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A Multi-load Wireless Power Transfer System with Series-parallel-series (SPS) 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 (SPS) compensation method is adopted for each repeater unit. With a proper resonant condition proposed in this paper, the constant load current can be obtained for all the loads when neglecting the coils' parasitic resistances. An experimental setup has be constructed and the effectiveness of the proposed multi-load WPT system is validated by the experimental.[1]**

***Index Terms*— Wireless power transfer (WPT), multiple load, repeater coil, constant load current, SPS compensation.**

I. Introduction

In 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 from the same transmitting coil. By changing the operational frequency of the source, the receiving coil with the same resonant frequency can receive power. However, only one receiver works at a certain moment.

In a multi-load WPT system, the control of the load power is challenging because of the various coupling effects between different coils. In [4], the buck converter is used at each receiving circuit to control the load power. Repeater coils are used in [5] and each repeater coil is connected to a load. It is derived in [5] that the load resistance should meet a certain condition to realize equal power distribution among all the loads. It means that the load power is coupled with each other, which makes it difficult to control the load power in practical applications.

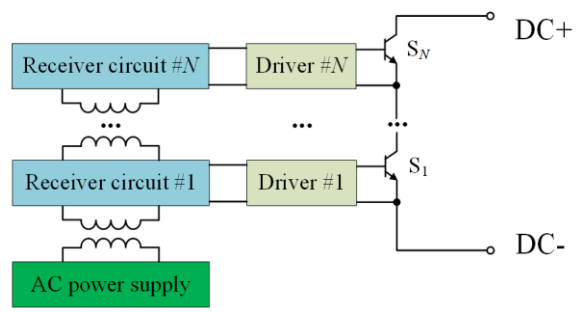

Fig. 1. The WPT system providing power to the driver circuits in a multilevel converter.

In this letter, a novel multi-load WPT system is proposed. The repeater unit containing two repeater coils is designed and a suitable magnetic decoupling can be achieved. The series-parallel-series (SPS) compensation method is used for each repeater unit. The constant load current can be obtained for the proposed system, which facilitates the power control of all the loads. The proposed WPT system can be used to power multiple loads such as the driver circuits of the power electronics switches in a multilevel converter as illustrated in Fig. 1. These switches are connected in series to withstand the high voltage. Since the reference potential of these IGBTs are different, multiple isolated power supplies are needed for the IGBTs' driver circuits. Thus, the proposed multi-load WPT system provides an ideal solution for these driver circuits [6].

II. System Design

A. System Description

The structure of the proposed multi-load WPT system is shown in Fig. 2. $\boldsymbol{V}_0$ is the high-frequency power supply. The transmitting coil L_{0_t} is connected with $\boldsymbol{V}_0$ to transmit power to the subsequent coils, which makes up the transmitting unit #0. There are (N-1) repeater units in Fig. 2, each of which contains two repeater coils, i.e. L_{n_r} and L_{n_t} (n = 1, 2, …, N-1). The

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letter "*r*" and "*t*" in the subscript represent receiving and transmitting respectively. The number "*n*" in the subscript indicates the unit number. For example, L_{1_r} is the receiving coil in repeater unit #1. The last unit is the receiving unit #*N*, where only the receiving coil is needed. In both the transmitting and receiving units, a compensation capacitor (C_{0_t} or C_{N_r}) is connected in series with the corresponding coil respectively. In each repeater unit, three compensation capacitors (C_{n_r}, C_{n_t} and C_{fn} where n = 1, 2, …, N-1) form a series-parallel-series (SPS) compensation topology for the two repeater coils. $\boldsymbol{I}_{0\_t}$, $\boldsymbol{I}_{1\_r}$, $\boldsymbol{I}_{1\_t}$, … , $\boldsymbol{I}_{N\_r}$ 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 modelled as R_n (n = 1, 2, …, 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 next section, only the coupling effects between the two adjacent coils in the two adjacent unit, such as L_{1_t} and L_{2_r}, 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,

$$k_n = M_n \Big/ \sqrt{L_{n-1\_t} \cdot L_{n\_r}}\,, \quad n = 1, 2, ..., N \tag{1}$$

where M_n is the mutual inductance between $L_{n\text{-}1\_t}$ and L_{n_r}.

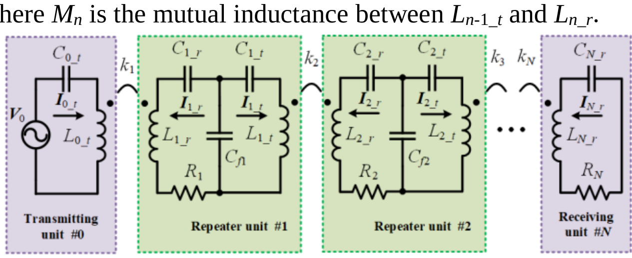

Fig. 2. The structure of the proposed multi-load WPT repeater system.

