

## Parameter Optimization for Single-Switch Inverter ICPT Systems with Dynamic Nonlinear Loads (Post-Print)

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### Abstract

Addressing the stability issues of switch voltage and output voltage in single-switch Inductively Coupled Power Transfer (ICPT) systems under dynamic nonlinear load transients, this paper investigates in detail the parameter optimization problem for single-switch ICPT systems with primary-parallel secondary-series (PS) compensation networks. It compares the characteristics of single-switch ICPT systems with primary-parallel secondary-parallel (PP) compensation networks and PS compensation networks respectively; presents the primary and secondary equivalent circuits of the studied system; performs modeling and analysis using the mutual inductance equivalent model method; derives expressions for system voltage gain, output power, efficiency, etc.; plots and analyzes the curves of voltage gain, output power, and switch peak voltage versus operating frequency under different parameter variations; and finally completes the optimal design of system parameters, enabling the system to achieve maximum power output under soft-switching control, with experimental verification confirming the correctness of the design.

### Full Text

## Parameter Optimization of a Single-Switch Inverter ICPT System for Dynamic Nonlinear Loads

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## Abstract

This paper addresses the stability issues of switch voltage and output voltage in single-switch inductively coupled power transfer (ICPT) systems when subjected to sudden changes in dynamic nonlinear loads. The parameter optimization problem for a single-switch ICPT system with primary-parallel secondary-series (PS) compensation network is investigated in detail. The characteristics of single-switch ICPT systems with primary-parallel secondary-parallel (PP) compensation network and PS compensation network are compared. The primary and secondary equivalent circuits of the studied system are presented, and system modeling is performed using the mutual inductance equivalent model method. Expressions for voltage gain, output power, and efficiency are derived, and the variation curves of voltage gain, output power, and switch peak voltage with operating frequency under different parameter conditions are plotted and analyzed. Finally, system parameter optimization design is completed, enabling maximum power output under soft-switching control. Experimental results verify the correctness of the design.

**Keywords:** Inductively coupled power transfer, dynamic nonlinear load, compensation network, modeling analysis

## 1 Introduction

In recent years, with the rapid development of inductively coupled power transfer (ICPT) technology, wireless power supply equipment has been widely applied in various fields, including electric vehicle wireless charging [?], implantable biomedical systems [?], and cordless household appliances [?]. The main circuit topologies of ICPT systems predominantly employ full-bridge inverters [?], half-bridge inverters [?], and single-switch inverters [?]. The first two topologies suffer from relatively complex circuit structures, higher power supply costs, and risks of shoot-through between upper and lower bridge switches that can cause damage. The single-switch inverter circuit represents a novel wireless power transfer topology offering advantages such as low cost, simple control, high power transfer capability, and soft-switching realization.

Commonly used compensation topologies include primary-parallel secondary-parallel (PP), primary-parallel secondary-series (PS), primary-series secondary-parallel (SP), and primary-series secondary-series (SS) [?]. Single-switch ICPT systems generally adopt PP compensation topology [?]. While this topology enables normal load operation for constant-voltage output devices, it produces significant fluctuations in output voltage and switch voltage during sudden changes in dynamic nonlinear loads, potentially damaging components and reducing system reliability.

[Figure 1: see original paper] shows the compensation topology structures for single-switch ICPT systems. The PP compensation topology exhibits high voltage gain and relatively high transmission efficiency and power factor. However, its output voltage and switch voltage fluctuate substantially during dynamic

nonlinear load transients, frequently causing device damage and reduced reliability. In contrast, the PS compensation topology offers higher transmission efficiency with smaller fluctuations in output voltage and switch voltage during dynamic nonlinear load changes, though with lower voltage gain [?]. For applications such as fruit and vegetable processors, the voltage gain of PS compensation topology can be improved through parameter optimization to meet requirements.

This paper proposes a single-switch ICPT system with PS compensation topology. Through systematic parameter optimization design, the fluctuations in output voltage and switch voltage during dynamic nonlinear load transients are significantly reduced, thereby enhancing system reliability.

## 2 Single-Switch ICPT System Compensation Network

The single-switch ICPT system studied in this paper is designed for dynamic nonlinear loads such as fruit and vegetable processors and soy milk makers, which require a 100 Hz, 220 V (RMS) “bun-top” waveform power supply. To improve the overall system power factor, transmission power, and efficiency, compensation of both primary and secondary coils is necessary [?]. To achieve zero-voltage soft-switching and bipolar power transmission, the primary coil must employ parallel compensation, while the secondary coil can use either parallel or series compensation. The specific compensation topologies for the single-switch ICPT system are illustrated in [Figure 1: see original paper], where Fig. 1a shows the PP compensation topology and Fig. 1b shows the PS compensation topology.

