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A Fractional-Order Resonant Wireless Power Transfer System With Inherently Constant Current Output

YANWEI JIANG, BO ZHANG, (Senior Member, IEEE), AND JIALI ZHOU, (Student Member, IEEE)

School of Electric Power, South China University of Technology, Guangzhou 510641, China

Corresponding author: Bo Zhang (epbzhang@scut.edu.cn)

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ABSTRACT Wireless power transfer (WPT) using magnetic-coupling resonant has been proved to be a promising transmission method. At present, most of the existing resonant WPT systems adopt integer-order inductors and capacitors. In fact, in addition to integer-order components, there also exists fractional-order inductors and capacitors, which possess richer characteristics than integral-order inductors and capacitors. However, there are few studies on the application of fractional-order components in resonant WPT system. Therefore, this paper proposes a fractional-order resonant WPT system, which is based on a fractional-order resonant circuit only incorporating a fractional-order capacitor. The coupled-mode theory model of the proposed WPT system is established, and the impact of different loads and orders on transfer characteristics is explored. The theoretical analysis demonstrates that the proposed system can achieve constant current output that is independent of load, just by choosing appropriate parameters of the fractional-order capacitor. Finally, an experimental prototype of the fractional-order resonant WPT system is built, and the experiment results verify the correctness of the theoretical analysis.

INDEX TERMS Wireless power transfer, fractional-order capacitor, fractional-order resonant.

I. INTRODUCTION

Near-field magnetic-coupling resonant wireless power transfer (WPT) is a promising alternative to traditional wired power transfer, because of its flexibility, safety, convenience [1]. In recent years, WPT technology has been applied in many occasions, such as portable electronic devices, kitchen appliances, implantable medical devices, electric vehicles, lighting application and so on [2]. For the application of constant current load, such as LEDs, batteries and supercapacitors, WPT system is required to have the characteristic of constant current output [3]. Moreover, considering the limited space of electrical devices, the structure of receiver should be as simple as possible.

Currently, there are four main methods to realize constant current output in a WPT system [4]–[10]. The first method relies on designing the high-order compensation topology without closed loop control schemes [4], [5], but the control accuracy are limited. The second method adopt the close-loop methods on the receiver, requiring additional circuits,such as DC-DC converter, so it will greatly increase the weight and volume of the receiving device [6], [7]. The third method only performs closed-loop control on the transmitter but require dual-side wireless communication between transmitter and receiver to adjust the output current, and this has the disadvantages of system instability and failure when wireless communication is disturbed [8], [9]. The forth method is only based on primary-side control method without dual-side wireless communication, but it generally uses the parameter identification strategy to identify the secondary side parameters for feedback control, and requires high frequency sampling and complex identification algorithms [10]. Therefore, it is still a challenge to realize a high performance WPT system with constant current output.

This paper proposes a novel fractional-order resonant WPT system with inherently constant current output. The proposed resonant WPT system contains a fractional-order capacitor (FOC) in the transmitter and the constant current properties

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just only rely on choosing an appropriate order of the FOC. Generally, the traditional WPT systems are realized by using integer-order components, such as integer-order inductors and capacitors [11]–[13]. In fact, in addition to integer-order components, there are also fractional-order components that are described by fractional-order calculus, such as fractional-order capacitors [14], [15]. The fractional-order components are not yet standard market-oriented components, but various fractional-order capacitors and fractional-order inductors have been manufactured in the laboratory [16]–[18], paving the way for the application of fractional-order components.

In recent years, the properties of DC-DC converters containing fractional-order capacitors or fractional-order inductors were discussed in [19], [20], their results show that the output voltage gain can be not only controlled by duty cycle, but also the orders of the fractional-order components. In RLC circuit, the orders could help improve the quality factor and control the resonance frequency of the circuit [21]. The properties of fractional-order components applied in filter circuits, impedance networks and power factor correction were also explored [22]–[24].The above studies demonstrate that fractional-order components could bring in more flexibility and higher performance than the integer-order components in circuit design and applications.

The applications of fractional-order components in WPT system are also studied [25]–[27]. In [25], a mathmatical model of a fractional-order WPT system is presented. In [26], a resonant WPT system consisting of four fractional-order components is proposed, and the effect of fractional-orders on the transfer power and efficiency is analyzed. In [27], a FOC can help WPT system realize that the transfer efficiency and output power are insensitive to the resonant frequency. However, they does not give the analysis about the impact of load on output current, and can not output constant current.

