Fractional-order time-sharing-control-based wireless power supply for multiple appliances in intelligent building

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GRAPHICAL ABSTRACT

The wireless power transfer scheme is based on fractional-order time-sharing control for a variety of household appliances in intelligent building. In the scheme, by adding a fractional-order capacitor in the transmitter, the time-sharing resonant charging is realized without changing the traditional receivers.
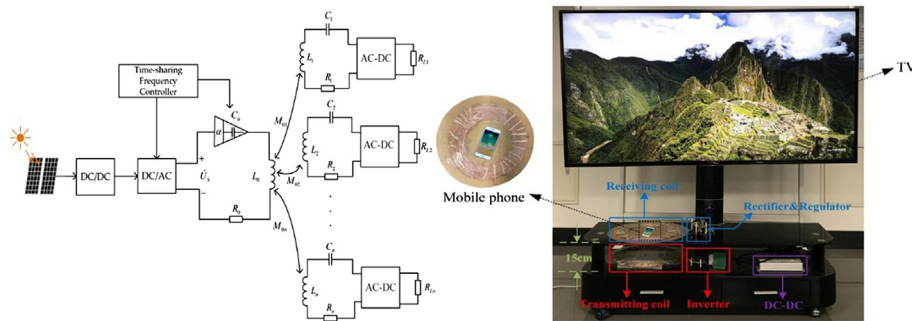
ARTICLE INFO

ABSTRACT

The wired power transmission is usually adopted to supply power for the devices in the traditional buildings. With the development of intelligent buildings, the way of wired power supply would greatly increase the complexity and consumption of laying the lines. To improve the flexibility of power supply and reduce the cost of wiring, wireless power transfer technology has been used in smart buildings. However, it remains a fundamental challenge to create a simple wireless power transfer system in which power can be wirelessly transferred to multiple appliances. Therefore, this paper proposes a wireless power transfer scheme based on fractional-order time-sharing control for a variety of household appliances in intelligent building. In the proposed scheme, only one fractional-order capacitor in the transmitter is needed to realize the time-sharing resonant charging. In contrast, the traditional multiple-receiver systems require complicated control scheme, for example, controlling a plurality of sets of series-parallel capacitors through a series of relay switches. To demonstrate the method, a 150 W LED TV with 300 kHz and a 5 W mobile phone charger with 127 kHz serve as the actual loads. The experimental results show that the proposed system can supply power to the TV and the mobile phone by a time-sharing way wirelessly.

Introduction

Environmental protection and energy conservation have gradually become two major issues of worldwide concern. The existing pollution and destruction come not only from the wrong behavior of human beings, but also in various tools and buildings. The buildings consume about 40% of the world's energy and account for 36% of the total global carbon dioxide emissions [1–3]. Besides, the current power system of buildings uses wired methods to power household appliances, in which the intricate wires not only increase the loss of metal materials, but also bring inconvenience to people's lives. Therefore, smart buildings with wireless power supply systems have become a trend [4,5].

In the very beginning of wireless power transmission (WPT), the electric power is transferred inductively just as Nicola Tesla's work presented [6]. However, this inductive way of transmission has very short transfer distance, which is a main constraint to household applications. In 2007, researchers from MIT proposed the idea of magnetic coupled resonance (MCR) and they lit up a 60 W bulb in 2 m distance with efficiency of 40% [7]. Together with other work on MCR [8–10], it sheds new light of extensive promotion of the WPT technology into home appliance applications.

Compared with the traditional wired household appliances, the household appliances using the WPT technology have the advantages of high security, high convenience and so on. Combined with the development trend of smart building, wireless home appliances will have a broad market prospect [11–18]. The existing applications are all for wireless power supply of single electrical appliance. However, in intelligent buildings, it is necessary to provide wireless power for multiple loads. Reference [19] demonstrates a selective wireless power transfer methodology for a multiple-receiver system, this method controls a plurality of sets of series-parallel capacitors through a series of relay switches to adjust the resonant frequency of the transmitter, thereby granting full control over power division ration to each receiver by time multiplexing, but the adjustment of transmitter's resonant frequency is mechanical and complicated, which results in low efficiency, and is only applicable to electronic communication devices with small power levels. In [20], the mutual inductance between the transmitting coil and the receiving coil at different positions is made uniform by optimizing the structure of the transmitting coil, but the transmitting coil still needs multiple capacitors in series or parallel to adjust the resonant frequency.

