Extendible slot-type wireless power transfer system with load-independent output voltage based on solenoid coil

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Abstract: An innovative extendible wireless power transfer system with load independent output voltage is developed in this paper. This system eliminates the interference caused by the cross coupling between nonadjacent coils and unrelated circuit networks among the receiving coils. The wireless power transfer system consists of a full-bridge converter power supply, transmitting resonator, relay resonators, and multiple receiving resonators. The theory of load independent output voltage is demonstrated in detail in this paper. The structure and features of the system has also been carefully illustrated. The simulation and experimental results show that the multiple receiving resonators do not affect each other when obtaining power and that the system can obtain load-independent output voltage. Experimental results and simulation analysis are highly consistent and the integrity of the theory is verified.

Keywords: wireless power transfer, solenoid coil, load independent output voltage, K inverter, slot type

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

[1] H. Hu and S. V. Georgakopoulos: “Wireless power transfer in human tissue via conformal strongly coupled magnetic resonance,” 2015 IEEE Wireless Power Transfer Conference (WPTC) (2015) 1 (DOI: 10.1109/WPT.2015.7140150).

[2] S. Y. R. Hui, et al.: “A critical review of recent progress in mid-range wireless power transfer,” IEEE Trans. Power Electron. 29 (2014) 4500 (DOI: 10.1109/TPEL.2013.2249670).

[3] U. Surendrakumaran and A. Nachiappan: “Performance analysis of wireless power transfer (WPT) through two-coil and three-coil structure,” 2017 International Conference on Innovative Research In Electrical Sciences (II CIRES) (2017) 1 (DOI: 10.1109/II CIRES.2017.8078308).
[4] K. K. Ean, et al.: “Novel band-pass filter model for multi-receiver wireless power transfer via magnetic resonance coupling and power division,” WAMICON 2012 IEEE Wireless & Microwave Technology Conference, (2012) 1 (DOI: 10.1109/WAMICON.2012.6208428).

[5] P. Meyer, et al.: “Design of a contactless energy-transfer system for desktop peripherals,” IEEE Trans. Ind. Appl. 47 (2011) 1643 (DOI: 10.1109/TIA.2011.2153812).

[6] W. X. Zhong, et al.: “A novel single-layer winding array and receiver coil structure for contactless battery charging systems with free-positioning and localized charging features,” IEEE Trans. Ind. Electron. 58 (2011) 4136 (DOI: 10.1109/TIE.2010.2098379).

[7] K. Amano, et al.: “Proposal of isolated outlet socket and plug using capacitive power transfer,” 2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 - ECCE Asia) (2017) 648 (DOI: 10.1109/IFEEC.2017.7992115).

[8] Y. Miiura, et al.: “Voltage control of inductive contactless power transfer system with coaxial coreless transformer for DC power distribution,” 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA) (2014) 1430 (DOI: 10.1109/IPEC.2014.6869773).

[9] X. Liu and S. Y. Hui: “Optimal design of a hybrid winding structure for planar contactless battery charging platform,” IEEE Trans. Power Electron. 23 (2008) 455 (DOI: 10.1109/TPEL.2007.911844).

[10] Y. Cheng, et al.: “Modeling and optimization of mm-sized solenoid coils for biomedical implants,” 2016 IEEE Biomedical Circuits and Systems Conference (BioCAS) (2016) 324 (DOI: 10.1109/BioCAS.2016.7833797).

[11] B. Luo, et al.: “Flexible design method for multi-repeater wireless power transfer system based on coupled resonator bandpass filter model,” IEEE Trans. Circuits Syst. I, Reg. Papers 61 (2014) 3288 (DOI: 10.1109/TCSI.2014.2327331).

[12] Y. Yang, et al.: “A combined transmitting coil design for high efficiency WPT of endoscopic capsule,” 2015 IEEE International Symposium on Circuits and Systems (ISCAS) (2015) 97 (DOI: 10.1109/ISCAS.2015.7168579).

[13] S. Lukic and Z. Pantic: “Cutting the cord: Static and dynamic inductive wireless charging of electric vehicles,” IEEE Electrific. Mag. 1 (2013) 57 (DOI: 10.1109/MELE.2013.2273228).

