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Research on Push-pull-type Inductively Coupled Power Transfer System for ZVS

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Abstract. According to the poor stability of the output constant current and the control complexity of the existing Inductive Coupled Wireless Power Transmission System, a series-parallel compensation network is applied to push-pull converter. And the soft switch is realized by configuring the parameters of compensation network, and the constant-current output of the wireless power is realized without additional complex control system. Firstly, analysis of the push-pull converter to achieve the conditions of soft-switching. Secondly, based on the leakage inductance model of the transformer, combined with the Thevenin equivalent theorem, the parameters of the string-and-compensation are designed. Lastly, the push-pull soft-switching inductive coupled power transfer converter is designed and built.The feasibility of theoretical analysis and parameter design method are verified by the experimental results.

1. Introduction

Inductively coupled power transfer (ICPT) is a safe, reliable and flexible power access technology. The electrical energy is transmitted to the powered device through electromagnetic induction between the two coils. It has been widely used in recent years[1-3].

In order to improve the transmission efficiency and reduce the loss of the switching tube, soft switching technology is generally adopted. In [4], the push-pull transformer is introduced on the basis of the traditional ICPT converter, The voltage-current zero-crossing detection circuit existing in the conventional ICPT soft-switching converter simplifies the design of the converter; however, the article cannot realize constant current output under the condition of variable load. In [5], the BUCK variator is added to the secondary side to adjust the charging current, and the PI control algorithm is used to realize the constant-current charging of the variable load. However, this document is mainly applied to high power.

Based on the above problems, this paper uses the serial-to-parallel (SP) topology to compensate the leakage inductance of the loosely coupled transformer based on the push-pull converter. The system can realize soft switching, achieve constant current within a certain load range and improve system stability[6-7].

2. Circuit structure and soft switch working principle

2.1 Push-pull converter circuit

Figure 1 is a block diagram of the push-pull converter ICPT used in this paper[8], which mainly includes: switching transistors Q1 and Q2, push-pull transformers T, C_p and C_s which are the compensation capacitors of the primary and secondary sides, the transmitting coil L_p , and the receiving coil L_s . L_p and C_p are series structures, while L_s and C_s are parallel structures. D1~D4 are rectifier diodes, followed by filter capacitor C_o and load RL. C_{s1} and C_{s2} are drain-source parallel capacitors for switching transistors Q1 and Q2.

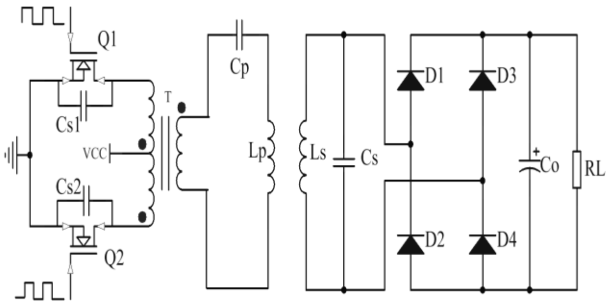

Figure 1. Push-Pull Converter ICPT.

During normal operation, the two power switches Q1 and Q2 are alternately turned on and off by PWM complementary pulse driving; during the half cycle of each conduction, the input DC voltage *V*cc is converted into a high-frequency square wave pulse voltage, which is alternately applied to each other.

2.2 Zero voltage working conditions

The switch tube Q1 and Q2 of the push-pull converter are respectively connected with a large capacitance at both ends of the drain and the source. Since the voltage of the capacitor cannot be abruptly changed, the circuit can realize zero voltage shutdown. To realize the zero voltage of the circuit, the compensation network needs to be inductive; The primary compensation network of the loosely coupled transformer is L and C series. To make it inductive, the traditional method is to take the circuit operating frequency greater than the L and C natural resonant frequency. In this paper, the operating frequency of the circuit is the primary leakage inductance of the loosely coupled transformer and the frequency of the compensation capacitor resonance. At this time, the compensation network is inductive.