Different with literature [24]–[26], this paper proposes a fractional-order resonant WPT system only incorporating one fractional-order componets in the transmitter, and the impact of changing loads and orders on output current is also studied. The remainder of this paper is organized as follows. Section II details the structure of the proposed WPT system and its coupled-mode theory model. Section III analyzes the characteristics of the proposed WPT system. Section VI shows the experiment results. Finally, Section V draws the main conclusions of this paper.

II. SYSTEM STRUCTURE AND MATHEMATICAL MODEL

A. SYSTEM STRUCTURE

The proposed fractional-order resonant WPT system with inherently constant current output is shown in Fig. 1. On the transmitter, a FOC C_α is connected in series with the transmitter coil L_T, the internal resistance R_{S1} and the external power source V_S. On the receiver, the load R_L, the internal resistance R_{S2}, the integer-order capacitor C_R and the receiver coil L_R are also in series. The transmitter coil L_T and the receiver coil L_R are coupled by mutual inductance M.

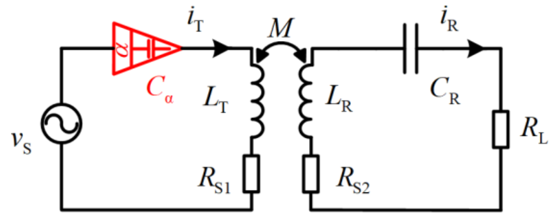

FIGURE 1. System structure of the proposed fractional-order resonant WPT system.

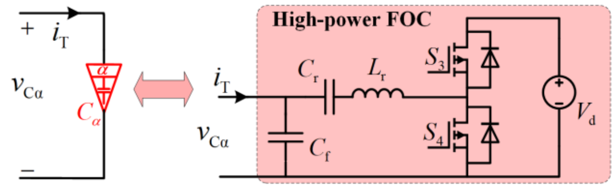

FIGURE 2. Realization schematic diagram of the high power FOC.

Different with integer-order capacitor, the current-voltage relationship of the FOC is defined as [14]

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

where $i(t)$ and v(t) are the current and voltage of the FOC respectively, α (0< α <2) is the order of the FOC and C_α is the capacitance expressed in Farad/(second)$^{1-\alpha}$, d^α/dt^α is termed as the fractional-order derivative [28]. The impedance of a FOC can be described as [21]

$$Z_C = \frac{1}{\omega^\alpha C_\alpha}\cos(0.5\pi\alpha) - j\frac{1}{\omega^\alpha C_\alpha}\sin(0.5\pi\alpha) \tag{2}$$

where ω is the operating angular frequency, so a FOC has not only capacitor reactance but also resistance, which is determined by α. However, the integer-order capacitor, i.e. $\alpha = 1$, only has a capacitor reactance. From (2), it can be seen that the resistance of FOC is positive when the order is less than 1, and the smaller the order, the greater the resistance. When the order is greater than 1, the resistance of FOC is negative. Moreover, the phase angle of FOC is $0.5\pi\alpha$, which only depend on the order α. Therefore, a FOC has the characteristic of constant phase angle.

A high-power FOC constructed in [17] is adopted. The correponding realization schematic diagram is also shown in Fig. 2. A single-port circuit is used to emulate the current–voltage characteristic of FOC by controlling the relationship between input current i_T and the input voltage $v_{C\alpha}$. From Fig. 2, a power converter is applied to control the input current i_T, so that the relationship between i_T and $v_{C\alpha}$ can meet the characteristics of FOC.Therefore, the single-port circuit can simulate a FOC.

In a resonant WPT system, the transmitter and receiver are required to have the same natural resonant frequency. For the proposed fractional-order WPT system,the resonant frequency ω_R of the receiver is

$$\omega_R = \frac{1}{\sqrt{L_R C_R}}. \tag{3}$$

However, the resonant frequency ω_T of the transmitter is expressed as [21]

$$\omega_T = \left[\frac{\sin(0.5\pi\alpha)}{L_T C_\alpha}\right]^{\frac{1}{\alpha+1}}, \tag{4}$$

so when designing the resonant frequency ω_T, not only the inductance and capacitance, but also the order α should be considered.