B. Coil Design

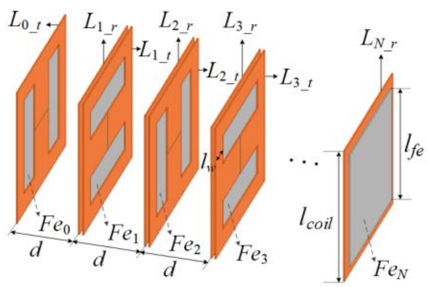

Fig. 3. The coil structure of the proposed WPT system.

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.

TABLE I.
THE COUPLING COEFFICIENTS FOR THE PROPOSED COIL DESIGN

k_{1r_1t}	k_{1r_2r}	k_{1r_2t}	k_2
0.0001	0.0001	0.0064	0.257

The distance between every two adjacent units is d = 60mm as required for the multilevel converter. All the coils are square with the side length l_{coil} = 160mm and the width of the coils is l_w = 20mm. The ferrite plates are also square with the side length l_{fe} = 120mm. Because of the symmetric characteristics of the system, only unit #1 and #2 are simulated and the results are listed in Table. I. k_{1r_1t} is the coupling coefficient between L_{1_r} and L_{1_t}; k_{1r_2r} is the coupling coefficient between L_{1_r} and L_{2_r}; k_{1r_2t} is the coupling coefficient between L_{1_r} and L_{2_t}; k_2 is the coupling coefficient between L_{1_t} and L_{2_r}, 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,

$$\begin{cases} Z_{r,N\_r} = 0 \\ Z_{r,n-1\_t} = (\omega_0 M_n)^2 \big/ (r_{n\_r} + R_n + Z_{r,n\_r}), n = 1, 2, \ ... \ , N \\ Z_{r,n\_r} = 1 \big/ [(\omega_0 C_{fn})^2 \cdot (r_{n\_t} + Z_{r,n\_t})], n = 1, 2, \ ... \ , N-1 \end{cases} \tag{2}$$

where ω_0 is the operational angular frequency of the system. The subscript "*r*" represents the reflected impedance; the subscript "*n_t*" or "*n_r*" represents the coil that the reflected impedance is in. So $Z_{r,\, n\_t}$ is the reflected impedance in coil L_{n_t} and $Z_{r,\, n\_r}$ is the reflected impedance in coil L_{n_r}. Then the currents flowing through the coils can be calculated as,

$$\begin{cases} \boldsymbol{I}_{0\_t} = \boldsymbol{V}_0 \big/ (r_{0\_t} + Z_{r,0\_t}) \\ \boldsymbol{I}_{n\_r} = -j\omega_0 M_n \boldsymbol{I}_{n-1\_t} \big/ (r_{n\_r} + R_n + Z_{r,n\_r}), n = 1, 2, \ ... \ , N \\ \boldsymbol{I}_{n\_t} = -\boldsymbol{I}_{n\_r} \big/ [j\omega_0 C_{fn} (r_{n\_t} + Z_{r,n\_t})], \ \ n = 1, 2, \ ... \ , N-1 \end{cases} \tag{3}$$

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

$$\omega_0^2 = \frac{1}{L_{0\_t} C_{0\_t}} = \frac{1}{L_{1\_r}} \left(\frac{1}{C_{f1}} + \frac{1}{C_{1\_r}} \right) = ... = \frac{1}{L_{N\_r} C_{N\_r}} \tag{4}$$

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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.

$$k_1 = k_2 = ... = k_N = k, \quad M_1 = M_2 = ... = M_N = M \tag{5}$$

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

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

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

$$\boldsymbol{I}_{1\_r} = \boldsymbol{I}_{2\_r} = \boldsymbol{I}_{3\_r} = ... = \boldsymbol{I}_{N\_r} = \boldsymbol{V}_0/(j\omega_0 M) \tag{7}$$

It can be seen from (7) that the load currents only depend on the input voltage $\boldsymbol{V}_0$, the mutual inductance between adjacent units M and the angular frequency ω_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 η. The efficiency of each repeater unit is defined as η_n (n = 1, 2, …, N). Thus, $\eta = \eta_1$. η_n and η_{n+1} have the following relationship,

$$\begin{aligned} \eta_n &= Z_{r,n-1\_t} R_n / [(r + Z_{r,n-1\_t}) \cdot (r + R_n + Z_{r,n\_r})] \\ &\quad + Z_{r,n-1\_t} Z_{r,n\_r} \eta_{(n+1)} / [(r + Z_{r,n-1\_t}) \cdot (r + R_n + Z_{r,n\_r})], \\ n &= 1,\ 2,\ ...,\ N-1 \end{aligned} \tag{8}$$