[14] J. T. Conway: “Exact solutions for the magnetic fields of axisymmetric solenoids and current distributions,” IEEE Trans. Magn. 37 (2001) 2977 (DOI: 10.1109/20.947050).

[15] R. Hagel, et al.: “On the magnetic field of an infinitely long helical line current,” IEEE Trans. Magn. 30 (1994) 80 (DOI: 10.1109/20.272518).

[16] J. Zhou, et al.: “Extendible load-isolation wireless charging platform for multi-receiver applications,” IET Power Electron. 10 (2017) 134 (DOI: 10.1049/iet-pel.2016.0432).

[17] B. Luo, et al.: “Flexible design method for multi-repeater wireless power transfer system based on coupled resonator bandpass filter model,” IEEE Trans. Circuits Syst. I, Reg. Papers 61 (2014) 3288 (DOI: 10.1109/TCSI.2014.2327331).

[18] Z. Pantic, et al.: “Receivers for multifrequency wireless power transfer: Design for minimum interference,” IEEE J. Emerg. Sel. Topics Power Electron. 3 (2015) 234 (DOI: 10.1109/JESTPE.2014.2356853).

[19] Y. Kim, et al.: “Selective wireless power transfer for smart power distribution in a miniature-sized multiple-receiver system,” IEEE Trans. Ind. Electron. 63 (2016) 1853 (DOI: 10.1109/TIE.2015.2493142).

[20] Y. Zhang, et al.: “Employing load coils for multiple loads of resonant wireless
power transfer,” IEEE Trans. Power Electron. 30 (2015) 6174 (DOI: 10.1109/TPEL.2015.2396943).

1 Introduction

In 2007, a new wireless power transfer (WPT) technology based on magnetic-resonance was proposed [1]. Magnetic resonant WPT has the advantages of safety, simple structure, mid-range transfer and high efficiency [2]. The coil structure of WPT has been extensively researched in recent years [3, 4].

In view of a multi-load WPT system, the expansion of the system is very tedious, and most of the platforms are flat. Based on the planar spiral quadrilateral, a multi-layered array-type original side magnetic energy transfer network for multi-load power supply was proposed and was expansible [5]. Because of the uneven distribution of magnetic field in a single-layer array, it is very difficult for the WPT system to use and cover a large area. In [6], a magnetic energy transfer network with a single-layer winding array with iron core was proposed. The receiver was placed arbitrarily and the transfer network was extended. However, the implementation of this network faces difficulties because of the strict technical requirements for iron core materials and the position of each expansion. In previous research, capacitor-type power transfer was applied to slot-type power supply [7]. In addition, the slot-type charging device with transformer was also designed [8].

These kinds of wireless charging devices have many drawbacks, where complex structure is a typical one [9]. The charging device in this paper uses a solenoid coil to produce a uniform magnetic field, based on magnetic coupling resonant WPT technology [10]. The plane-type wireless charging device occupies large space. In order to reduce the volume of the charging device, a new type of solenoid coil with many slots is adopted to design a wireless charging device with load-independent output voltage. The receiving part of the device consists of multiple resonators [11]. This device is very easy to expand by extending the length of relay coil. The system consists of an inverter alternating current (AC) power supply, K converter, square transmitting coil, square solenoid receiving coil and load receiving coils. Firstly, the direct current (DC) voltage is inverted to the AC voltage with resonant frequency, followed by transferred to the source coil. The source transmitting coil transfers the energy to the relay coil through the magnetic coupling resonance [12], and then the rectification filter rectifies the AC voltage with resonant frequency to the load receiver coils. This device can be applied to various scenarios, e.g. multi-load non-conductor contact wireless charging sockets, household electrical socket-type wireless charging equipment and large underground parking lot with wireless charging stations [13].

The rest of the paper is organized as follows. The second section introduces the structure and operation principle of the proposed system. The simulation analysis and experimental measurement are performed in the third section. The fourth section concludes the whole paper.
2 The proposed structure and the operation principle

2.1 Overall structure

As shown in the Fig. 1, the left part of the system is transmitting coil fixed on a square relay solenoid coil. The four or more slots in the middle are used to provide power for the loads. The diameter of the four receiver coils is less than that of the relay coils. As for the power supply, the power circuit is connected with the transmitting coil after two conversions of AC-DC and DC-AC.