The working principle of the ZVS push-pull resonant converter is analyzed below. When it reaches steady state, the working principle waveform is shown in Figure 2.

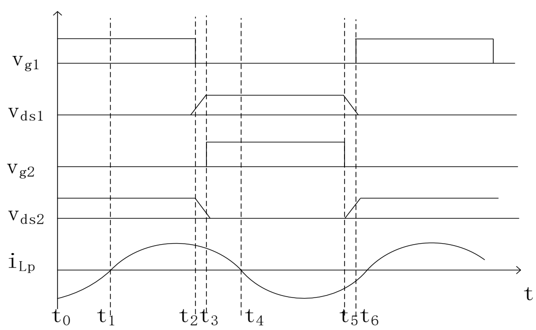

Figure 2. Working waveform of Converter Circuit.

Make the following assumptions before the analysis:

(1) All switching tubes and diodes are ideal components;

(2) Inductance and capacitance are ideal components, $C_{s1}=C_{s2}$;

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(3) The circuit has entered steady state.
In one switching cycle, there are six switching modes, and the operation of each mode is described as follows:

Mode 1: when it is at t_0, Q1 zero voltage is turned on. Due to the clamping action of the body diode, the voltage across Q1 is approximately 0. So Q1 is zero voltage open. At this time, the resonant network composed of C_p and L_{l1} has resonated, the current flowing through the primary side of the transformer gradually decreases, and the resonant current begins to prepare for zero crossing. At time t_1, i_p rises to zero and switch mode 1 ends.

Modal 2: when it is at t1,the primary current is zero. Due to the forward voltage, the forward current flows and the primary compensation network continues to resonate.

Mode 3: Turn off Q1 at time t_2. At this time, the current flowing through the power tube is relatively large. Since the power tube has a large capacitance in parallel, the voltage across the capacitor cannot be abruptly increased from zero, so Q1 is zero voltage off. C_{s1} starts to charge while C_{s2} starts to discharge.

In the next three modes, Q2 is turned on, and the working condition of the circuit is similar to the previous three modes, which will not be described here.

3. SP leakage compensation principle and its characteristics analysis

3.1. Transformer leakage inductance model

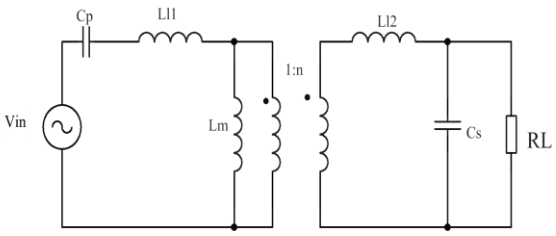


Figure 3. Leakage sensing model of transformer

Like the T-type equivalent model of the ordinary transformer, the secondary side of the loosely coupled transformer can also be converted to the primary side. Regardless of the loss of iron among others, the leakage inductance model of the coupling transformer is shown in Figure 3.In order to simplify the analysis, the parasitic resistance of the primary and secondary coils of the loosely coupled transformer is neglected. L_1 and L_2 respectively represent the primary and secondary side self-inductance of the transformer, and L_{l1} and L_{l2} respectively represent the leakage inductance on the equivalent primary side and secondary side of the loosely coupled transformer. n is the equivalent voltage ratio. L_m is the equivalent magnetizing inductance, and M is the mutual inductance between the transmitting and receiving coils[9]. According to the two-port equivalent characteristics:

$$L_m = \frac{M}{n} \tag{1}$$

$$L_{l1} = L_1 - \frac{M}{n} \tag{2}$$

$$L_{l2} = L_2 - nM \tag{3}$$

3.2. SP leakage compensation principle analysis

Traditional ICPT compensation is divided into two types: unilateral compensation and bilateral compensation. The unilateral compensation is to add the resonant compensation capacitor only on the side of the loosely coupled transformer, and the bilateral compensation is to add the compensation capacitor on both sides of the loosely coupled transformer; the resonant mode of the resonant network composed of the loosely coupled transformer coil and the compensation capacitor may have two modes: series resonance and parallel resonance. In [10], the voltage gain, current gain and power factor characteristics of various modes of the two compensation types are analyzed in detail, and the effect of the bilateral compensation network is far superior to that of unilateral compensation.

