

# Letters

## A Multi-Load Wireless Power Transfer System With Series-Parallel-Series Compensation

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**Abstract**—This letter proposes a novel wireless power transfer (WPT) system with repeater coils for multiple loads. Every two repeater coils form a repeater unit where one is used to receive power from its preceding unit and the other transmits power to the subsequent unit. Each load is connected to a repeater unit and multiple loads can be powered with several repeater units. The two coils in the same repeater unit are both bipolar ones, which are placed perpendicularly so that the magnetic coupling between them can be eliminated. In order to obtain independent power control of all the loads, the series-parallel-series compensation method is adopted for each repeater unit. With a proper resonant condition proposed in this letter, the constant load current can be obtained for all the loads when neglecting the coils' parasitic resistances. An experimental setup has been constructed and the effectiveness of the proposed multi-load WPT system is validated by the experimental.

**Index Terms**—Constant load current, multiple load, repeater coil, series-parallel-series (SPS) compensation, wireless power transfer (WPT).

### I. INTRODUCTION

**I**N THE conventional wireless power transfer (WPT) system, the energy is usually transferred from the source to only one load [1]. Recently the WPT system with multiple receivers has attracted more and more attentions where multiple loads can be powered simultaneously [2]–[5].

In [2], a WPT system with multiple receivers was proposed for the battery cell voltage equalization. The multiple receiving coils are placed in the same plane and receive power from a big transmitting coil. However, the cross-coupling between different receiving coils is neglected. In [3], multiple receiving coils with different resonant frequencies are used to receive power

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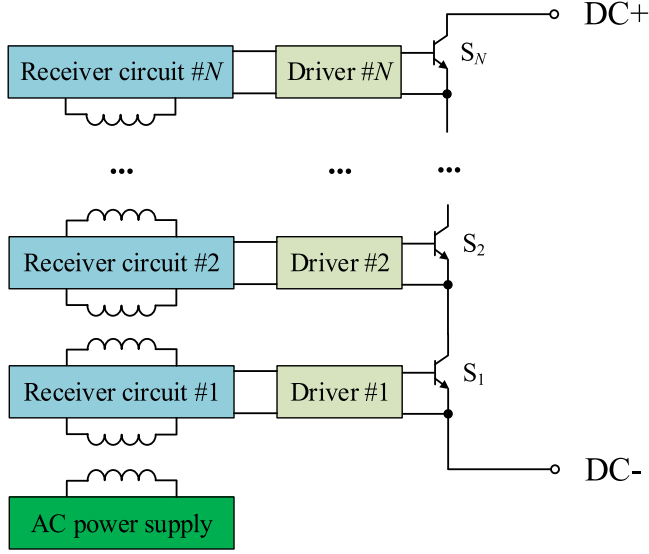


Fig. 1. WPT system providing power to the driver circuits in a multilevel converter.

receiving units, a compensation capacitor ( $C_{0,t}$  or  $C_{N,x}$ ) is connected in series with the corresponding coil, respectively. In each repeater unit, three compensation capacitors ( $C_{n,x}$ ,  $C_{n,t}$ , and  $C_{fn}$  where  $n = 1, 2, \dots, N-1$ ) form an SPS compensation topology for the two repeater coils.  $I_{0,t}$ ,  $I_{1,x}$ ,  $I_{1,t}$ ,  $\dots$ ,  $I_{N,x}$  are the currents flowing through the corresponding coils. These currents are positive when they flow into the dot terminals of the coils. In order to power the driver circuits for the IGBTs, a receiving circuit consisting of an uncontrolled rectifier and a dc/dc converter to regulate the output power is used to generate a stable dc voltage source for the driver circuit. Considering that the voltage across the rectifier and the current flowing into the rectifier are in phase, the receiving circuit and the driver circuit can be regarded as resistive. Thus, the load is modeled as  $R_n$  ( $n = 1, 2, \dots, N$ ) for simplification, which is connected in series with the receiving coil in each repeater unit and the receiving unit  $\#N$  as shown in Fig. 2.

