

Mitigation of Bifurcation Effect in Wireless Power Transfer Systems Using a Tunable Fractional-Order Capacitor

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Abstract

In most cases, Wireless Power Transfer (WPT) systems operate at the resonant frequency, as this condition maximizes both transfer capability and efficiency. One major challenge of WPT system under magnetic coupling variation is the bifurcation phenomenon, which induces resonant frequency splitting and consequently decreases output power while narrowing the control range. This paper presents a method to mitigate the bifurcation effect through the use of a Fractional-Order Capacitor (FOC). Compared to conventional tunable capacitors, the FOC approach offers an additional degree of freedom, enabling high-resolution control of capacitance. Simulation results obtained from MATLAB/Simulink demonstrate that the proposed FOC technique effectively eliminates bifurcation by adjusting the duty cycle of the FOC converter. Consequently, the output power is enhanced by 385% compared to a conventional system operating under bifurcation conditions. The proposed method offers strong theoretical validation of the FOC's potential and establishes a foundation for future practical implementation.

Keywords: Bifurcation, Fractional-Order Capacitor (FOC), Wireless Power Transfer (WPT)

1. Introduction

Wireless Power Transfer systems have attracted considerable attention owing to their capability to transmit electrical power without physical contact, a feature that is particularly advantageous for applications such as electric vehicles (EVs), consumer electronics, and biomedical devices. [1 – 3]. In practical operation, WPT systems inevitably experience variations in load resistance and magnetic coupling between the transmitter and receiver coils. This may lead to a bifurcation phenomenon if the load resistance or magnetic coupling exceeds the critical value. Under bifurcation, the system no longer exhibits a unique resonant frequency; that is, the frequency at which the phase angle of the input impedance is zero, commonly referred to as the Zero Phase Angle (ZPA) frequency. Instead, multiple resonant frequencies occur, which reduce the output power, narrow the controllable operating range, and loss of frequency stability [4 – 6].

Several methods have been proposed to address the bifurcation issue in WPT systems. A design guideline introduced in [7] can prevent bifurcation, but it is limited to parameters corresponding to a given load. Nonidentical

transmitter and receiver coil is presented in [8] to eliminate the bifurcation under over coupling conditions. Although this method is simple, it can only be applied to certain applications and is not suitable for those that require interoperability, such as wireless chargers for EVs. In [9], a series inductor is added to the primary circuit to increase the magnitude of the input impedance, aiming to alleviate the bifurcation phenomenon. However, for systems with parameter variations, a controllable inductor is required, which is difficult to design and can regulate the inductance only within a limited range.

The bifurcation phenomenon in WPT systems is influenced by the parameters of the primary circuit, and it can be mitigated by appropriately adjusting these parameters. However, because the value of the primary coil inductance cannot be altered, the resonant capacitance remains the only adjustable parameter. To vary the capacitance in the primary circuit, an array of tunable capacitors has been introduced [10 – 12]. Nevertheless, the use of integral-order capacitors restricts the capacitance to a narrow range and limits its resolution, which reduces their effectiveness in preventing bifurcation.

To overcome the limitations of conventional capacitance-tuning methods, this paper proposes a novel approach by introducing a Fractional-Order Capacitor (FOC) [13 – 15] into the primary circuit. The high-resolution capacitance, at the fractional scale, can be easily adjusted by controlling the duty cycle of the FOC converter, which operates as a half-bridge inverter. This expands the tuning range of the capacitor, leading to increased controllability. The proposed method is validated through computer simulations using MATLAB/Simulink, in which the performance of the tuned and untuned systems is compared.

2. Circuit analysis

2.1 Impedance Analysis

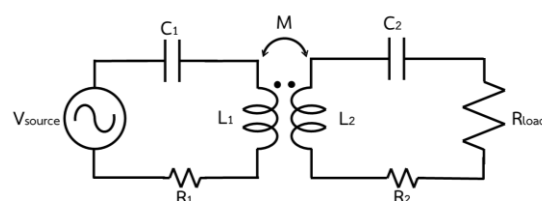


Fig. 1 Equivalent circuit of WPT system with SS resonant compensation topology

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The simplified equivalent circuit of the WPT system is shown in Fig. 1, where the sinusoidal input voltage (V_{source}) represents the fundamental component of the inverter output. The self-inductance of the transmitter coil and that of the receiver coil are denoted by L_1 and L_2 , respectively. The mutual inductance between the two coils is defined as M . Resonant compensation capacitors C_1 and C_2 are connected in series with the coils, forming a Series-Series (SS) compensation topology. The load's equivalent AC resistance is indicated by R_{load} .