2.2 Solenoid coil of the system

The long square solenoid coil is used as the relay coil of this system. The solenoid coil is uniformly made of the wire [14] with a high ratio of length to diameter. The magnetic strength of the solenoid coil is related to the number of coil turns, the thickness of wire tube, and the current of iron core. When the current goes through the solenoid coil, the uniform magnetic field will be formed inside the solenoid coil [15].

2.3 System principle

The system is composed of transmitting resonators, relay resonators and receiving resonators [16]. The whole circuit diagram is presented in Fig. 2.

The AC source of the device is transformed by AC-DC-AC circuit. The internal resistance of the AC source is very small indicating a small switching loss. Therefore it can be regarded as an AC voltage source without internal resistance. The other parameters are as follows:

- \( L_i \) - the inductance of the \( i^{th} \) coils, where \( i = 1, 2, 3, \ldots, N \);
- \( L_p \) - the inductance of the source coil;
- \( L_r \) - the inductance of the relay coil;
- \( C_i \) - the \( i^{th} \) compensation capacitors;
- \( C_p \) - the compensation capacitor of the relay resonator;
- \( R_i \) - loss resistance in the inductances and capacitors;
- \( R_s \) - the internal resistance of the voltage source;
- \( R_{lp} \) - the loss resistance in the inductance and capacitors of the relay resonator;
- \( M_{ij} \) - mutual inductance between the \( i^{th} \) and \( j^{th} \) coils, where \( i \) and \( j = 1, 2, 3, \ldots, N \) and \( i \neq j \);
- \( R_{L_i} \) - resistive loads of \( i^{th} \) RX.

The problem of frequency drift can be eliminated through LC network which is described as an equivalent resistance for simplicity. A two-coil magnetic coupling
resonator wireless power transfer (MCR-WPT) system can be equivalent to a T-type inductor network, which is displayed in Fig. 3.

However, a T-type inductor network circuit can be equivalent to a K-inverter, as shown in Fig. 4 [17]. The K-inverter inserted between the power supper and the transmitter resonator is a two-port lumped LC circuit. In Fig. 4, it can be realized by the inductance coupling circuit, where $M_{12} = K_{12}/\omega_0$. The K-inverter is also known as impedance converter [17]. The ‘K’ is the characteristic parameter of the K converter. The simplified equivalent diagram of the K-inverter is presented in Fig. 5.

The system has two important features, i.e. controllable power distribution and the elimination of interference between loads in the system. In the traditional multi-load WPT system, the interference between the loads comes from two aspects. One
is the interference caused by the mutual inductance between the loads; the other is
the voltage division effect of the circuit. In order to eliminate the voltage division
effect, a load isolation scheme is proposed, which is also called K-inverter scheme.
The K-inverter can stabilize and control the voltage and power of loads. Besides, it
has potential applications to various multi-load WPT systems. Combined with this
scheme and MCR-WPT technology, an expandable WPT system with multi-load
isolation characteristics is developed.

2.4 Characteristics of load-independent output voltage
In the multi-load WPT system, the instability of the load power supply mainly
results from the cross mutual inductance of the load which is a very common
interference phenomenon [18]. For the system with relay coil, the coupling
condition of the transfer and receiving of the WPT system is $K_{S1} R_{Q1} = 1$. The
relay coil is no longer suitable when it is close to 1. The system adopts the scheme
of source - relay - load receiving coil, and there is a cross coupling coefficient.
Obviously, for single relay coil, the effects of K should be reduced as much as
possible. Under the above conditions, the equivalent diagram of the circuit is shown
in Fig. 6 [19, 20].