There are four basic compensation networks (SS, SP, PS, and PP) for bilateral compensation. According to the principle, they can be divided into two types: constant voltage output and constant current output.In the actual circuit, to achieve constant voltage and constant current output within a certain load range, the compensation network must be operated in a resonant state. Besides the equivalent impedance of the coil and the loss of the MOS tube should be as small as possible. For example, SS can theoretically achieve constant current output. In actual circuits, it is necessary to reduce the switching and coil losses as much as possible in a certain load range. The coil loss can be made by using multiple strands and winding the Litz wire to make a loosely coupled transformer coil. To reduce switching losses, soft-switching techniques must be used to achieve ZVS by adding a voltage zero-crossing detection circuit and corresponding control circuitry[11-12].

In this paper, SP can compensate for leakage inductance, which can realize soft switching and realize output constant current. It does not need additional control circuit, and the constant current characteristics are better. The principle of SP leakage compensation is as follows:

The SP compensation method is analyzed by the leakage inductance model. If the primary and secondary compensation capacitors C_p and C_s resonate with the leakage inductance respectively, the equation is satisfied:

$$f_{sw} = \frac{1}{2\pi\sqrt{L_{l1}C_p}} = \frac{1}{2\pi\sqrt{L_{l2}C_s}} \tag{4}$$

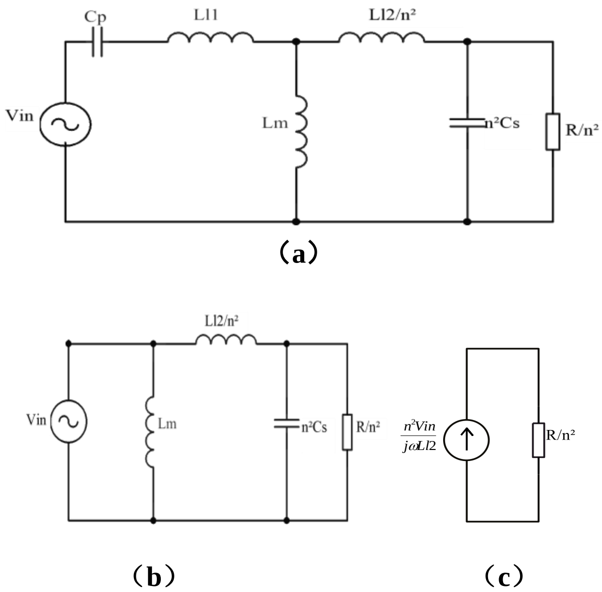


Figure 4. Compensating leakage of SP topology

Figure. 4(a) is an equivalent circuit diagram of the secondary side converted from Figure 3 to the primary side. The series resonance of C_p and L_{l1} is equivalent to a short circuit, so that Figure 4(b) can be obtained. Figure 4(b) L_{l2}/n^2 and n^2C_s resonance, after the equivalent conversion of the power supply can be obtained Figure 4(c), the output is the current source. When the system parameters are determined, the secondary output current is only related to the compensation network port voltage V_{IN}. The current expression is:

$$i_o = \frac{nv_{IN}}{j\omega L_{l2}} \tag{5}$$

The input impedance ZIN obtained from Figure 4(a) is:

$$\begin{aligned} Z_{IN} &= j\omega L_M //(\frac{j\omega L_{i2}}{n^2} + \frac{1}{j\omega n^2 C_S} // \frac{R}{n^2}) \\ &= j\omega L_M //(\frac{1}{n^2} \frac{1}{\omega^2 C_S^2 R - j\omega C_S}) \end{aligned} \tag{6}$$