The input impedance of the circuit in Fig. 1 can be expressed as:

$$Z_{in} = R_1 + j\omega L_1 + \frac{1}{j\omega C_1} + \frac{\omega^2 M^2 (R_{load} + R_2) - j\omega^2 M^2 (\omega L_2 - \frac{1}{\omega C_2})}{(R_{load} + R_2)^2 + (\omega L_2 - \frac{1}{\omega C_2})^2} \quad (1)$$

From (1), the real and imaginary parts of the input impedance are given as:

$$\text{Re}\{Z_{in}\} = R_1 + \frac{\omega^2 M^2 (R_{load} + R_2)}{(R_{load} + R_2)^2 + (\omega L_2 - \frac{1}{\omega C_2})^2} \quad (2)$$

$$\text{Im}\{Z_{in}\} = \omega L_1 - \frac{1}{\omega C_1} - \frac{\omega^2 M^2 (\omega L_2 - \frac{1}{\omega C_2})}{(R_{load} + R_2)^2 + (\omega L_2 - \frac{1}{\omega C_2})^2} \quad (3)$$

The frequency at which the imaginary part of the input impedance is zero is known as the resonant frequency, or zero-phase-angle frequency. From (3), three possible resonant frequencies are given as:

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \quad (4)$$

$$\omega_{1,2} = \sqrt{\frac{-\beta \pm \sqrt{\beta^2 - 4(1 - k^2)}}{2(1 - k^2)}} \times \omega_0 \quad (5)$$

$$\text{where } \beta = \left[\frac{L_2}{\omega_0 C_1 L_1 (R_{load} + R_2)} \right]^2 - 2$$

The natural resonant frequency is defined as ω_0 , whereas the split resonant frequencies are denoted by ω_1 and ω_2 . In normal operation, the circuit exhibits only the natural resonant frequency (ω_0). However, during over-coupling or over-loading conditions, a bifurcation phenomenon occurs, resulting in two additional resonant frequencies (ω_1 and ω_2), as shown in Fig. 2. This causes the output power to drop. Moreover, it shifts the ZVS region, or inductive region, which may lead to non-ZVS operation and frequency instability. As noted in (5), if the primary capacitance (C_1) is properly adjusted, the complex frequency can be achieved, thereby eliminating the split resonant frequency.

2.2 Bifurcation Criteria

A bifurcation phenomenon will arise in WPT if the magnetic coupling coefficient and/or load resistance exceed the critical values, which are defined as follows:

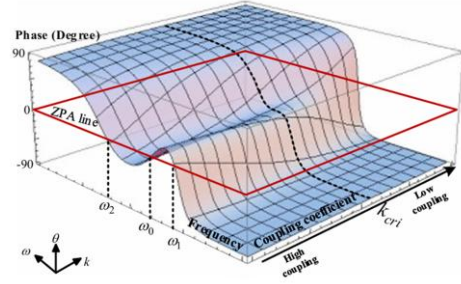


Fig. 2 3D plot of input impedance phase angle as a function of frequency and magnetic coupling.

$$k_{cri} = \frac{L_2}{\omega_0 C_1 L_1 (R_{load} + R_2)} \sqrt{1 - \frac{1}{4} \left[\frac{L_2}{\omega_0 C_1 L_1 (R_{load} + R_2)} \right]^2} \quad (6)$$

$$R_{Lcri} = \omega_0 L_2 \sqrt{2 - 2\sqrt{1 - k^2}} - R_2 \quad (7)$$

As indicated in (6) and (7), the bifurcation criteria depend on the primary capacitance (C_1). Therefore, bifurcation phenomenon in WPT system can be avoided by tuning the value of this capacitance.