For a system working at the frequency of $\omega_0$, the input impedance at the load
part is $Z_{in}$. By circuit analysis, the input impedance can be calculated by,

$$Z_{in} = \frac{K^2}{R_S + \sum_{i=1}^{N} \frac{\omega_0^2 M_i^2}{(R_i + R_{Li})}}$$  \hspace{1cm} (1)

The information on the phase of load voltages is lost during these trans-
formations processes, which however does not affect the whole system [5]. The
voltage $V_i$ across the load $R_i$ and $R_{Li}$ in $i^{th}$ RX, is calculated by
The voltage $V_{Li}$ with the resistance $R_{Li}$ in each RX can be calculated by

$$V = V_S \frac{Z_{in}}{Z_{in} + R_S}$$  \hspace{1cm} (2)$$

Combining the above three equations, the voltage amplitude of the $R_{Li}$ can be expressed as

$$|V_{Li}| = \frac{R_{Li}\omega_0 M_{P1} V_S}{K(R_i + R_{Li}) \left(1 + \frac{R_S R_P}{K^2} + \sum_{i=1}^{N} \frac{\omega_0^2 M_{P1}^2 R_S}{K^2 (R_{Li} + R_i)} \right)}$$  \hspace{1cm} (4)$$

In order to reduce the power loss from the source resonators to the receiving resonators, the loss resistors $R_S$, $R_P$, and $R_i$ should be small enough. Overall, the loss resistance $R_i$ should be much smaller than $R_{Li}$, and the value of $R_S$ is almost $0 \, \Omega$ in the whole system. The above conditions can be expressed as

$$\frac{R_S R_P}{K^2} \ll 1$$  \hspace{1cm} (5)$$

$$\frac{\omega_0^2 M_{P1}^2 R_P}{K^2 (R_{Li} + R_i)} \ll 1$$  \hspace{1cm} (6)$$

$$\frac{R_i}{R_{Li}} \ll 1$$  \hspace{1cm} (7)$$

And the voltage amplitude of the $R_{Li}$ can be expressed as

$$|V_{Li}| = \left| \frac{R_{Li}\omega_0 M_{P1} V_S}{KR_{Li} + KR_i} \right| \approx \left| \frac{\omega_0 M_{P1}}{K} V_S \right|$$  \hspace{1cm} (8)$$

$$\omega = \frac{1}{\sqrt{L_S C_S}}$$  \hspace{1cm} (9)$$

When the inner resistance of the coil is ignored, we have:

$$j\omega_0 L_S + \frac{1}{j\omega_0 C_S} = 0$$  \hspace{1cm} (10)$$

$$I_T = \frac{V_S}{j\omega_0 M_{SP}}$$  \hspace{1cm} (11)$$

$$V_{Li} = I_{Li} R_{Li} = j\omega_0 M_{P1} I_T = \frac{V_S M_{P1}}{M_{SP}}$$  \hspace{1cm} (12)$$

It can be seen from the above equations that the voltage of the load $R_{Li}$ is only related to the value of $M_{P1}/M_{SP}$ and the power supply voltage, and not related to other external factors or the resistance itself. Therefore, the voltage of any load will not be affected by adding or removing the load randomly in this system [6].

The power of $R_{Li}$ is expressed as

$$P_{Li} = \frac{\omega_0^2 M_{P1}^2 V_S^2}{2K^2 R_{Li}}$$  \hspace{1cm} (13)$$

Correspondingly, the total transmission efficiency of the system is expressed as

$$\eta = 2 \sum_{i=1}^{N} \frac{P_{Li}}{R_i(V_S)}$$  \hspace{1cm} (14)$$
\[
\eta = \frac{\sum_{i=1}^{N} \frac{\varepsilon_0^2 M_{p_i}^2 R_{Li}}{(R_{Li} + R_i)}^2}{\sum_{i=1}^{N} \left[ \frac{\varepsilon_0^2 M_{p_i}^2}{(R_{Li} + R_i)} + R_{TX} \right]}
\]  

(15)

Similarly, power acquisition is only related to transfer ratio factor \(M_{p_1}/M_{SP}\), power supply voltage, and load size, and not related to other factors. With the combination of load voltage and power, the voltage effect is partially eliminated, and the load has been separated from each other. For any single charging slot, the power gain of the load is stable and reliable, which generates load-independent output voltage.