To solve the above-mentioned problems on WPT system for multiple loads, in this paper, a simple and reliable wireless power supply system containing a fractional-order capacitor for multiple appliances is proposed. In contrast to an integer-order capacitor that is described by first-order calculus, fractional-order capacitor is a kind of capacitor modeled by fractional calculus. In recent years, the application of fractional-order capacitors is also a hot spot. The fractional-order capacitor can be used in DC-DC converters, filters, and impedance matching, which demonstrated that the fractional-order capacitor has demonstrated more beneficial characteristics than the integer-order capacitor [21–23]. Moreover, fractional-order capacitor is also applied in WPT system, but they are only used for wireless power supply of single load [24]. However, in our proposed scheme, time-sharing resonant wireless charging for multiple loads is achieved by using a fractional-order capacitor. Time-sharing WPT system is also introduced in [25], which proves that the time-sharing control could reduce cross-coupling effect between the receiver coils. The time-sharing control in [25] is realized by using an active-bridge rectifier in every receiver with the same resonant frequency. Different from [25], this paper uses fractional-order circuit to realize time-sharing control only at the transmitter without increasing the space and cost of the receiver. Moreover, the proposed scheme can provide wireless power for receivers with different resonant frequencies. Finally, taking the TV and mobile phone as experimental prototype, theoretical analysis and experimental verification were carried out.

Principle of the wireless power supply scheme for multiple appliances

Structure of multiple appliances wireless power supply system in intelligent building

A simple conceptual graph of the intelligent building is shown in Fig. 1.

As can be seen from Fig. 1, a WPT system contains power source, transmitter and multiple receivers connected to different loads, such as TV, mobile phone, refrigerator, laptop, induction cooker, etc. To promote energy conservation in buildings, the power source is a high-frequency alternating current generated by a solar panel through a voltage regulator and a high-frequency inverter circuit, which is used to power the transmitter. The transmitter is composed of a transmitting coil and a fractional-order capacitor, in which the transmitting coil is buried under the floor or hidden under the carpet and the fractional-order capacitor is used to adjust the resonant frequency of the transmitter. The receiver comprises multiple receiving coil circuits having different resonant frequencies, each of the receiving coil circuits consists of a receiving coil, a resonant capacitor and a load, in which the receiving coil is installed on the bottom of the household appliances.

The detailed schematic diagram of the whole intelligent building is shown in Fig. 2, which is a multi-load WPT system. By selecting source frequency and the corresponding value of fractional-order capacitor, only one receiver is powered at a time. The operation of each receiver is independent of each other, the cross-coupling effect between the receivers can be ignored.

Principle of time-sharing control

Fig. 3 shows the operating period of each load in the multi-load time-sharing-control-based WPT system. At time $S(n,1)$, only the load R_{L1} is working and the source frequency is f_1. At time $S(n,2)$, the source frequency is changed to f_2, only the load R_{L2} is working. Similarly, at time $S(n,n)$, the source frequency is f_n, only the load R_{Ln} is working. Thus, only one receiver is powered at a time.

In the proposed system, variable resonant frequencies are served as time-sharing switches First, different receivers are set to have different resonant frequencies. Then, according to the preset time sequence and frequency values, the power supply and transmitter adjust their own operating frequency and resonant frequency respectively at the same time. Therefore, each time only the receiver with the same resonant frequency as the transmitter is powered, and no matter which receiver operates, the system can be always in an efficient resonant state. The resonant frequency of transmitter is adjusted by changing the order of fractional-order capacitor, and the operating frequency is adjusted by changing the switching frequency of power supply. Here, class E converter is used as high frequency power supply, which is shown in Fig. 4.

Since the process of obtaining energy for each receiver is independent of each other, the analysis of the proposed system can start with a single receiver and then extends to a multi-load system. For a magnetic resonant WPT system, the important factor affecting the transfer power and the efficiency is that whether the system satisfies the resonant condition. Thus, the resonant frequency of the system is necessary to be considered. Therefore, vari-
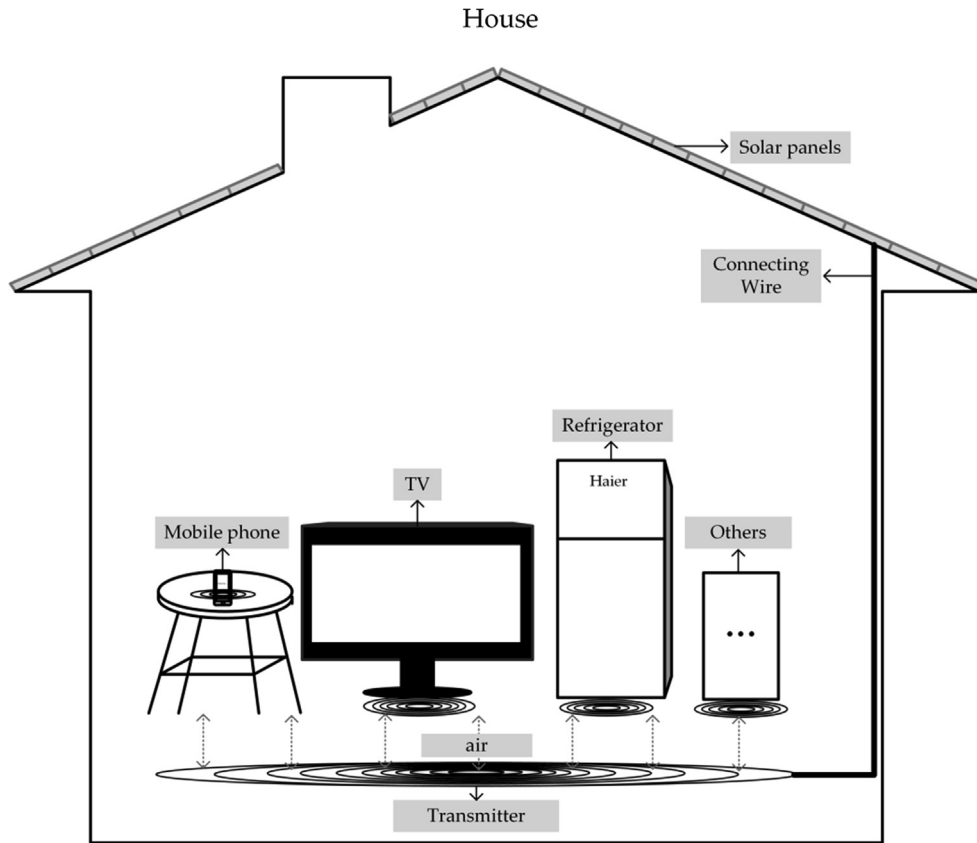
House