B. COUPLED-MODE THEORY MODEL

To study the properties of the fractional-order resonant WPT system, a coupled-mode theory model is built in this section. Based on coupled-mode theory [28], the model of Fig. 1 can be described by:

$$\begin{cases} \dfrac{d\boldsymbol{a}_T}{dt} = j\omega_T \boldsymbol{a}_T - (\tau_{S1} - g_T)\boldsymbol{a}_T + j\kappa \boldsymbol{a}_R + Fe^{j\omega t} \\ \dfrac{d\boldsymbol{a}_R}{dt} = j\omega_R \boldsymbol{a}_R - (\tau_R + \tau_{S2})\boldsymbol{a}_R + j\kappa \boldsymbol{a}_T \end{cases} \tag{5}$$

where $\boldsymbol{a}_T$ and $\boldsymbol{a}_R$ are defined as the modal amplitudes respectively, such that $|\boldsymbol{a}_T|^2$ and $|\boldsymbol{a}_R|^2$ represent the energy stored in the transmitter and receiver; τ_{S1} and g_T are the intrinsic loss rate and gain coefficient of the resonant circuit on the transmitter, τ_{S2} is the intrinsic loss rate of the resonant circuit on receiver, τ_R is the load loss rate, κ is the energy coupling coefficient of the transmitter and the receiver; $Fe^{j\omega t}$ is the expression of the external excitation in the coupling mode formula, and F is the amplitude of the external excitation. Because of the energy coupling between the transmitter and receiver circuits, the energy is continuously exchanged back and forth between the two circuits.

As can be seen from Fig. 1, a FOC is on the transmitter, and its impedance has not only the imaginary part, but also the real part. When the order α of FOC is less than 1, the real part is a positive resistance, which would consume energy. When the order α is greater than 1, the real part is a negative resistance, which would provide gain for the system. Therefore, according to the relationship between coupled-mode theory coefficients and the circuit parameters [120], the expressions of τ_{S1}, g_T, τ_{S2}, τ_R, κ and F can be described respectively as follows.

$$\tau_{S1} = \begin{cases} \dfrac{R_{S1}}{2L_T} + \dfrac{\omega_T^{\alpha+1}}{2\omega^\alpha}\text{ctg}\left(\dfrac{\pi}{2}\alpha\right) & 0 < \alpha < 1 \\ \dfrac{R_{S1}}{2L_T} & 1 \le \alpha < 2 \end{cases} \tag{6}$$

$$g_T = \begin{cases} 0 & 0 < \alpha < 1 \\ -\dfrac{\omega_T^{\alpha+1}}{2\omega^\alpha}\text{ctg}\left(\dfrac{\pi}{2}\alpha\right) & 1 \le \alpha < 2 \end{cases} \tag{7}$$

$$\tau_{S2} = \frac{R_{S2}}{2L_R} \tag{8}$$

$$\tau_R = \frac{R_L}{2L_R} \tag{9}$$

$$\kappa = \frac{M}{2\sqrt{L_T L_R}}\sqrt{\omega_T\omega_R} \tag{10}$$

$$F = \frac{V_S}{2\sqrt{L_T}} \tag{11}$$

where V_S is the root mean square (RMS) value of the high frequency power source in Fig.1. In particular, from (6) and (7), when the system is resonant, i.e. $\omega = \omega_T = \omega_R$, the difference between intrinsic loss rate and gain coefficient can be derived as

$$\tau_{S1} - g_T = \frac{R_{S1}}{2L_T} + \frac{\omega}{2}\text{ctg}\left(\frac{\pi}{2}\alpha\right) \tag{12}$$

By solving the first order differential equations in (5), the steady-state solutions of $\boldsymbol{a}_T$ and $\boldsymbol{a}_R$ can be expressed as follows.

$$\boldsymbol{a}_T = \frac{(\tau_{S2} + \tau_R)\, Fe^{j\omega t}}{\text{A}} \tag{13}$$

$$\boldsymbol{a}_R = \frac{j\kappa Fe^{j\omega t}}{\text{A}} \tag{14}$$

where

$$\text{A} = \kappa^2 + (\tau_{S1} - g_T)(\tau_{S2} + \tau_L) \tag{15}$$

III. CHARACTERISTIC ANALYSIS

A. ENERGY CHARACTERISTIC

Since wireless power transfer is essentially the transmission of energy, this section studies the energy characteristics of the fractional-order resonant system. According to (13) and (14), the energy of transmitter and receiver can be obtained as

$$|\boldsymbol{a}_T|^2 = \frac{(\tau_{S2} + \tau_R)^2 F^2}{\text{A}^2} \tag{16}$$

$$|\boldsymbol{a}_R|^2 = \frac{\kappa^2 F^2}{\text{A}^2} \tag{17}$$

Differentiating A^2 with respect to order α, the following equaqion can be acquired.