### 2.5 Source circuit

This device uses high-frequency AC, so the household electricity should be rectified to DC, and further inverted to high-frequency AC. Inversion is the reverse process of rectification, and DC is converted to high-frequency AC. As for the design of inverter circuit, there are two options. One is to convert DC to high-frequency AC using inverter, and the other is to amplify the output signal of the signal generator directly. But the signal power is relatively small. Through power amplifier circuit, the power is reduced again, and the transfer power is not very large, so further improvement is required for practicability of the designed platform. Therefore, the using of inverter can provide a larger transfer power.

The full-bridge inverter circuit is adopted in this design. Compared with half-bridge inverter, the switching current of full-bridge inverter is reduced by half. So full-bridge inverter circuit has been widely used in high-power situations, and is able to provide large power.

### 3 Simulation and experiment

In order to verify the characteristics of the developed system with multi-load independent output voltage, a long straight solenoid coil with four loads coils was selected as the experimental platform. The experimental platform is shown in Fig. 7.

![Fig. 7. (a) “Experiment platform with four loads”; (b) “experiment platform with two loads”.
](image)
As shown in Fig. 7, the experimental platform consists of a half-bridge inverter driven by a DC power supply. This power supply provides a large power, and it also considered as a voltage supply with almost zero output impedance. In the experiment, a power supply of 12 V DC was provided. The output of the half-bridge inverter was an AC voltage with voltage amplitude of 12 V. The relay solenoid coil was wound by enameled copper wire with a wire diameter of 1 mm. The side length of the coil was 6 cm.

A full-bridge inverter consists of two half-bridge inverters, including two MOSFETs IRF3205, IR2110 chip and diodes. The V15 represents the DC input of 15 V, and VN represents the input range of 0~55 V. For convenience, this experiment used a half-bridge inverter.

The frequency of the low-frequency band proposed in this paper outperformed the frequency of the high-frequency band in improving the quality factor of the resonator and improving the transfer efficiency in the system. Therefore, the operating frequency of the experimental platform was set at about 85 kHz. The parameters of each resonator are shown in Table I.

### Table I. Resonator parameters in experimental platform

| Coil         | TX | REX | RX1&2&3&4 |
|--------------|----|-----|----------|
| Number of turns | 9  | 64  | 13       |
| Wire diameter (mm) | 1  | 1   | 1        |
| Radius of coil (cm) | 7  | 6   | 5        |
| Inductance (µH)  | 13 | 198 | 8.6      |
| Compensation capacitor (nF) | 267 | 18  | 408      |
| Loss resistance (Ω) | 0.12 | 0.37 | 0.11     |

In this experiment, four receiving resonators (RX1, RX2, RX3 and RX4,) were connected to four resistors of $R_{L1}$, $R_{L2}$, $R_{L3}$ and $R_{L4}$, respectively. The four receiving resonators were placed equidistantly in the slots of the relay resonator.

Table III lists the efficiency values and the voltage values $V_{L1}$, $V_{L2}$, $V_{L3}$ and $V_{L4}$ of the load resistances $R_{L1}$, $R_{L2}$, $R_{L3}$ and $R_{L4}$. The values of $R_{L1}$, $R_{L2}$, $R_{L3}$ and $R_{L4}$, are 5 Ω, 10 Ω, 50 Ω and 100 Ω, respectively.

### Table II. Mutual inductance among resonator coils

| Unit: µH | TX | REX | RX1 | RX2 | RX3 | RX4 |
|----------|----|-----|-----|-----|-----|-----|
| TX       | -  | 18  | 0.98| 0.65| 0.42| 0.13|
| REX      | -  | -   | 10.45| 10.02| 10.67| 10.38|
| RX1      | -  | -   | -   | 0.39| 0.27| 0.11|
| RX2      | -  | -   | -   | -   | 0.43| 0.32|
| RX3      | -  | -   | -   | -   | -   | 0.36|