The operating process of the PS compensation topology single-switch ICPT system is as follows: AC 220 V mains frequency voltage is converted to slowly varying DC through a rectifier bridge and  $L_1C_1$  filter circuit. Controlling the on/off switching of switch  $Q_1$ , energy is transferred from the primary side to the secondary side through inversion and resonance of the PS compensation topology. After high-frequency rectification, this is converted to a 100 Hz AC 220 V (RMS) bun-top waveform to power the load motor.

## 3 System Parameter Optimization Design

The PS compensation topology single-switch ICPT system is modeled and analyzed using the mutual inductance equivalent model method [?], with its equivalent circuit shown in [Figure 2: see original paper]. In the figure,  $L_1$  and  $L_2$  constitute the loosely coupled transformer;  $C_1$  is the primary compensation capacitor;  $C_2$  is the secondary compensation capacitor;  $M$  is the mutual inductance between primary and secondary coils;  $R_1$  and  $R_2$  are the internal resistances of the primary and secondary coils, respectively; and  $R_q$  is the equivalent load.

The KVL equations for the equivalent circuit in [Figure 2: see original paper] are:

$$U_{C_p} = I_p Z_p - j\omega M I_s \quad (1)$$

$$j\omega M I_p = I_s Z_s \quad (2)$$

where  $Z_p$  is the primary impedance and  $Z_s$  is the secondary impedance, expressed respectively as:

$$Z_p = R_p + j\omega L_p \quad (3)$$

$$Z_s = R_s + R_{eq} + j\omega L_s + \frac{1}{j\omega C_s} \quad (4)$$

From equation (1), the primary current  $I_p$  and secondary current  $I_s$  are:

$$I_p = \frac{Z_s U_{C_p}}{Z_p Z_s + \omega^2 M^2} \quad (5)$$

$$I_s = \frac{j\omega M U_{C_p}}{Z_p Z_s + \omega^2 M^2} \quad (6)$$

Equation (3) yields the primary equivalent circuit shown in [Figure 3: see original paper]. The reflected impedance  $Z_f$  from the secondary side to the primary side can be derived as:

$$Z_f = \frac{\omega^4 M^2 R_{eq} C_s^2}{[1 - \omega^2 L_s C_s]^2 + (\omega R_{eq} C_s)^2} + j \frac{\omega^3 M^2 C_s (1 - \omega^2 L_s C_s)}{[1 - \omega^2 L_s C_s]^2 + (\omega R_{eq} C_s)^2}$$

The real and imaginary parts of the reflected impedance are:

$$R_f = \text{Re}(Z_f) = \frac{\omega^4 M^2 R_{eq} C_s^2}{[1 - \omega^2 L_s C_s]^2 + (\omega R_{eq} C_s)^2} \quad (7)$$

$$X_f = \text{Im}(Z_f) = \frac{\omega^3 M^2 C_s (1 - \omega^2 L_s C_s)}{[1 - \omega^2 L_s C_s]^2 + (\omega R_{eq} C_s)^2} \quad (8)$$

The open-circuit voltage of the secondary coil is:

$$U_{oc} = j\omega M I_p$$

From equations (1) and (8), the secondary equivalent circuit is shown in [Figure 4: see original paper]. The output voltage  $U$  can be derived as:

$$U_o = \frac{2\omega^2 C_s^2 - j\omega R_{eq} C_s}{(\omega^2 L_s C_s - 1)^2 + (\omega R_{eq} C_s)^2} U_{oc}$$

Based on equations (3), (8), and (9), the voltage gain is:

$$G_v = \frac{R_{eq} \omega^2 M C_s}{[R_{eq} \omega^2 C_s^2 + (\omega^2 L_s C_s - 1)^2] Z}$$

where  $Z = Z_p + Z_f$ .

From equation (4), the output power  $P_o$  is:

$$P_o = \frac{|U_o|^2}{R_{eq}} = \frac{\text{Re}(Z)}{[R_p + R_f]^2} |U_{Cp}|^2$$

where  $P_i$  is the input active power.

[Figure 5: see original paper] shows the voltage gain curves under different parameter variations. For the PS compensation topology single-switch ICPT system, there exists an operating frequency that maximizes voltage gain. [Figure 5: see original paper]a indicates that increasing the secondary compensation capacitor does not affect the voltage gain peak but approximately shifts the curve leftward. [Figure 5: see original paper]b shows that when the coupling coefficient changes, the voltage gain curves shift vertically. As the coupling coefficient increases, the voltage gain peak increases, but the peak point deviates from the resonant frequency. Therefore, the coupling coefficient should be appropriately selected—not too large—to prevent excessive deviation. [Figure 5: see original paper]c demonstrates that increasing the primary inductance reduces the voltage gain peak and approximately shifts the curve downward, so the primary inductance should not be too large. [Figure 5: see original paper]d reveals that secondary inductance variation does not change the voltage gain peak, but larger secondary inductance makes the voltage gain curve steeper near its resonant frequency, causing greater output voltage variation near resonance. For constant-voltage output single-switch ICPT systems, this is difficult to control, so the secondary inductance should not be too large.