$$\frac{d\text{A}^2}{d\alpha} = 2\left[\kappa^2 + (\tau_{S2} + \tau_L)(\tau_{S1} - g_T)\right] \times \left[-\frac{\omega}{2}(\tau_{S2} + \tau_L)\sin^2\left(\frac{\pi}{2}\alpha\right)\right] \tag{18}$$

If $\alpha = \alpha_C$, $d\text{A}^2/d\alpha = 0$, then α_C can be deduced as

$$\alpha_C = \frac{\text{arcctg}\left[-\frac{\kappa^2}{0.5\omega(\tau_{S2}+\tau_L)} - \frac{R_{S1}}{\omega L_T}\right]}{0.5\pi} \tag{19}$$

By substituting α_C into (15), A would be equal to zero, so $|\boldsymbol{a}_T|^2$ and $|\boldsymbol{a}_R|^2$ at this time are infinite. The main reason for the above phenomenon is as follows. When $\alpha = \alpha_C$, the gain generated by the FOC exactly offsets all the losses of the system. Therefore, in terms of external excitation, the system is equivalent to being in a short-circuit state. Hence, the selection of the order should be less than α_C.

From (18), when $\alpha < \alpha_C$, $dA^2/d\alpha < 0$, A^2 decreases with increasing order. Therefore, based on (16) and (17), $|\boldsymbol{a}_T|^2$ and $|\boldsymbol{a}_R|^2$ increase monotonically with the increase of order, as shown in Fig. 3. Interestingly, from Fig. 3b, it can be found that under different loads, there exists a order α_0 that keeps the energy $|\boldsymbol{a}_R|^2$ constant, that is, $|\boldsymbol{a}_R|^2$ is independent of the load.

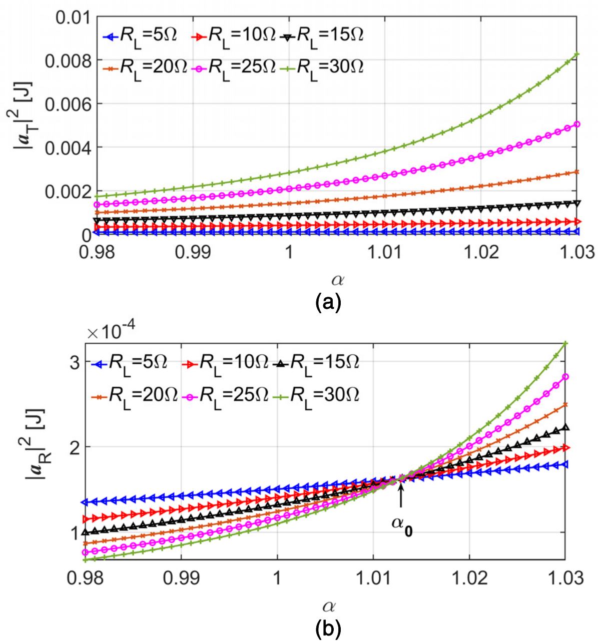

FIGURE 3. Curves of energy of the system as a function of orders. (a) Energy of Transmitter (b) Energy of Receiver.

According to (12), the curve of $(\tau_{S1} - g_T)$ with the order α is shown in Fig. 4. It can be found that $\tau_{S1} - g_T$ decreases with the increase of order α. Moreover, when $\alpha = \alpha_0$,

$$\tau_{S1} - g_T = 0 \tag{20}$$

which make the transmitter equivalent to a "lossless" resonant circuit. Therefore, in the process of energy exchange between the transmitter and the receiver, $|\boldsymbol{a}_{\mathbf{R}}|^2$ would not produce loss in the transmitter, so that $|\boldsymbol{a}_{\mathbf{R}}|^2$ would remain constant. Furthermore,substituting (20) into (17), the energy of receiver can be also drived as

$$|a_R|^2 = \frac{F^2}{\kappa^2} \tag{21}$$

Equation (21) demonstrates that when $\tau_{S1} - g_T$, the energy $|\boldsymbol{a}_{\mathbf{R}}|^2$ is only determined by the amplitude F and the energy coupling coefficient κ, but is independent of the load resistance.