Fig. 8(a) and Fig. 8(b) show the voltage amplitude-frequency curve and the efficiency curve respectively. Table IV lists the voltage values of $R_{L2}$ and $R_{L3}$, as well as the overall efficiency values under the condition that $R_{L1}$ and $R_{L4}$ are
removed. Fig. 8(c) and Fig. 8(d) show the voltage amplitude-frequency curve of $R_{L2}$, $R_{L3}$ and the efficiency curve under the condition that $R_{L1}$ and $R_{L4}$ are removed, respectively. $V_{Li}$ represents the simulated voltage value and $V_{Li}^{\prime}$ represents the measured voltage value. $\eta$ and $\eta^{\prime}$ represents the overall system efficiency of the simulation and experiment, respectively. It can be seen from Table III and Table IV that the cross-coupling phenomenon has little effect on the system and has no influence on the experimental results, which can be ignored. The cross-coupling phenomenon can be adjusted according to the distance between the coils. From the experimental data in Table III and Table IV, it can be found that the solenoid coil has a uniform magnetic field. When the receiving resonators with different load resistances were added, the voltages received by the each resonator did not affect each other, so it can be deduced that the system has the characteristics of load-independent output voltage.

The frequency splitting phenomenon can be clearly observed in Fig. 8(a), and the operating frequency is almost at the position of the trough. According to the previous research [17], the maximum output power can be obtained when the power frequency is set at the peak position (when the system has been detuned). But for most household appliances, it is more important to obtain the appropriate power rather than the largest power, and the system’s resonant angular frequency $\omega_0$ is also a key factor for achieving load-independent output voltage. The system must follow the principle of maximum efficiency. For different loads, an appropriate power can be obtained by adjusting the parameters of the K converter or the mutual inductance between the TX and REX. The operating frequency of the system can also be changed by adjusting the parameters in the above-mentioned equation.

Fig. 9(a) shows that the wireless system successfully illuminates the LED light, the four receiving resonators with load-independent output voltage. Fig. 9(b) shows that when there are two LEDs, the load-independent output voltage can still be obtained. The theory proposed in the paper has been verified.

| Table III. Simulated calculation and measured results with four receivers |
|------------------|----------|----------|----------|----------|------|
| Unit of voltage: V | $V_{L1}$ | $V_{L2}$ | $V_{L3}$ | $V_{L4}$ | $\eta$ |
| Simulated results (with ICCS) | 6.83 | 6.55 | 7.2 | 6.21 | 73% |
| Simulated results (without ICCS) | 6.98 | 6.85 | 7.02 | 7.15 | 74.5% |
| Measured results | 6.03 | 6.12 | 7.26 | 6.39 | 68.9% |
| Calculated results | 6.52 | 6.39 | 7.21 | 6.52 | 72.7% |

| Table IV. Simulated calculation and measured results with two receivers |
|------------------|----------|----------|------|
| Unit of voltage: V | $V_{L2}$ | $V_{L3}$ | $\eta$ |
| Simulated results (with ICCS) | 6.62 | 6.73 | 71% |
| Simulated results (without ICCS) | 6.93 | 6.85 | 71.9% |
| Measured results | 6.35 | 7.28 | 66.9% |
| Calculated results | 7.98 | 6.85 | 67.3% |
4 Conclusion

In this paper, a slot-type load-independent charging device is developed, which is made of a new type of solenoid coil. The whole system is composed of power supply, transmitting coil relay coil and load receiving coils. The device has only one relay, and the expansibility of the system can be achieved only by extending the length of the relay. In this paper, the structure and characteristics of the system are analyzed. The feasibility of the theory is verified by simulations and experiments. In addition, the transfer efficiency of the system can be further improved in the future. The developed device has promising application to intelligent home and can be used as a safe charging socket to replace the traditional one. In the future research, more attention should be paid to improving its efficiency and power.

![Fig. 8](image_url1)

Fig. 8. (a) “Measured and simulated voltage with four loads”; (b) “measured and simulated efficiency with four loads”; (c) “Measured and simulated voltage with two loads”; (d) “measured and simulated efficiency with two loads”.

![Fig. 9](image_url2)

Fig. 9. (a) “Experiment platform with lighting up one LED”; (b) “Experiment platform with lighting up two LED”.

© IEICE 2018
DOI: 10.1587/elex.15.20180925
Received October 9, 2018
Accepted October 18, 2018
Published November 5, 2018
Copyedited November 25, 2018
Acknowledgments

This work was supported by the National Natural Science Foundation of China under grant number 61461031, Natural Science Foundation of Jiangxi, China under grant number 20161BAB202044, China scholarship Council under grant number 201706825057.