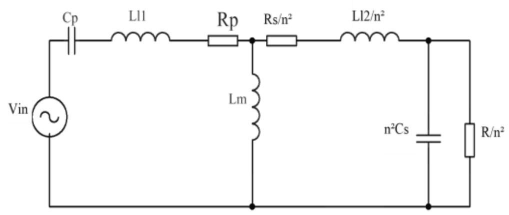
From equation (6), we can obtain equation (7):

$$Z_{IN} = \mathrm{j}\frac{\omega R L_M n^2}{\omega^2 C_S{}^2 R^2 + n^4} + \omega^2 (\frac{R^2 L_M C_S}{\omega^2 C_S{}^2 + n^4} - \frac{L_M L_{L2}}{n^2}) \tag{7}$$

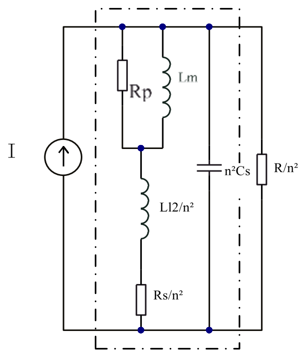
From the formula (7), Z_{IN} can be obtained as an inductive property, which satisfies the condition for realizing ZVS.

3.3. Analysis of the influence of coil parasitic resistance

Considering the parasitic resistance of the coil,the SP leakage compensation circuit model is shown in Figure 5(a). C_p and L_{l1} are in series resonance. In the case of system parameter determination, the ICPT system can be equivalent to the actual current source model according to the Norton equivalent transformation. The dotted line portion in Figure 5(b) is equivalent to the impedance Z, thereby analyzing the influence of the coil parasitic parameters on the output constant current.



(a)



(b)

Figure 5. Including coil parasitic resistor equivalent circuit

The original secondary side ratio of the loosely coupled transformer is approximately 1, and the equivalent current and equivalent impedance are obtained. The effective value I_o of the output current can be obtained by simplification:

$$I_o = \frac{C_S L_M U_{\text{in}} \omega}{\sqrt{A^2 + B^2}} \tag{8}$$

where:

$$A = (C_S + L_{l2} + L_M) R R_P + C_S R_P R_S$$
$$B = \omega(L_{l2} L_M R + C_S (L_{l2} R_P + L_M (R + R_P + R_S - L_{l2}\omega)))$$

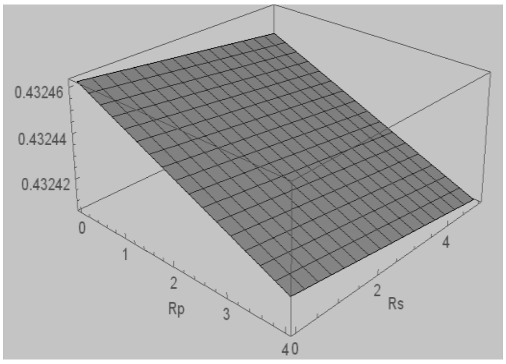


Figure 6. Effect of R_p and R_s on output current I_o

Assuming that the system parameters are fixed, the influence of R_p and R_s on Io is studied according to equation (8). As shown in Figure 6, the output current I_o decreases slightly with the increase of Rp and Rs. Among them, Rp has a greater influence on the output current Io. When the coil is actually designed, the coil should be optimized to reduce the influence of the parasitic resistance of the coil on the constant current characteristics.

4. Experimental verification

In order to verify that the SP can compensate for the leakage inductance under the push-pull soft switch, the constant current output can be realized. According to Figure 1, the push-pull soft-switch ICPT experimental prototype is built.

In this experiment, the self-inductance of the primary coil of the loose coupling transformer is 142.4μH at a distance of 3.5cm. The leakage inductance of the primary side is 132.5μH.The self-inductance of the secondary coil is 123μH.The leakage inductance of the secondary coil is 115.4μH, and the mutual inductance is 32.6μH.The primary compensation capacitor C_p is 28nF, and the secondary compensation capacitor is 32nF. The input voltage is DC30V, and the load current is tested for 5Ω, 50Ω, 100Ω and 200Ω output currents.