2.3 Concept of Fractional-Order Capacitor

The Fractional-Order Capacitor (FOC) exhibits a unique impedance behavior governed by the fractional-order derivative, enabling it to function as a dynamically tunable capacitive element. The FOC is characterized by a non-integer-order derivative in its voltage-current relationship, which can be expressed as:

$$i_{c_\alpha}(t) = C_\alpha \frac{d^\alpha v_{c_\alpha}(t)}{dt^\alpha} \quad (8)$$

where $\frac{d^\alpha}{dt^\alpha}$ is defined as the fractional-order derivative, $v_{c_\alpha}(t)$ and $i_{c_\alpha}(t)$ are the voltage and current of FOC, and α is the order of the capacitor obtained from FOC. The impedance of FOC is described in [15] as:

$$Z_C(j\omega) = \frac{1}{(j\omega)^\alpha C_\alpha} \angle -\frac{\alpha\pi}{2} = \frac{1}{(j\omega)^\alpha C_\alpha} \left(\cos\left(\frac{\alpha\pi}{2}\right) - j \sin\left(\frac{\alpha\pi}{2}\right) \right) \quad (9)$$

It can be seen from (9) that the impedance of the FOC can be adjusted by modifying the order α ($0 < \alpha < 1$). This range of orders has an impedance composite characteristic, such as parasitic resistance [16]. In this order range, parasitic resistance is a small positive value and increases when the order is decreased.

To effectively control the capacitance in the primary circuit of the WPT system, an FOC is introduced, as shown in Fig. 3, where C_α represents the tunable capacitance provided by the FOC. Its complete circuit configuration is illustrated in Fig.4, which consists of a half-bridge inverter, a filter inductor (L_f), a filter capacitor (C_f), and a parallel capacitor (C_p). The current through the FOC is given by:

$$I_{C_\alpha}(j\omega) = I_{Zf}(j\omega) + I_{C_p}(j\omega) = \frac{V_{C_\alpha}(j\omega) - V_f(j\omega)}{Z_f(j\omega)} + (j\omega C_p)V_{C_\alpha}(j\omega) \quad (10)$$

By adjusting the duty cycle of the inverter voltage (V_f), the magnitude and phase of the voltage across the FOC (C_{C_α}) can be modulated. This results in an effective change in both the order-dependent capacitance and the appearance of an impedance characteristic, which can be exploited to modify the input impedance of the WPT system under parameters variation. Therefore, the capacitance tuning capability of the FOC can be adopted to address the bifurcation issue in the WPT system.

3. Simulation Result

To validate the proposed bifurcation mitigation technique using the FOC, a computer simulation of the circuit shown in Fig. 5 was performed using MATLAB/Simulink, with the circuit parameters as listed Table 1.

Table 1 Circuit Parameters

Parameter	Value
Inductance of Primary Coil (L_1)	68.6 μ H
Inductance of Secondary Coil (L_2)	68.6 μ H
Mutual Inductance (M)	20.58 μ H
Magnetic Coupling Coefficient (k)	0.3
Primary Compensation Capacitor (C_1)	51.1nF
Secondary Compensation Capacitor (C_2)	51.1nF
Resistance of Primary Coil (R_1)	0.2 Ω
Resistance of Secondary Coil (R_2)	0.2 Ω
Natural Resonant Frequency (f_0)	85 kHz
Load Resistance (R_{load})	6 Ω
Critical Coupling Coefficient (k_{crit})	0.163
Critical Load Resistance ($R_{L,crit}$)	10.92 Ω
FOC Parallel Capacitance (C_p)	200 nF
FOC Filter Inductance (L_f)	100 μ H
FOC Filter Capacitance (C_f)	34 nF
Quality Factor of Primary circuit (Q_1)	6.106
Quality Factor of Secondary circuit (Q_2)	6.106
Ripple Filter Capacitance (C_{out})	100 μ F

To highlight the influence of the FOC on the WPT system's behavior, two operating scenarios were investigated and compared.

- Case I: The WPT system operates under bifurcation conditions without FOC
- Case II: Under the same condition as Case I, the FOC is applied to the system with the aim of eliminating the bifurcation.

In both cases, the DC-bus voltage of the full-bridge inverter was fixed at 20 V, the DC-link voltage of the half-bridge inverter was fixed at 40 V, and all other circuit parameters were kept identical.