For the last load, the efficiency η_N can be calculated as,

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

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

III. Experimental Results

TABLE II.
System Parameters of the Experimental Setup

Parameter	Value	Parameter	Value
V_{dc}	30V	f_s	200kHz
L_{0_t} ~ L_{10_r}	94μH	Q	280
C_{1_r} ~ C_{9_t}	8.87nF	k	0.24
C_{0_t}, C_{10_r}	6.74nF	C_{f1} ~ C_{f9}	28.02nF

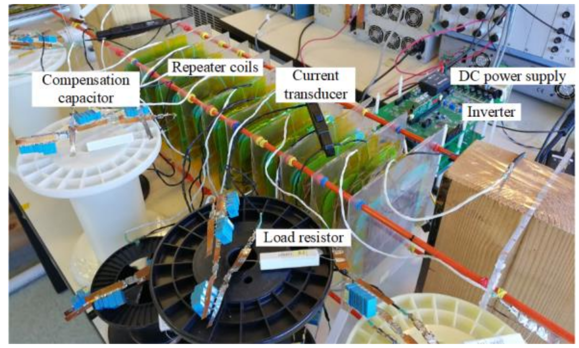

Fig. 4. The experimental setup.

An experimental setup with 10 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 200kHz AC power supply from a DC source of 30V. All the system parameters are listed in Table II.

The coils' parasitic resistances can be measured using a LCR meter. In our experimental system, the coils' quality factor is around 280. Thus, the parasitic resistances can be calculated as,

$$r_i = \omega_0 L_i / Q_i \tag{10}$$

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 in (11).

$$R_b = \omega_0 M, \quad I_b = V_0 / R_b \tag{11}$$

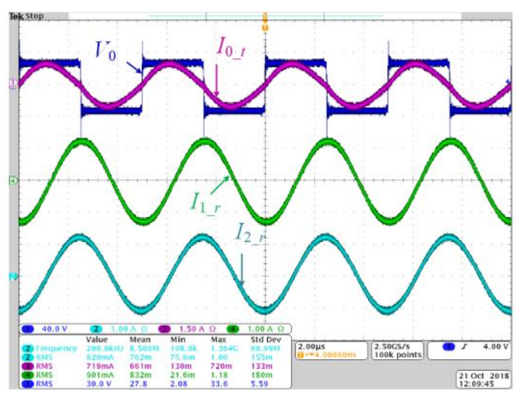

Fig. 5. Experimental waveforms of the voltages and currents.

The experimental waveforms are shown in Fig. 5. The current $\boldsymbol{I}_{0\_t}$ and the input voltage $\boldsymbol{V}_0$ 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 2Ω are captured using the oscilloscope and re-drawn using MATLAB as

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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.

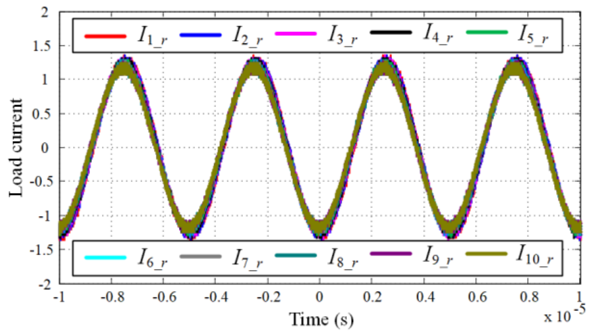

Fig. 6. The waveforms of the ten load currents.

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

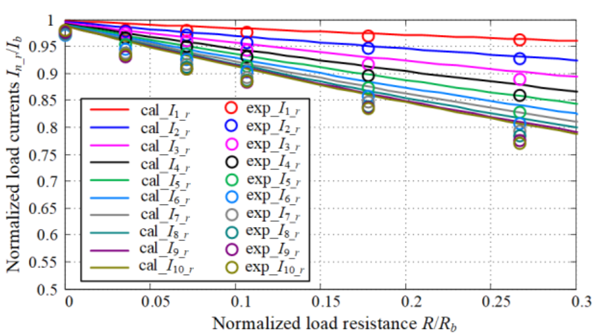

Fig. 7. The load current variation against the load resistance.

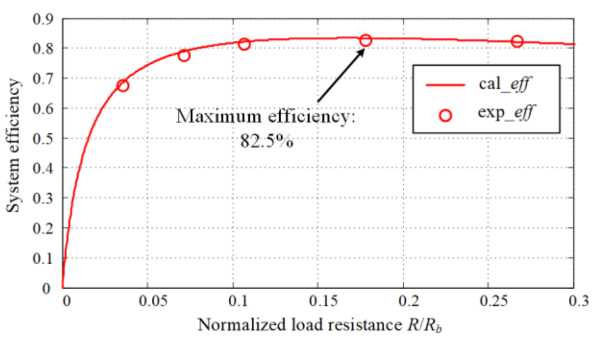

Fig. 8. The system efficiency of the experimental setup (k = 0.24, Q = 280).

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 0.85A and the total load power is approximately 30W at the maximum system efficiency when the input DC voltage is 30V. 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. A 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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