[Figure 6: see original paper] presents the output power curves under different parameter variations. For the PS compensation topology, there exists an operating frequency that maximizes output power. [Figure 6: see original paper]a shows that secondary compensation capacitor variation does not affect the output power peak, but on the right side of the peak, output power decreases as the capacitor increases. [Figure 6: see original paper]b indicates that increasing the coupling coefficient raises the output power peak. Since the designed household appliance ICPT system has a rated output power of 1 kW, and considering the coupling coefficient's influence on both voltage gain and output

power, the coupling coefficient should be selected between 0.5 and 0.6. [Figure 6: see original paper]c shows that at the same operating frequency, larger primary inductance results in smaller output power. To meet design requirements, the primary inductance should be approximately 170 H. [Figure 6: see original paper]d demonstrates that changing secondary inductance does not affect the output power peak, but larger secondary inductance makes the output power curve steeper near the resonant frequency. To ensure smooth output power variation during frequency tuning, the secondary inductance should not be too large.

According to literature [?], the switch peak voltage curves under different parameter variations are shown in [Figure 7: see original paper]. For the PS compensation topology, switch peak voltage decreases as switching frequency increases. [Figure 7: see original paper]b shows that at the same operating frequency, switch peak voltage decreases as the coupling coefficient increases. [Figure 7: see original paper]c indicates that primary inductance variation has no effect on switch peak voltage.

Considering the relationships between voltage gain, output power, switch peak voltage, device switching frequency, and system parameters, this paper determines the operating frequency as 22 kHz. A loosely coupled transformer with shielding layers is selected. Through theoretical calculation and analysis, the primary coil inductance is determined to be approximately 170 H and the secondary coil inductance about 360 H. Based on winding 工艺, the actual primary coil inductance is 173 H, secondary coil inductance is 365 H, and coupling coefficient  $k$  is 0.532.

To achieve maximum power output and minimize reactive power components, the system operating frequency must be near the natural resonant frequencies of both primary and secondary sides. For the secondary equivalent circuit, setting the imaginary part of secondary impedance  $Z$  in equation (2) to zero yields the required secondary compensation capacitor:

$$C_s = \frac{1}{\omega^2 L_s}$$

This gives  $C = 143$  nF.

From [Figure 3: see original paper], the total equivalent impedance  $Z$  of the entire system is:

$$Z_t = (Z_p + Z_f) \parallel \frac{1}{j\omega C_p}$$

To improve the overall system power factor, the imaginary part of the total equivalent impedance  $Z$  must be zero, which yields the primary compensation capacitor:

$$C_p = \frac{1}{\omega L_p + X_f} \cdot \frac{R_p + R_f}{(R_p + R_f)^2 + (\omega L_p + X_f)^2}$$

This gives  $C = 292$  nF. However, simulation reveals that zero-voltage switching cannot be achieved when  $C = 292$  nF. To enable zero-voltage switching without excessively high voltage across the switch,  $C = 183$  nF is selected.

## 4 Experimental Verification

Based on the above analysis, a 1 kW single-switch ICPT experimental system with PS compensation topology was built. The system parameters are listed in the table below.

[TABLE:N]  
**System Parameters**

Parameter	Value
C (nF)	183
C (nF)	143
L (H)	173
L (H)	365

[Figure 8: see original paper] shows the experimental waveforms of switch voltage  $U_s$  and drive voltage  $U_d$ . The circuit achieves zero-voltage turn-on and zero-voltage turn-off. The system switch peak voltage is 992 V, which is 200 V lower than that in literature [?] under the same power transfer condition, significantly improving circuit reliability.

[Figure 9: see original paper] presents the experimental curves of voltage gain, output power, efficiency, and switch peak voltage versus switching frequency. As shown in Figs. 9a, 9b, and 9c, voltage gain, output power, and efficiency reach their maximum values near 22 kHz, with maximum efficiency of 96%. [Figure 9: see original paper]d shows that switch peak voltage decreases with increasing switching frequency, consistent with theoretical derivation.

## 5 Conclusion

When dynamic nonlinear loads change rapidly, PP-compensated single-switch ICPT systems are prone to overvoltage damage to the switch and secondary rectifier bridge. This paper investigates the PS-compensated single-switch ICPT system and performs parameter optimization. The variation patterns of voltage gain, output power, and switch peak voltage with operating frequency under different parameter conditions are analyzed. Experimental results demonstrate that through parameter optimization, maximum voltage gain, transmission power, and efficiency are achieved near the resonant frequency. The system

realizes zero-voltage switching while significantly reducing switch voltage stress, thereby decreasing switching losses and improving power factor and efficiency. For the prototype under study, the output power reaches 1,080 W at the resonant frequency with 96% efficiency.

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