application area. The theory and design criteria for achieving these objectives have been presented and explained. The theory has been practical proven with the use of practical prototypes. This approach is envisaged to be an elegant solution to design planar wireless charging systems for

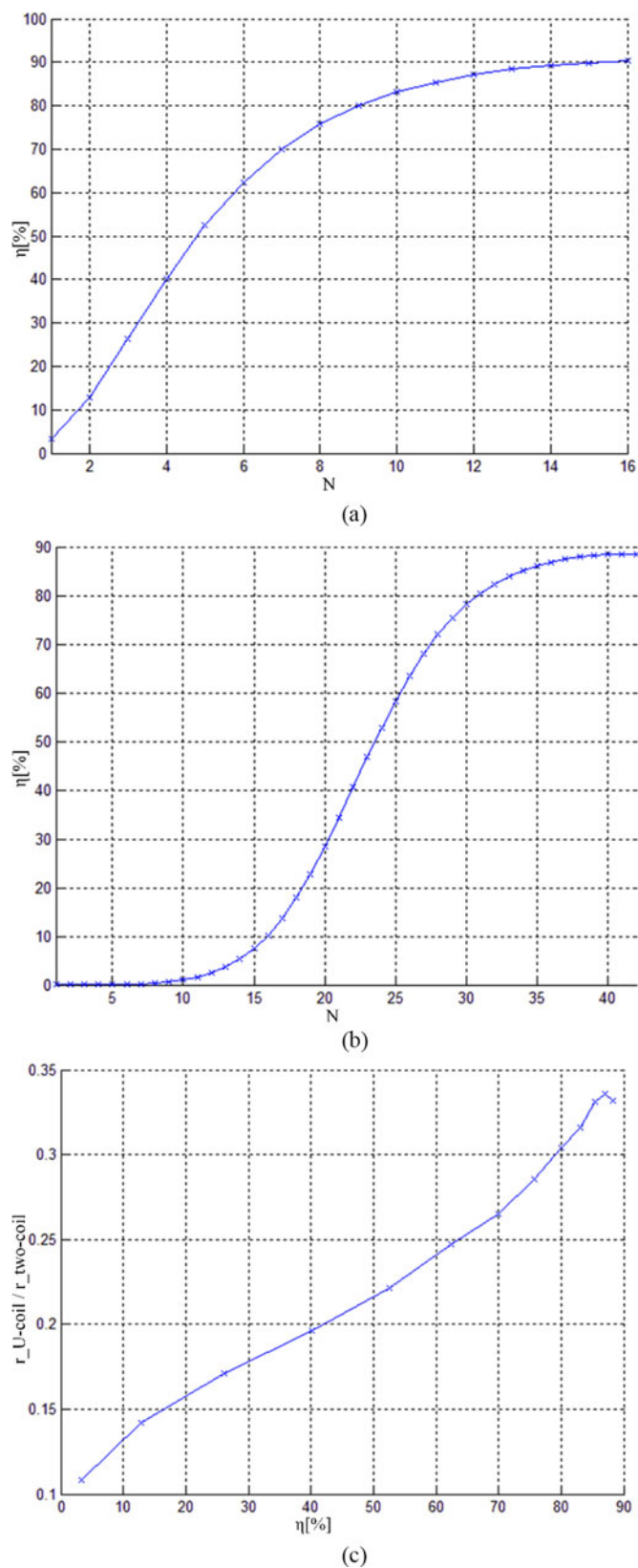


Fig. 14. Efficiency comparison between U-coil and two-coil system under different turns of coil conditions. (a) Efficiency curve with different turns of nonrelay coil in U-coil system. (b) Efficiency curve with different turns of coils in two-coil system. (c) Radius ratio curve of coils between U-coil and two-coil system.

tridimensional storages application such as adjacent storages, in which the primary coil and relay coil are embedded in the perpendicular wall of one storage and the load coil is embedded in the wall (parallel with primary coil) of another storage.

In this paper, the U-coil concept is demonstrated with the primary and relay coils arranged on the perpendicular plane for medium-power applications. However, it can be applied to low-power applications such as wireless charging of kitchen appliances needed cleanliness in energy transfer direction (range hood, disinfect cabinet, etc.), and it is envisaged that the same efficient principle can be applied to high-power applications such as wireless charging of electric vehicles. Comparing with traditional two-coil wireless charging system of electric vehicles, the same efficiency can be achieved using U-coil WPT system in which the dimensions of primary and load coils are much smaller than that of two-coil system.

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