With the coil design method in the following section, only the coupling effects between the two adjacent coils in the two adjacent unit, such as  $L_{1,t}$  and  $L_{2,x}$ , need to be considered. The coupling between other coils, even the two coils in the same unit, can be neglected. The coupling coefficient between unit  $\#(n-1)$  and  $\#n$  is defined as

$$k_n = M_n / \sqrt{L_{n-1,t} \cdot L_{n,x}}, \quad n = 1, 2, \dots, N \quad (1)$$

where  $M_n$  is the mutual inductance between  $L_{n-1,t}$  and  $L_{n,x}$ .

### B. Coil Design

The coil structure of the proposed WPT system is shown in Fig. 3. Bipolar coils [7] are adopted and the two coils in the same repeater unit are placed perpendicularly, so that the coupling effects between them can be neglected. The ferrite plates are inserted in every unit, which not only increase the

coupling coefficient between adjacent units but also suppress the coupling effects between other coils.

The distance between every two adjacent units is  $d = 60$  mm as required for the multilevel converter. All the coils are square with the side length  $l_{coil} = 160$  mm and the width of the coils is  $l_w = 20$  mm. The ferrite plates are also square with the side length  $l_{fe} = 120$  mm. Because of the symmetric characteristics of the system, only unit  $\#1$  and  $\#2$  are simulated and the results are given in Table I.  $k_{1r,1t}$  is the coupling coefficient between  $L_{1,x}$  and  $L_{1,t}$ ;  $k_{1r,2r}$  is the coupling coefficient between  $L_{1,x}$  and  $L_{2,x}$ ;  $k_{1r,2t}$  is the coupling coefficient between  $L_{1,x}$  and  $L_{2,t}$ ;  $k_2$  is the coupling coefficient between  $L_{1,t}$  and  $L_{2,x}$ , which is also defined as the coupling coefficient between repeater unit  $\#1$  and  $\#2$ . It can be seen that the other coupling can be neglected when compared with the coupling between two adjacent units.

### C. Operational Principle

In order to analyze the operational principle of the proposed WPT system, the reflected impedances in each coil can be used and calculated as

$$\begin{cases} Z_{r,N,x} = 0 \\ Z_{r,n-1,t} = (\omega_0 M_n)^2 / (r_{n,x} + R_n + Z_{r,n,x}), \quad n = 1, 2, \dots, N \\ Z_{r,n,x} = 1 / [(\omega_0 C_{fn})^2 \cdot (r_{n,t} + Z_{r,n,t})], \quad n = 1, 2, \dots, N-1 \end{cases} \quad (2)$$

where  $\omega_0$  is the operational angular frequency of the system. The subscript “r” represents the reflected impedance; the subscript “n-t” or “n-x” represents the coil that the reflected impedance is in. So,  $Z_{r,n,t}$  is the reflected impedance in coil  $L_{n,t}$  and  $Z_{r,n,x}$  is the reflected impedance in coil  $L_{n,x}$ . Then the currents flowing through the coils can be calculated as

$$\begin{cases} I_{0,t} = V_0 / (r_{0,t} + Z_{r,0,t}) \\ I_{n,x} = -j\omega_0 M_n I_{n-1,t} / (r_{n,x} + R_n + Z_{r,n,x}), \quad n = 1, 2, \dots, N \\ I_{n,t} = -I_{n,x} / [j\omega_0 C_{fn} (r_{n,t} + Z_{r,n,t})], \quad n = 1, 2, \dots, N-1. \end{cases} \quad (3)$$

In the proposed system, the compensation capacitors and inductors are designed to meet the following resonant condition:

$$\omega_0^2 = \frac{1}{L_{0,t} C_{0,t}} = \frac{1}{L_{1,x}} \left( \frac{1}{C_{f1}} + \frac{1}{C_{1,x}} \right) = \dots = \frac{1}{L_{N,x} C_{N,x}}. \quad (4)$$