Simulation results of the circuit's frequency response under Case I are shown in Fig. 6. It can be clearly seen that three distinct ZPA frequency (f_0 , f_1 , and f_2) occur during bifurcation. The magnitude of the primary current is minimum at natural resonant frequency (ω_0), which is the normal operating frequency. This results in reduced output power. On the other hand, with the use of the FOC

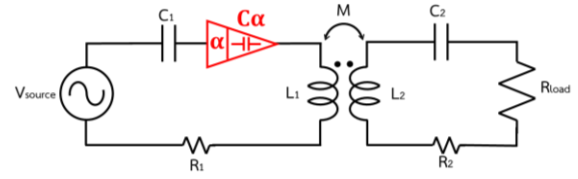


Fig. 3 Equivalent circuit of the SS-WPT system with FOC in the primary circuit

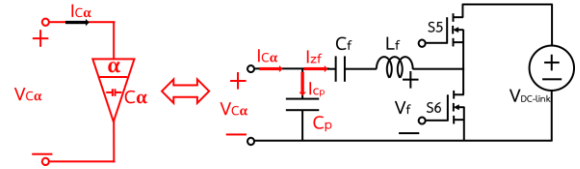


Fig. 4 Circuit diagram of the FOC

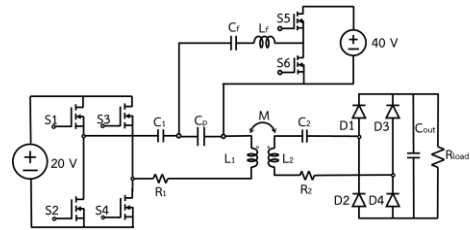


Fig. 5 Circuit configurations used in the simulation

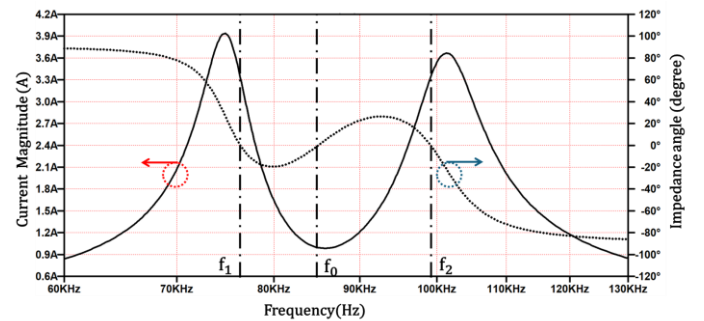


Fig. 6 Frequency response of the magnitude of primary current (I_1) and the input impedance angle under Case I

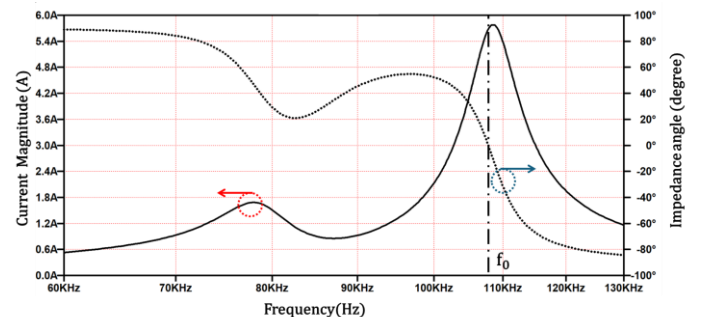


Fig. 7 Frequency response of the magnitude of primary current (I_1) and the input impedance angle under Case II

in case II, bifurcation can be eliminated, as shown in Fig. 7, where a single resonant frequency appears.

Table 2 FOC order and circuit impedance under changing duty cycle conditions

FOC Duty cycle	FOC Order	FOC Impedance	FOC Phase angle (degree)	FOC Capacitance (nF)	Total Capacitance (nF)	Frequency Resonance (kHz)
0.5	0.989	0.0019-j0.134	89.044	191.411	40.333	109.493
0.4	0.994	0.0001-j0.109	89.489	171.246	39.356	109.794
0.3	0.99	0.0018-j0.111	89.091	183.953	39.991	109.697
0.2	0.983	0.0028-j0.105	88.463	192.224	40.368	109.503

Furthermore, the primary current reaches its maximum at this frequency, which increases the output power.