Fig. 1. Simple conceptual graph of the intelligent building with wireless power supply for household appliances.
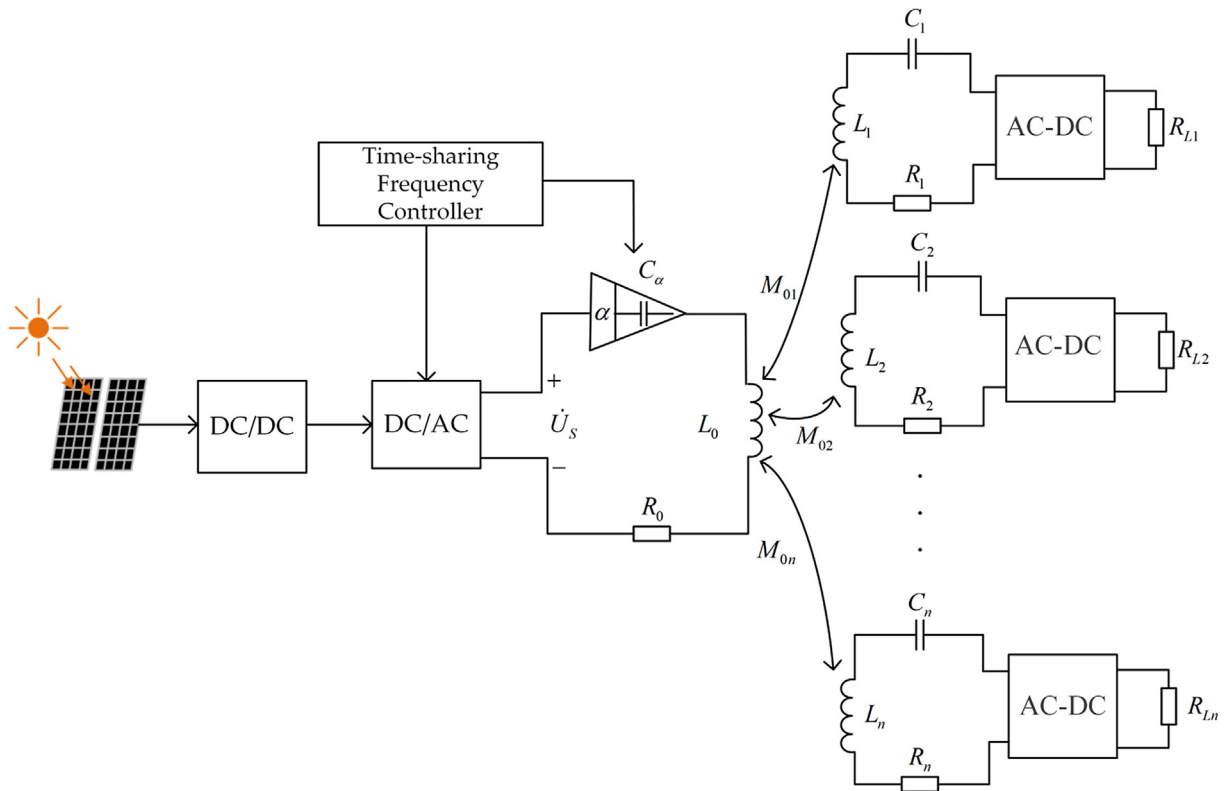

Fig. 2. Detailed schematic diagram of the whole *intelligent* building.
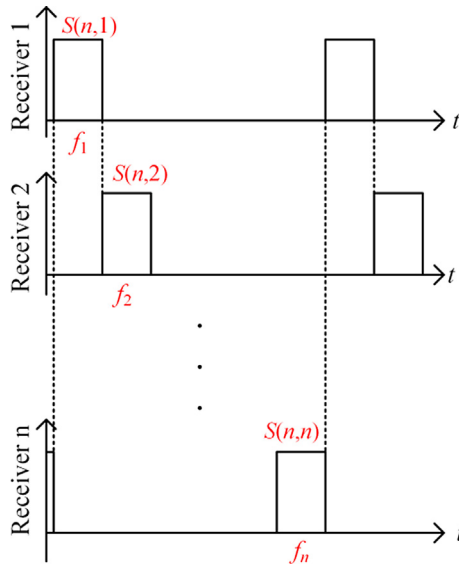
Fig. 3. Frequency response of each receiver.

able resonant frequency can be served as time-sharing switches frequency.