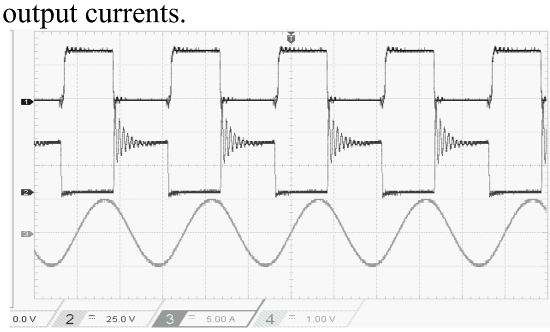


Figure 7. Converter operating wave forms

Figure 7 is a working waveform diagram of the bit converter. From top to bottom, they are the waveform of the switch tube driven, the waveform of the drain and source of the switch tube and the current waveform of the resonant network. It can be seen from the figure that the resonant current lags the voltage.

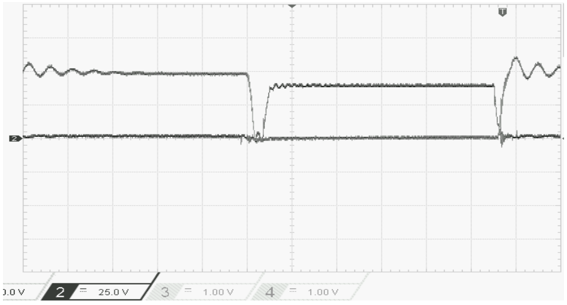
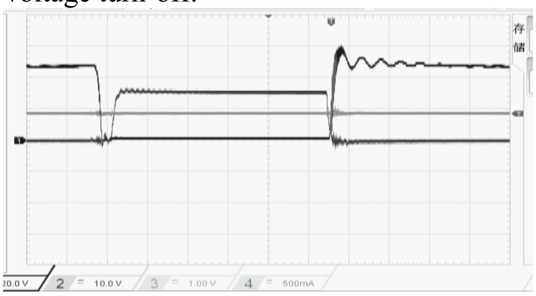


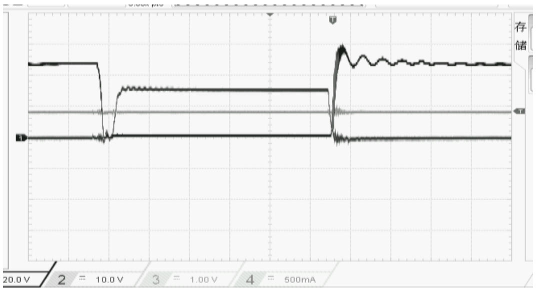
Figure 8. Switching tube voltage waveform

Figure 8 is a voltage waveform diagram of the driving and draining sources when the switching transistor is turned on and off. When the switch tube starts to work, the voltage across the DS has dropped to zero, achieving zero voltage turn-on. When the driving voltage becomes zero, the voltage across the drain source rises from zero, achieving zero voltage turn-off.

（a）5Ω load



（b）50Ω load



（c）100Ω load

（d）200Ω load

Figure 9. Switch-tube drive, drain source and output current waveform under each load

Figure 9 shows the switching transistor drive, the drain and source ends, and the output current waveform for each load value. It can be seen that the soft switch can be realized in the 5-200Ω load range, and the output current is basically maintained at 0.43A with the load increase. As can be seen from the experimental waveforms, the simulation and experiment are in very good agreement.

5. Conclusion

Based on the push-pull converter, the SP compensation compensation method is used to realize the soft switching of the converter without increasing the voltage zero-crossing detection circuit. At the same time, the ICPT is realized in the 5-200Ω load range. The constant current output of the system is analyzed. The influence of switching loss on the constant current characteristics of ICPT is analyzed. The soft switching circuit is designed based on the SP leakage compensation characteristic. The theoretical verification is carried out by using Matlab simulation software. The simulation and experimental results show that the SP leakage is adopted. The sense compensation combined with the soft switching characteristics of the push-pull converter can achieve a constant current output characteristic.

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