Simulation waveforms of the circuit under Case I are shown Fig. 8 for operation at the natural resonant frequency (f_0) of 85 kHz. The magnitude of the primary current and output power is obtained as 1.418 A and 15 W, respectively. For Case II, as shown in Fig. 9, the operation of the FOC shifts the natural resonant frequency to 109.493 kHz, which increases the magnitude of primary current and output power to 3.487 A and 72.82 W, respectively. These results validate the effectiveness of the proposed bifurcation mitigation technique using the FOC.

Figure 10 illustrates the voltage-current phase relationship of the FOC, confirming its ability to vary impedance when the FOC converter's duty cycle is set to 0.5. The phase angle between $V_{C\alpha}$, $I_{C\alpha}$ is 89.04 degree. The fractional order is calculated as 0.989, yielding an effective FOC capacitance of 191.411 nF. The resulting equivalent circuit capacitance is 40.333 nF, and the FOC impedance is 0.0019-j0.134 Ω .

Figure 11 shows the FOC operation when the converter duty-cycle is reduced to 0.4. The phase angle between $V_{C\alpha}$, $I_{C\alpha}$ is 89.484 degree. From these values the fractional order is 0.994, corresponding to an effective FOC capacitance of 171.246 nF. The equivalent circuit capacitance is therefore 39.356 nF, and the FOC impedance is 0.0001 - j0.109 Ω . This result shows that when the order changes with the duty cycle, the impedance of the FOC can change. More detailed simulation results of the FOC concept with impedance changing are shown in Table 2.

Table 2 demonstrates how changes in the DC-link voltage—and thus the converter duty cycle—affect the FOC's fractional order, its impedance, and the circuit's matched resonance frequency. As the duty cycle is reduced, the phase shift between the FOC voltage and current, the impedance magnitude, and the matched resonance frequency all increase, while the effective fractional order initially rises and then falls.