B. THE CONDITIONS OF CONSTANT OUTPUT CURRENT

Since $|\boldsymbol{a}_{\mathbf{R}}|^2$ means the energy stored in the receiver, $|\boldsymbol{a}_{\mathbf{R}}|^2$ can be expressed as

$$|a_R|^2 = L_R I_R^2 \tag{22}$$

where I_R is the RMS value of the output current. The receiver energy of the proposed resonant WPT system has a inherently constant characteristic, so from (22), the output current can also be independent of the load and remains constant. According to (11) and (20)-(21), the output current is decribed as

$$I_R = \frac{V_S}{\omega M} \tag{23}$$

When the frequency and distance are fixed, the output current is only determined by the input voltage Vs.

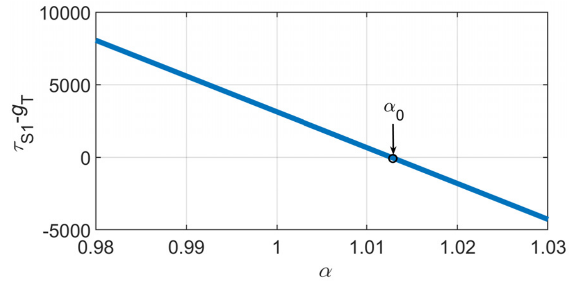

FIGURE 4. The difference of inherent Loss rate and gain Coefficient of transmitter as a function of order.

TABLE 1. Prototype parameters.

Description	Value
Input DC voltage(V_{DC})	30V
Tranmitter coil (L_T)	42.1μH
Receiver coil (L_R)	42.1μH
Mutual-Inductance(M)	19.1μH
Internal resistor(R_{S1})	0.27Ω
Internal resistor(R_{S2})	0.25Ω
Inductor(L_r)	460.6μH
Capacitor(C_r)	22nF
Filter Capacitor(C_f)	180nF
DC-link voltage(V_d)	250V
Operating frequency(f)	50kHz
Power switch(S_1,S_2)	IKP15N65H5

Since the WPT system must have the characteristic of constant current output when supplying power to constant current load, the constant current output characteristic of the proposed system has practical significance and potential application value. For this reason, the conditions required for constant current output of the fractional-order resonant system are solved as follows.

From (12), to keep output current constant, the required order of the FOC is

$$\alpha_0 = \frac{\arccos\left(-R_{S1}/\sqrt{(\omega L_T)^2 + R_{S1}^2}\right)}{0.5\pi} \tag{24}$$

In addtion, the required capacitance of the FOC can be obtained by (4) and (25) as follows.

$$C_{\alpha 0} = \frac{1}{\omega^{\alpha_0+1} L_T} \sin\left(\frac{\pi}{2}\alpha_0\right) \tag{25}$$

Therefore, when the parameters of FOC satisfies (24) and (25), the system has the characteristic that the output current is inherently independent of the load.

C. TRANSFER EFFICIENCY AND OUTPUT POWER

The general expression of transfer efficiency η and output power P_O based on coupled-mode theory are expressed as

$$\eta = \frac{\tau_L}{\tau_{S2} + \tau_L + \tau_{S1}\left(|a_T|^2/|a_R|^2\right)} \tag{26}$$

$$P_O = 2\tau_L |a_R|^2 \tag{27}$$

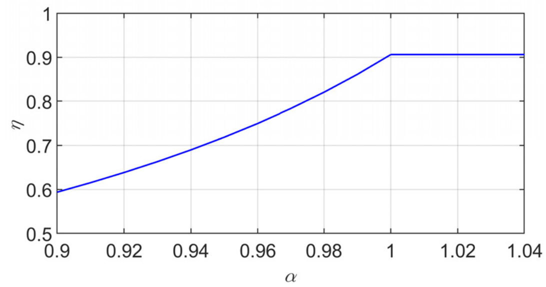

FIGURE 5. Transfer efficiency of the fractional-order resonant WPT system as a function of orders.