For a fractional-order capacitor, its current and voltage are related by [26,27]

$$i(t) = C_\alpha \frac{d^\alpha v(t)}{dt^\alpha}, 0 < \alpha < 2 \tag{1}$$

where $i(t)$ is the current flowing through the fractional-order capacitor, $v(t)$ is the voltage across the fractional-order capacitor, C_α is pseudo-capacitance value of the fractional-order capacitor, and α is fractional order, its value is between 0 and 2.

Assuming zero initial conditions, and applying the Laplace transform to Eq. (1), the electrical impedance of fractional-order capacitor is defined as

$$Z(j\omega) = \frac{1}{C_\alpha(j\omega)^\alpha} = \frac{1}{\omega^\alpha C_\alpha} \cos\frac{\alpha\pi}{2} - j\frac{1}{\omega^\alpha C_\alpha} \sin\frac{\alpha\pi}{2} \tag{2}$$

From Eq. (2), it can be seen that the fractional-order capacitor can be equivalent to a series connection of a resistor and a capacitor, both of which vary with operating frequency ω and fractional order α. Therefore, when a fractional-order capacitor C_α and an integer-order inductor L_0 resonate, the resonant frequency of the series branch RLC_α can be derived as [26]

$$\omega = \sqrt[\alpha+1]{\frac{\sin\frac{\alpha\pi}{2}}{L_0 C_\alpha}} \tag{3}$$

Assuming that the high-frequency input voltage of the transmitter is u_s, the ac equivalent load of the receiver is $R'_{Li}(i = 1,2,...,n)$, and the resonant frequencies of the receiving coils are

$$\omega_i = \frac{1}{\sqrt{L_i C_i}} \ (i = 1, 2, ...n) \tag{4}$$

In any period of time $S(n,i)$ ($i = 1,2,...,n$), only the receiver i works, thus, when the i-th receiver works, the corresponding resonant frequency of the transmitter and the operating frequency of the power supply satisfy

$$\omega = \sqrt[\alpha+1]{\frac{\sin\frac{\alpha\pi}{2}}{L_0 C_\alpha}} = \omega_i = \frac{1}{\sqrt{L_i C_i}} \tag{5}$$

where ω is the operating frequency of the power supply, ω_1 is resonant frequency of the transmitter.

From Eq. (5), it can be observed that the frequency is a function of the pseudo-capacitance value C_α and fractional order α, as shown in Fig. 5. The parameters used for analysis are: input power supply $U_s = 48$ V, transmitting coil's and receiving coil's inductance $L_0 = L_i = 61\mu H$. As can be seen from Fig. 5, the resonant frequency decreases with the increase of order or the increase of the capacitance.

Considering that the resonant frequency of receiver i is a fixed value, for example, taking the TV as an example, the resonant frequency of the TV receiver is designed as $f_i = 300$ kHz, thus, the resonant capacitance of receiver i is $C_i = 1/(4\pi f_i^2 L_i) = 4.7$nF. As illustrated in Fig. 5, when the resonant frequencies of receivers are distinct, different resonant frequency of transmitter can be realized by adjusting the fractional order α with constant capacitance.

Comparison with other method

Reference [25] is another typical time-sharing control method for multiple-receiver wireless power transfer system. The comparison between the method of [25] and the proposed scheme is shown in Table 1. Firstly, reference [25] needs to use an active rectifier bridge and corresponding control circuit on each receiver, while the proposed method mainly adds a fractional-order capacitor in the transmitter circuit, without changing the traditional receiver circuits. Therefore, the method proposed in this paper is more suitable for the wireless power transfer system with limited receiver space. In addition, reference [25] requires that the resonant frequencies of each receiver are the same, while the proposed method requires that the resonant frequencies of each receiver are different, so as to eliminate the interference between the receiving coils. Therefore, the method of reference [25] is suitable for single frequency band applications, but the proposed method is suitable for multi frequency band applications.