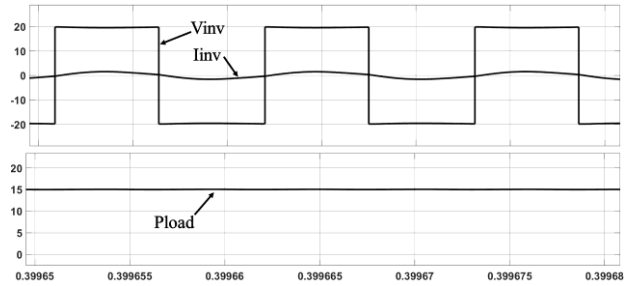


Fig. 8 Simulation waveforms of the system under case I

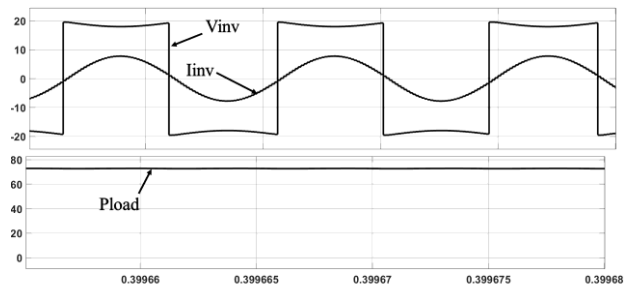


Fig. 9 Simulation waveforms of the system under case II

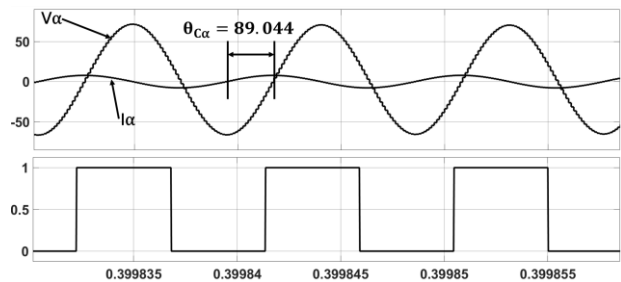


Fig. 10 Simulation

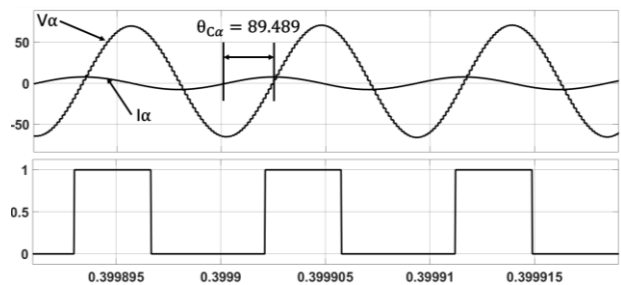


Fig. 11 Simulation

Table 2 demonstrates the effect of varying the inverter voltage duty cycle (V_f) on the FOC control, its impedance, and the resonant frequency. As the duty cycle decreases, the phase shift between the FOC voltage and current as well as the resonant frequency both increase. Meanwhile, the effective fractional order first increases and then decreases.

The maximum order reached in this setup is 0.994 at a duty cycle of 0.4; decreasing the duty cycle further causes the order to drop. This behavior establishes the practical upper limit for the fractional order attainable with the present circuit and confirms the feasibility of using the proposed FOC to prevent bifurcation.

Figure 12 plots the input impedance angle versus frequency for fractional orders of 0.983 and 0.994, which are obtained by setting the duty cycles to 0.2 and 0.4, respectively. In both FOC cases, only one ZPA point and a single ZVS region appear for each order–frequency pair. These results confirm that the proposed FOC strategy effectively reshapes the resonant behavior, ensuring that the system avoids the bifurcation region.

4. Conclusions

This paper presents a novel method to prevent bifurcation in wireless power transfer (WPT) systems by integrating a Fractional-Order Capacitor (FOC) into the primary resonant circuit. By controlling the duty cycle of the half-bridge inverter, the FOC enables real-time adjustment of the circuit's effective capacitance. This tunable behavior allows the system to dynamically shift its resonance frequency and maintain stable Zero Phase Angle (ZPA) operation, even in the presence of uncontrollable variables such as coupling coefficient fluctuations.

Simulation results validate the effectiveness of the proposed method in eliminating bifurcation-related issues, with the system achieving significantly higher output power and improved impedance matching. The resonance frequency is shifted from 85 kHz to 109.493 kHz under FOC control, and the output power increases from 15 W to 72.82 W under identical input conditions. These findings demonstrate that the FOC-based approach mitigates the bifurcation conditions in the WPT system.

5. Discussion and Future Work

This The simulation results presented in this paper strongly validate the theoretical concept of using a tunable FOC to mitigate bifurcation in WPT systems. By dynamically adjusting the input impedance, the proposed method successfully eliminates frequency splitting, stabilizes the operating point, and significantly enhances power transfer and efficiency under conditions that would otherwise cripple a conventional system.

However, we acknowledge that these findings are currently based on simulation. The immediate and essential next step is the experimental validation of the proposed FOC-based WPT system.

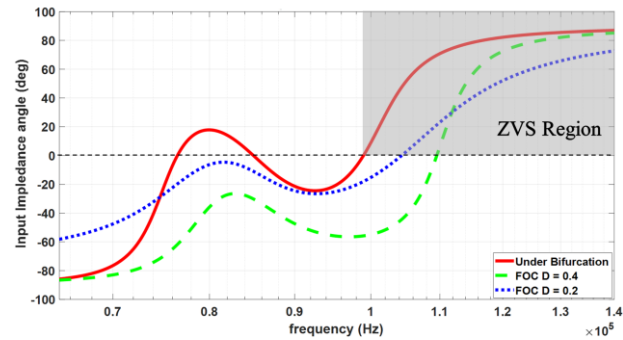


Fig. 12 The input impedance phase angle versus frequency for FOC

A hardware prototype is under development, which will consist of a full-bridge inverter for the primary coil, a c2000 Texas controller to manage the main operating frequency, and a dedicated half-bridge inverter circuit to implement the FOC as described in Fig 4. This experimental setup will allow for the verification of the FOC's performance in a real-world environment, including measurements of power transfer efficiency, thermal performance, and dynamic response to rapid changes in load and coil alignment. This future work will be critical for confirming the practical feasibility and scalability of this promising bifurcation mitigation technique.

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