Based on the coil topology in Section II-B, the dimensions of all the coils are identical with the same distance between adjacent units. Thus, the coupling coefficient and mutual inductance between adjacent units are identical, i.e.,

$$k_1 = k_2 = \dots = k_N = k, \quad M_1 = M_2 = \dots = M_N = M. \quad (5)$$

The compensation capacitance  $C_{fn}$  ( $n = 1, 2, \dots, N-1$ ) can be designed as

$$C_{f1} = C_{f2} = \dots = C_{fN-1} = C_f = 1 / (\omega_0^2 M). \quad (6)$$

In the idealized case, the coils' parasitic resistances can be neglected. Considering (5) and (6), the load currents in (3) can be simplified as

$$I_{1,x} = I_{2,x} = I_{3,x} = \dots = I_{N,x} = V_0 / (j\omega_0 M). \quad (7)$$

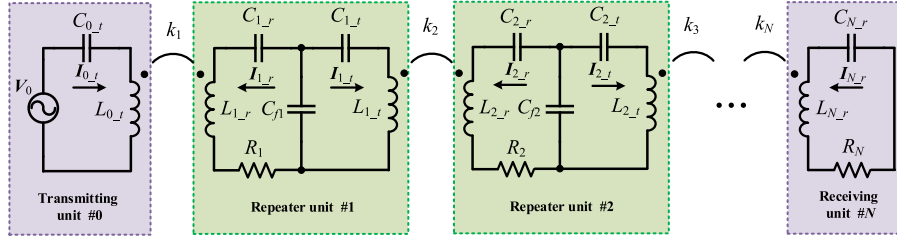


Fig. 2. Structure of the proposed multi-load WPT repeater system.

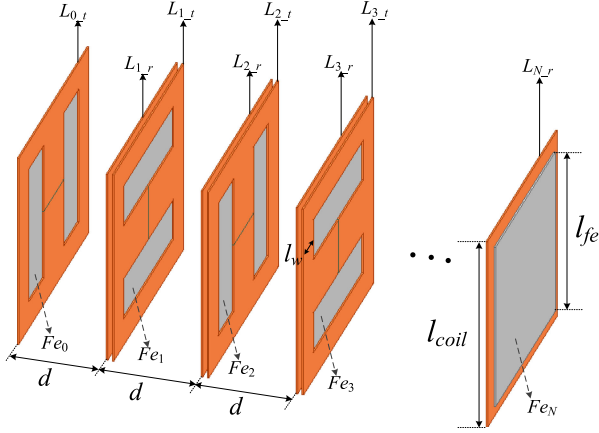


Fig. 3. Coil structure of the proposed WPT system.

TABLE I  
COUPLING COEFFICIENTS FOR THE PROPOSED COIL DESIGN

$k_{1r,1t}$	$k_{1r,2r}$	$k_{1r,2t}$	$k_{1,2}$
0.0001	0.0001	0.0064	0.257

It can be seen from (7) that the load currents only depend on the input voltage  $V_0$ , the mutual inductance between adjacent units  $M$  and the angular frequency  $\omega_0$ . Moreover, all the load currents have the same amplitude and phase. In a practical WPT system, the parasitic resistance is inevitable, the influence of which on the load currents can be calculated iteratively using (2) and (3) with the help of MATLAB.

#### D. System Efficiency

Since all the coils are identical, the parasitic resistances are also identical, which is defined as  $r$ . The system efficiency is denoted as  $\eta$ . The efficiency of each repeater unit is defined as  $\eta_n$  ( $n = 1, 2, \dots, N$ ). Thus,  $\eta = \eta_1 \cdot \eta_n$  and  $\eta_{n+1}$  have the following relationship:

$$\eta_n = \frac{Z_{r,n-1,t} R_n}{[(r + Z_{r,n-1,t}) \cdot (r + R_n + Z_{r,n,r}) + Z_{r,n-1,t} Z_{r,n,r} \eta_{(n+1)}] / [(r + Z_{r,n-1,t}) \cdot (r + R_n + Z_{r,n,r})]} \quad (8)$$