Transfer characteristics with different Fractional-order capacitor

The transfer characteristics of fractional-order wireless power transfer system with single load have been analyzed in [28]. In analogy with the analytical method of [28], and assuming that cross couplings among the loads are negligible, the transfer effi-
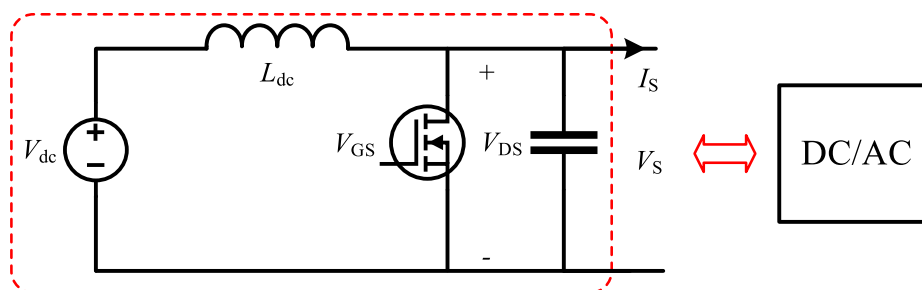

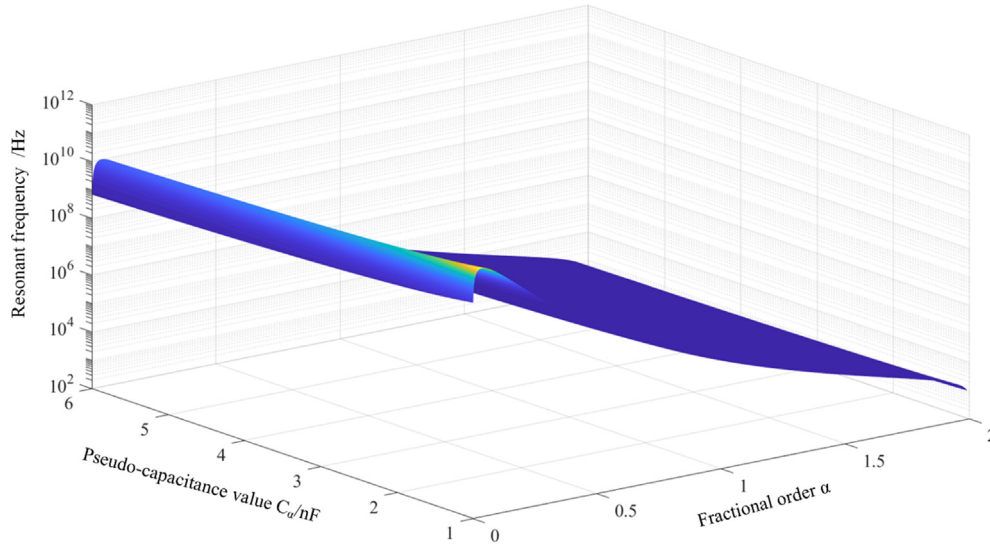**Fig. 4.** Topology of class-E inverter.

Fig. 5. Theoretical curves of resonant frequency of transmitter or operating frequency of the system as a function of fractional order α and the pseudo-capacitance value C_α.

Table 1
Comparison of realization methods of time-sharing control.

System type	Realization method	Transmitter circuit	Multiple Receiver circuits	Resonant frequency
Reference [25]	Integer-order circuit	Without adding other components	Adding an active-bridge rectifier	Same resonant frequency
Proposed Scheme	Fractional-order circuit	Adding an fractional-order capacitor	Without adding other components	Different resonant frequencies

ciency of the ith load of the proposed system in Fig. 2 can be derived as

$$
\eta_i = \frac{P_{iout}}{P_{in}} = \frac{|I_i|^2 R'_{Li}}{|I_0|^2 \left(R_0 + \frac{1-sgn(\alpha-1)}{2}R_C\right) + \sum_{j=1}^n |I_j|^2 \left(R'_{Lj}+R_j\right)}
$$
$$
= \frac{(\omega M_{0i})^2 R'_{Li}/\left(R_i+R'_{Li}\right)^2}{\left(R_0 + \frac{1-sgn(\alpha-1)}{2\omega^\alpha C_\alpha}\cos\frac{\alpha\pi}{2}\right) + \frac{(\omega M_{0i})^2}{R'_{Li}+R_i} + \sum_{j=1,j\neq i}^n \frac{(\omega M_{0j})^2}{R'_{Lj}+R_j}} \tag{6}
$$

where sgn(x) is defined as $sgn(x) = \begin{cases} 1 & x > 0 \\ -1 & x \leqslant 0 \end{cases}$. Hence, the total transfer efficiency of the proposed system can be written as $\eta_{total} = \sum_{i=1}^n \eta_i$.

As can be observed from (6), the transfer efficiency is related to the variation of fractional order α. Taking the parameters of TV system as an example, its transfer efficiency is shown in the Fig. 6. The parameters used for the analysis of Fig. 6 are: internal resistances of the transmitter and receiver i are $R_0 = R_i = 1$ Ω, the ac equivalent load resistance is R'_{Li} = 16.7 Ω, the coupling coefficient $k_{0i} = M_{0i}/\sqrt{L_0 L_i}$ is setting as 0.11, other parameters are the same as part 2.2. As the fractional order α changes, the transfer efficiency gradually increases until $\alpha = 1$, then, the transfer efficiency remains constant at 85% when $1 < \alpha < 2$, because fractional-order capacitor has negative resistance characteristic and does not consume electric energy for $\alpha > 1$. Therefore, in the practical application of the wireless power supply for household appliances, fractional-order capacitor with $\alpha > 1$ is very meaningful and valuable.