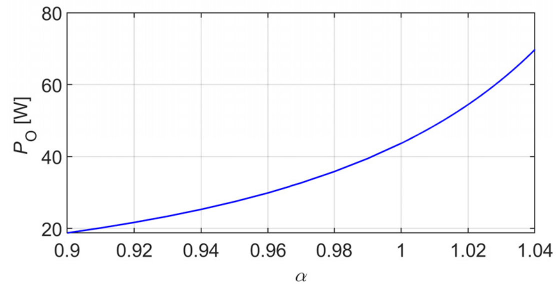

FIGURE 6. Output power of the fractional-order resonant WPT system as a function of orders.

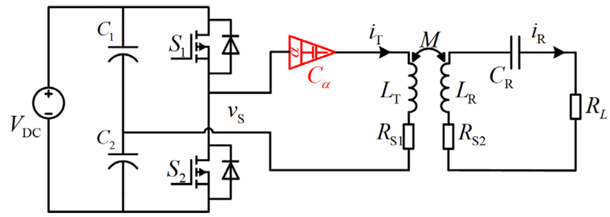

FIGURE 7. Implementation schematic diagram of the prototype.

Therefore, based on (6), (16)-(17) and (26)-(27), the transfer efficiency η and output power Po of the fractional-order resonant WPT system are drived as

$$\eta = \begin{cases} \dfrac{\kappa^2\tau_L}{\kappa^2(\tau_{S2}+\tau_L)+\left[\frac{R_{S1}}{2L_T}+\frac{\omega}{2}\text{ctg}\left(\frac{\pi}{2}\alpha\right)\right](\tau_{S2}+\tau_L)^2} & 0<\alpha<1 \\ \dfrac{\kappa^2\tau_L}{\kappa^2(\tau_{S2}+\tau_L)+\frac{R_{S1}}{2L_T}(\tau_{S2}+\tau_L)^2} & 1\le\alpha<2 \end{cases} \tag{28}$$

$$P_O = \frac{2\tau_L\kappa^2F^2}{\left[\kappa^2+\left[\frac{R_{S1}}{2L_T}+\frac{\omega}{2}\text{ctg}\left(\frac{\pi}{2}\alpha\right)\right](\tau_{S2}+\tau_L)\right]^2} \tag{29}$$

From (28), when the order is less than 1, the transfer efficiency is related to the order; when the order is greater than 1, the transfer efficiency is independent of the order, as shown in Fig. 5. From (25), whether the order is greater than 1 or less than 1, the output power is related to the order, as shown in Fig. 6. In particular, when the parameters of FOC satisfies the conditions of constant current output, the corresponding efficiency and output power can be obtained as

$$\eta_{Con} = \frac{\kappa^2\tau_L}{\kappa^2(\tau_{S2}+\tau_L)+\frac{R_{S1}}{2L_T}(\tau_{S2}+\tau_L)^2} \tag{30}$$

$$P_{O\_Con} = 2\tau_L\frac{F^2}{\kappa^2} \tag{31}$$

IV. EXPERIMENTAL VERIFICATION

To practically evaluate the constant current output performance of the proposed fractional-order resonant WPT system, an experimental prototype which contains a FOC is built. The implementation schematic diagram of the prototype is shown in Fig. 7. The input voltage V_S comes from the output fundamental voltage of the half-bridge and can be described as

$$V_s = \frac{\sqrt{2V_{DC}}}{\pi}, \tag{32}$$

where V_{DC} is the input voltage of the half-bridge. The main parameters are listed in Table 1. According to (24) and (25), the required order α of the FOC is 1.013, and the required capacitance C_α is 204.13nFarad/(second)$^{1-\alpha}$. FOC is still not a standardized market component. In order to facilitate the experimental verification of the proposed system, the FOC constructed in [17] is used in this paper, as shown in Fig. 2. Besides, FOC can also be manufactured by other methods [15], [16], such as electrochemistry, silicon technology, etc., so as to achieve a simpler structure. However, due to the lack of applications, FOCs constructed by silicon technology and other methods have not been put into the market and need special customization.

Fig. 8 shows the experimental waveforms of transmitter current i_T and output current i_R under different load resistances. From Fig. 8, the current i_R remain unchanged when the load is changed. The order and capacitance can be estimated by the following method [15]. For example, as can be observed in Fig. 8a, the current $i_{C\alpha}(i_T)$ of the FOC leads voltage $v_{C\alpha}$ 5.06μs, which means that the leading phase is 91.08°,so the order is $\alpha = 91.08°/90° = 1.012$, and capacitance of the FOC can be calculated as $C_\alpha = I_T/(\omega^\alpha V_{Ca}) =$ 210.44 nFarad/(second)$^{1-\alpha}$. Since input voltage v_s is in phase with the transmitter current i_T, the fractional-order wireless power transfer system is in resonance.