$$n = 1, 2, \dots, N - 1.$$

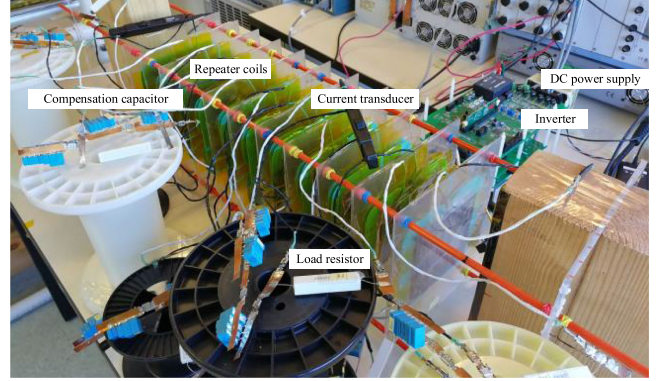


Fig. 4. Experimental setup.

TABLE II  
SYSTEM PARAMETERS OF THE EXPERIMENTAL SETUP

Parameter	Value	Parameter	Value
$V_{dc}$	30 V	$f_s$	200 kHz
$L_{0,t} \sim L_{10,t}$	94 $\mu$ H	$Q$	280
$C_{1,r} \sim C_{9,t}$	8.87 nF	$k$	0.24
$C_{0,t}, C_{10,r}$	6.74 nF	$C_{\beta} \sim C_{\theta}$	28.02 nF

For the last load, the efficiency  $\eta_N$  can be calculated as

$$\eta_N = \frac{Z_{r,N-1,t}}{r + Z_{r,N-1,t}} \cdot \frac{R_N}{r + R_N} = \frac{Q_{LN} \cdot (kQ)^2}{(1 + Q_{LN})^2 + (1 + Q_{LN})(kQ)^2} \quad (9)$$

where  $Q_{LN} = R_N/r$ . So, the whole system efficiency  $\eta$  can be calculated iteratively using (8) and (9).

### III. EXPERIMENTAL RESULTS

An experimental setup with ten loads ( $N = 10$ ) has been constructed as shown in Fig. 4. The coils are fixed on the plexiglass plates. The dimensions of the coils and ferrite plates are the same as the simulation model in Section II. The coupling coefficient  $k$  between adjacent units is measured around 0.24. An H-bridge inverter is used to generate a 200 kHz ac power supply from a dc source of 30 V. All the system parameters are given in Table II.

The coils' parasitic resistances can be measured using an LCR meter. In our experimental system, the coils' quality factor is

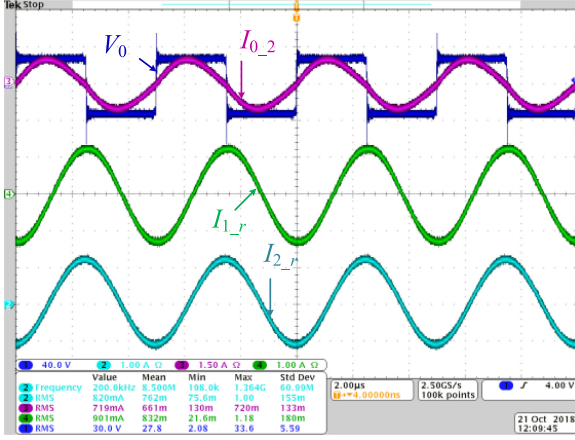


Fig. 5. Experimental waveforms of the voltages and currents.

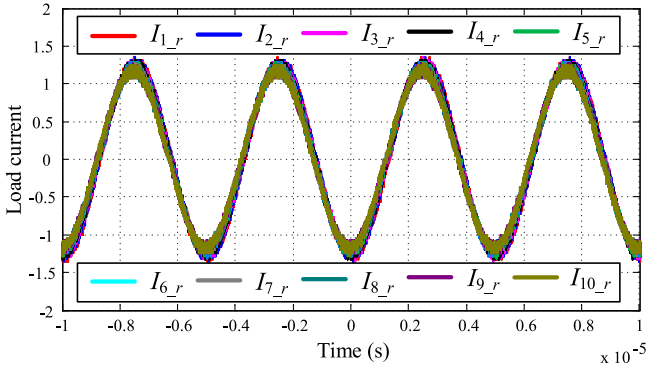


Fig. 6. Waveforms of the ten load currents.