Experiments

Visual experiment verification

To visually validate the feasibility of the proposed fractional-order WPT system in smart building, the experiment of wireless power supply for a TV and a mobile phone has been setup, which is shown in Fig. 7. The experimental prototype includes one trans-
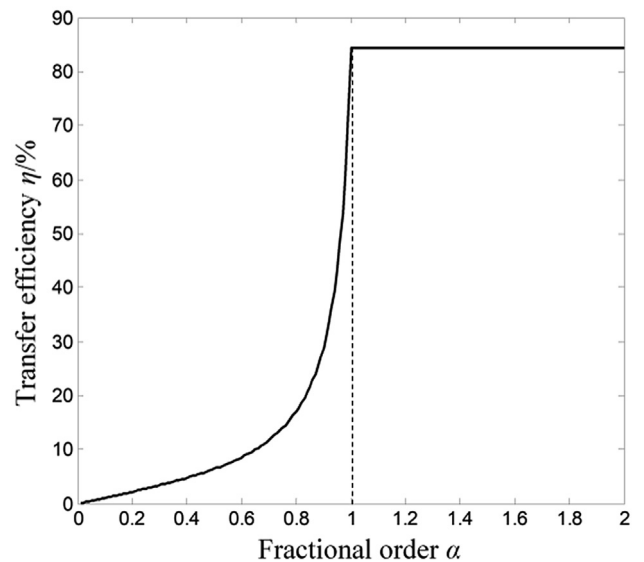

Fig. 6. Theoretical curves of transfer efficiency η versus fractional order α.

mitting coil and two receiving coils. One receiving coil provides power to the TV and the other the mobile phone. As can be seen from Fig. 7, both the TV and mobile phone are in normal operation.

Resonant frequency controlled by fractional-order capacitor

As can be seen from Fig. 2, the proposed WPT system contains a fractional-order capacitor which is not a marketed component. However, there are many fractional-order components which are suitable for various occasions that have been manufactured in the laboratory. Since the proposed WPT system is used to transfer
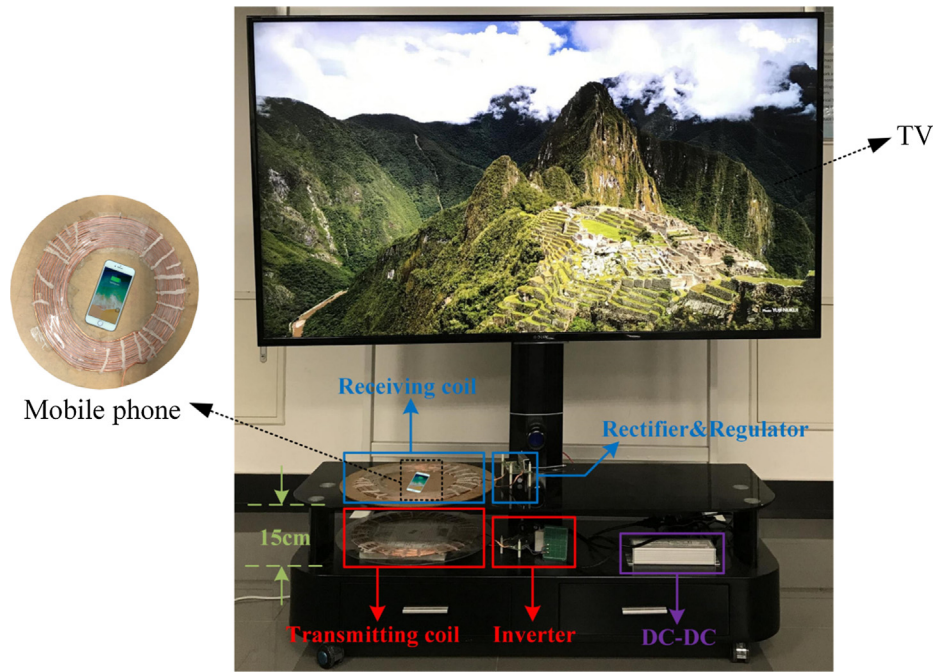
Fig. 7. The experimental prototype.

power, the fractional-order capacitor required to have the ability of processing power. Therefore, a high-power fractional-order capacitor constructed in [26] is adopted.