Fig. 9 shows the RMS values of transmitter current i_T and output current i_R varying with load. It can be seen that the input current increases with the increase of load, while the output current remains unchanged with the change of load. The curve of transfer efficiency η is shown in the Fig. 10. As can be observed from Fig. 9 to Fig. 10, all the experimental values have a good agreement with the theoretical values. Thus, the correctness and feasibility of the proposed WPT system with inherently constant current output have been proved.

In addition, for the LCC-type WPT system, it also has the property of constant current output. However, only when

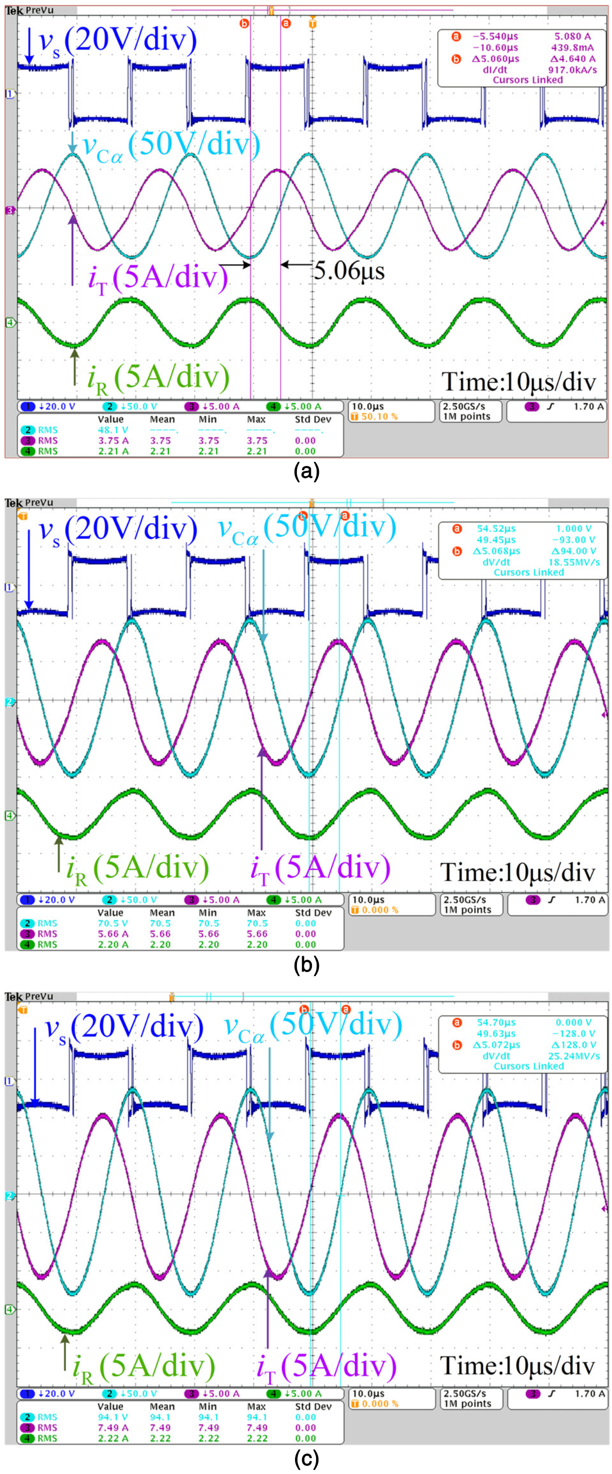

FIGURE 8. **The experimental waveforms of the the fractional-order resonant WPT system. (a) RL=10Ω. (b) RL=15Ω. (c) RL=20Ω.**

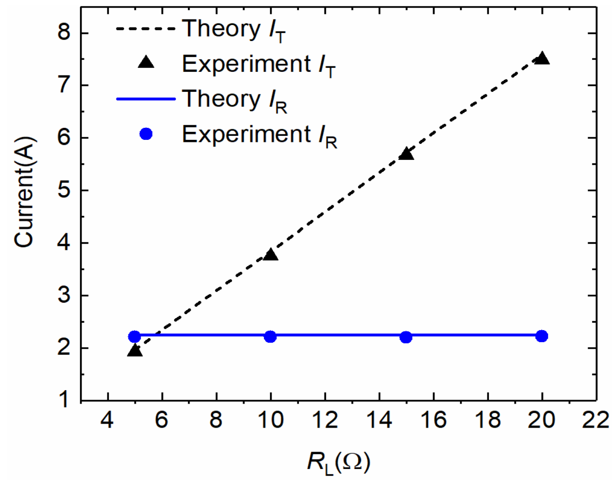

FIGURE 9. **The RMS values of transmitter current i_T and output current i_R varying with load.**