around 280. Thus, the parasitic resistances can be calculated as

$$r_i = \omega_0 L_i / Q_i \quad (10)$$

where  $i$  is the coil number. In order to facilitate the analysis, the load currents and resistances are normalized by dividing their base values defined as

$$R_b = \omega_0 M, I_b = V_0 / R_b. \quad (11)$$

The experimental waveforms are shown in Fig. 5. The current  $I_{0,t}$  and the input voltage  $V_0$  are nearly in phase so that the input power is nearly all active power. Fig. 5 also shows the waveforms of two load currents  $I_{1,r}$  and  $I_{2,r}$ . Since the oscilloscope only has four channels, the ten load currents cannot be captured simultaneously in the same figure. Thus, the load currents when the load resistance is  $2 \Omega$  are captured using the oscilloscope and re-drawn using MATLAB as shown in Fig. 6. All the load currents are in phase, which is consistent with the analysis in (7). The amplitudes of these currents are nearly the same. The current drop is due to the parasitic resistances.

The root mean square (rms) values of the calculated load currents using (2) and (3) together with the experimental results are shown in Fig. 7 with increasing load resistance. Because of the parasitic resistances, the load currents decrease gradually

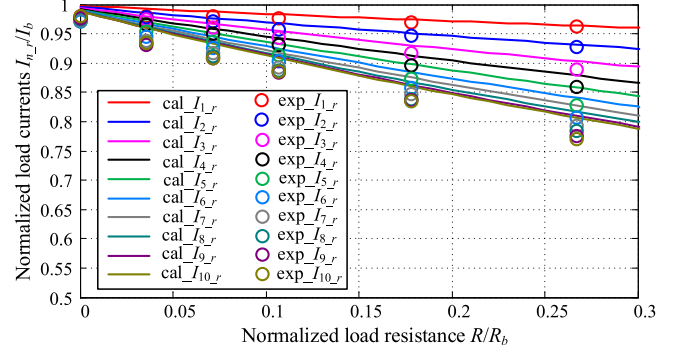
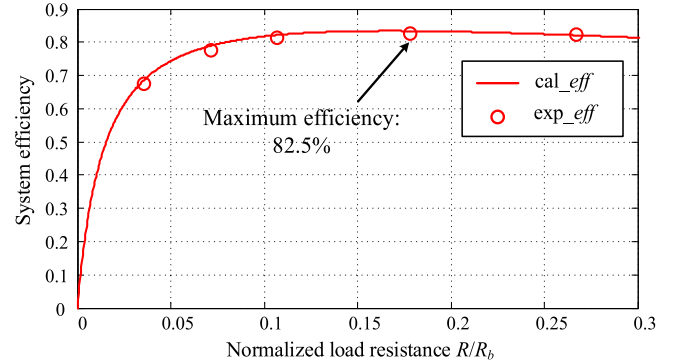


Fig. 7. Load current variation against the load resistance.


 Fig. 8. System efficiency of the experimental setup ( $k = 0.24$ ,  $Q = 280$ ).

as the load resistance increases. The experimental results are basically consistent with the calculated ones.

Fig. 8 shows the system efficiency variation of the experimental setup along with the load resistance. The solid line is the calculated efficiency using the load currents considering the parasitic resistance shown in (3) and the load resistance. The dot points are the measured system efficiency, which is consistent with the calculated one. As can be seen from Fig. 8, the maximum efficiency can reach 82.5% when the normalized load resistance is about 0.17, which is very high considering that there are totally ten loads in the system. In the experiment, the load current is about 0.85 A and the total load power is approximately 30 W at the maximum system efficiency when the input dc voltage is 30 V. When the dc voltage becomes larger, the load current and the load power will also increase.

#### IV. CONCLUSION

In this letter, a novel multi-load WPT system is proposed using repeater units, each of which contains two bipolar repeater coils placed perpendicularly. An SPS compensation topology is adopted for each repeater unit. The load is connected in series with the receiving coil in each repeater unit. With the proposed system structure and compensation topology, the constant load currents can be obtained for all the loads. Experimental results are provided to validate the effectiveness of the proposed multi-load WPT system.

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