Fig. 8 shows the voltage and current waveforms of the fractional-order capacitor with different fractional orders. In Fig. 8(a), the current of the fractional-order capacitor leads the corresponding voltage by about 116.9 degrees, which means the actual fractional order is $\alpha = 1.392$, and the actual pseudo-capacitance value can be calculated as $C_\alpha = 1/[(2\pi f_i)^2 V_{Cm}/I_{Cm}] = 279.3 \text{pF/s}^{1-\alpha}$. Similarly, in Fig. 8(b), the current of the fractional-order capacitor leads the corresponding voltage by about 135 degrees, which means the actual fractional order is $\alpha = 1.595$, and the actual pseudo-capacitance value is $C_\alpha = 15.1 \text{pF/s}^{1-\alpha}$. Therefore, by adjusting the values of fractional order α, different resonant frequencies of transmitter can be achieved.

Transfer characteristics with multiple loads

The experimental waveforms of V_{DS} and V_{GS} of class-E inverter are shown in Fig. 9(a). It can be observed that when drive signal V_{GS} goes to high voltage level, V_{DS} has already dropped to zero. Therefore, the MOSFET of class-E inverter operates on the ZVS condition. In addition, the voltage and current of the transmitter are shown in Fig. 9(b) and the receiver of TV shown in Fig. 9(c).

As can be seen from Fig. 9, there is a lot of reactive power involved because of the introduction of the reactive elements. It should be noted that only active power here should be concerned when analyzing the transfer efficiency of the proposed system. Thus, the transfer efficiency can be calculated by measuring the voltage, current and its phase angle. According to the measured results, the transmitted power is 167.7 W and the transfer efficiency is 82.9%, which are consistent with theoretical values.
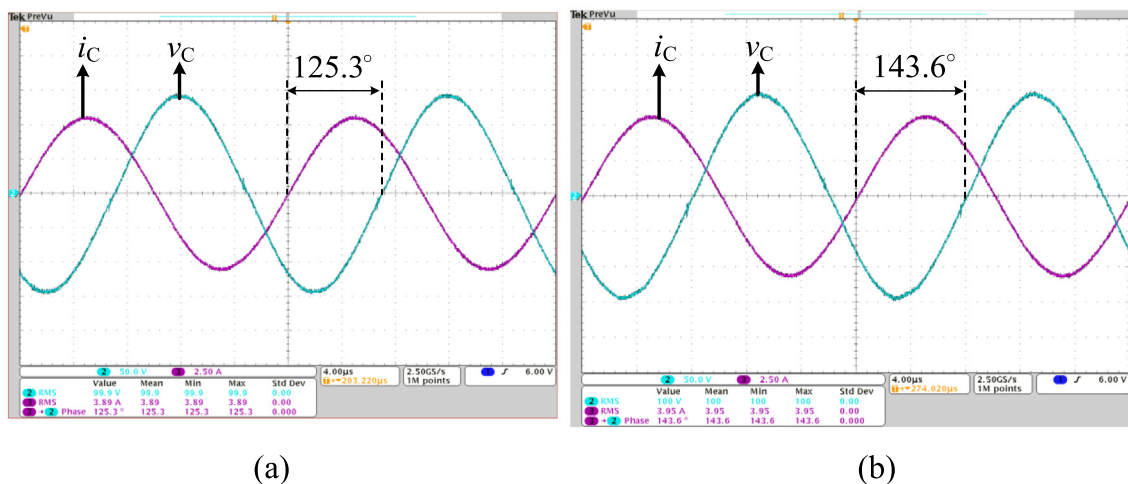

(a)   (b)