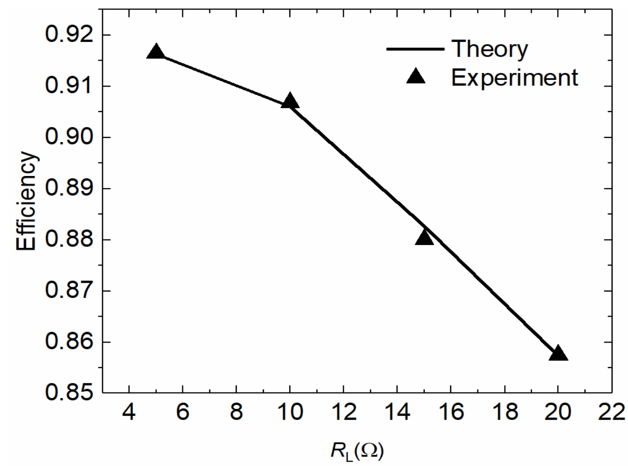

FIGURE 10. **The curve of transfer efficiency η varying with load.**

the internal resistance of the system is ignored, the accurately constant current output can be realized [5].In practical application, the internal resistance cannot be ignored, so the current accuracy of the LCC-type system is limited, while the proposed fractional-order WPT system considers the internal resistance of the system and can achieve precisely constant current output.

V. CONCLUSION

In this paper, a fractional-order resonant WPT system is proposed. By analyzing the energy characteristics of the system, it is found that the fractional-order resonant WPT system can realize constant current output inherently only by designing appropriate fractional-order α and capacitance C_α. Moreover, there is no need for the control of receiver and communication between transmitter and receiver. An experimental prototype was developed to validate the proposed WPT system. The experimental results show that the output current is independent of the load resistance. Therefore, the proposed system can be applied for the wireless power supply to constant current load.

In real-world applications, the inductance and internal resistance of the coil may change due to be interferenced, so the required order of the FOC may also vary, which is a flaw of the system at present. However, some potential methods could be used to make the proposed WPT system be much more suitable and flexible for practical applications. For example, by estimating the coil parameters and adjusting the order of capacitor online based on the identified parameters, the system could always satisfy the conditions of constant current output when the coil parameters are disturbed. As for the above issue, further works should still be done.

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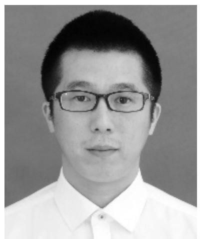

YANWEI JIANG received the B.S. degree in electrical engineering and the M.S. degree in control theory and control engineering from Fuzhou University, Fuzhou, China, in 2012 and 2015, respectively. He is currently pursuing the Ph.D. degree in power electronics with the School of Electric Power, South China University of Technology, Guangzhou, China. His research interests include wireless power transfer applications, power electronics converters, and fractional-order systems.

BO ZHANG (Senior Member, IEEE) was born in Shanghai, China, in 1962. He received the B.S. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 1982, the M.S. degree in power electronics from Southwest Jiaotong University, Chengdu, China, in 1988, and the Ph.D. degree in power electronics from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 1994.

He is currently a Professor with the School of Electric Power, South China University of Technology, Guangzhou, China. He has authored or coauthored over 450 articles and held 102 patents. He has authored eight monographs. His research interests include nonlinear analysis and control of power electronics, wireless power transfer technology, and ac drives.

JIALI ZHOU (Student Member, IEEE) was born in Hunan, China, in 1991. She received the B.S. degree in electrical engineering and automation from the School of Electric Power, South China University of Technology, Guangzhou, China, in 2012, where she is currently pursuing the Ph.D. degree in power electronics and power drives.

Her research interests include wireless power transfer, power electronic converters, and nonlinear analysis of circuits and systems.

Miss. Zhou was a recipient of the Best Student Paper Award at the 2018 IEEE Wireless Power Transfer Conference.