Fig. 8. Experimental waveform of the fractional-order capacitor: (a) $\alpha = 1.4$; (b) $\alpha = 1.6$.
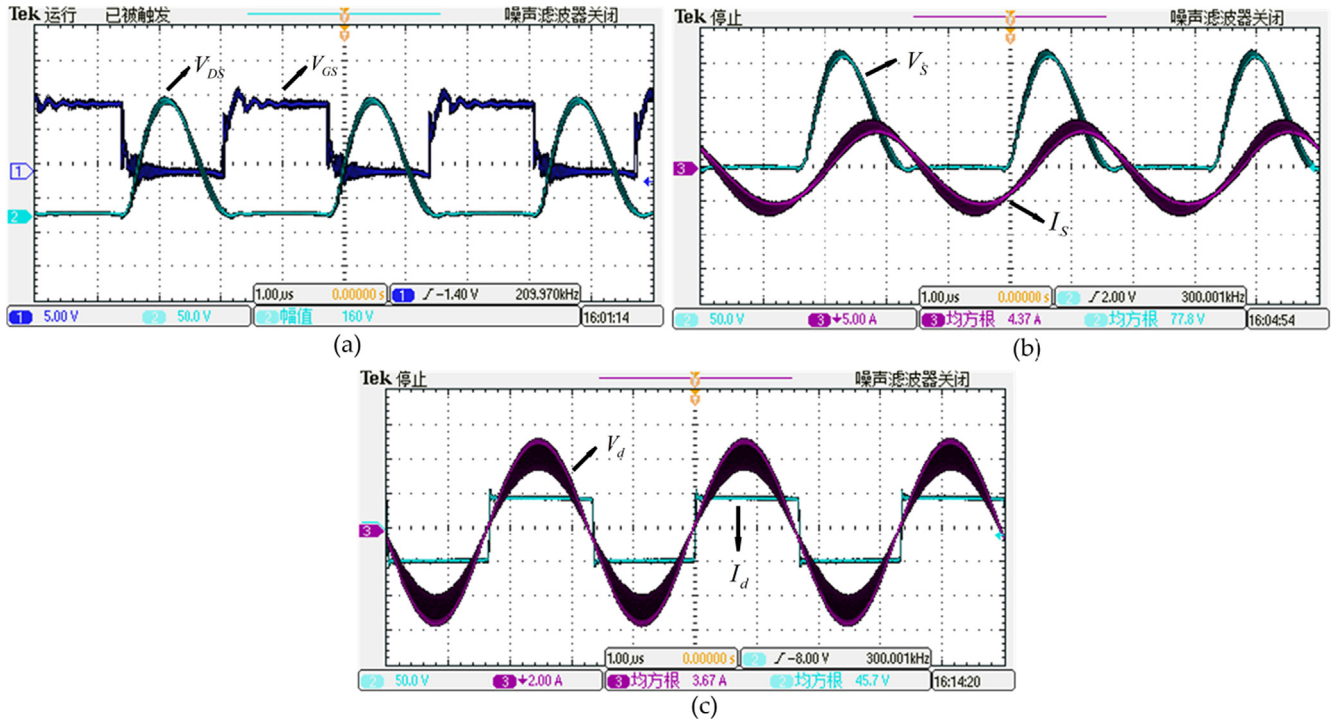
Fig. 9. Experimental waveforms of the TV: (a) Voltage waveform of V_{DS} and V_{GS} of MOSFET; (b) Voltage and current of the output of the high frequency inverter; (c) Voltage and current of the input of the rectifier.
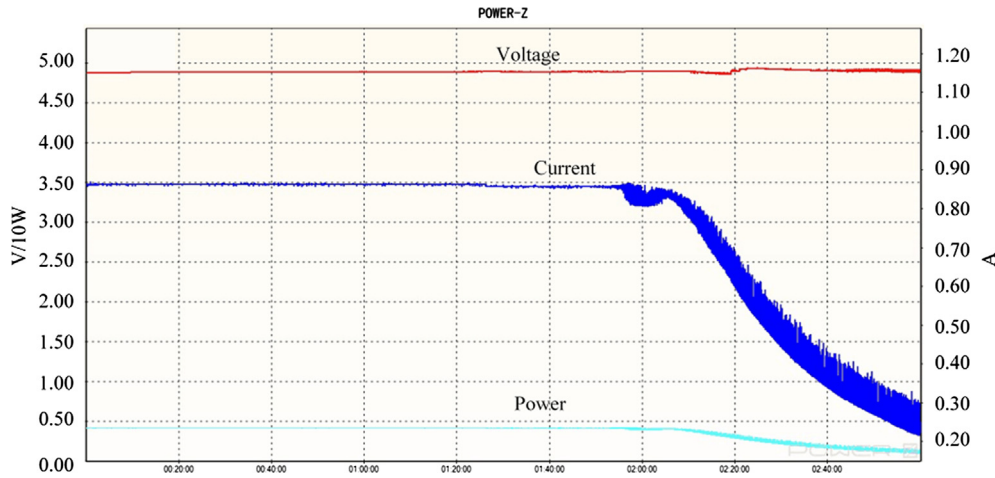

Fig. 10. Experimental waveforms of the mobile phone.

Fig. 10 shows the waveforms of charging voltage, current and power of the mobile phone, it can be seen that the mobile phone can be charged with a constant voltage of 5 V.

Conclusions

In this paper, a time-sharing-control-based wireless power transfer system with a fractional-order capacitor aiming at powering multiple household appliances is presented, which is the first application of fractional-order circuit in the wireless power supply system of intelligent buildings. To validate the feasibility of the proposed time-sharing system, the TV and a mobile phone are regarded as the actual prototype. The system works under different resonant conditions in a time-sharing manner and maintains high transfer efficiencies. A demonstration of experiment is conducted between 300 kHz and 127 kHz by adjusting the fractional order or pseudo-capacitance values of fractional-order capacitor, approximately 150 W power is transferred to the TV with an efficiency of 82.9% at the distance of 15 cm, and the charging characteristics of mobile phone are stable, in which the voltage of the mobile phone obtained are stable around 5 V. Therefore, time-sharing power supply for multiple loads with different resonant frequency by a fractional-order capacitor is feasible. In addition, the proposed system can also be used for wireless charging of medical equipment, electric vehicles, etc. although the system has disadvantages, such as the lack of standardized and marketized fractional-order elements, high cost, etc., these disadvantages would be overcome gradually with the continuous development of the fractional-order circuit.

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