Research of the Constant Current Characteristic of Symmetric AC-AC Inductive Coupled Power Transfer System

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Abstract: This study proposes a novel symmetric AC-AC converter for Inductive Power Transfer (ICPT) system which has simple and symmetric circuit topology without requiring large filter capacitor and rectifier. It takes 50 Hz sinusoidal mains input and generates 50 Hz sinusoidal mains output. The constant current characteristic of the system is verified by theoretical analysis based on impulse theorem. The parameter of the resonant link is also derived to ensure the frequency stability of the system. Preliminary simulation and experimental results have verified the validity of the system.

Key words: AC-AC, inductive coupled power transfer, constant current characteristic, impulse theorem

INTRODUCTION

Inductively coupled power transfer (ICPT) technology allows electrical energy to be transferred from a stationary primary source to one or more movable secondary loads over relatively large air gaps (Si et al., 2008; Li et al., 2008). Due to the elimination of physical electric contacts, it is widely used in special fields, such as inflammable and explosive areas and wet or undersea environment (Sample et al., 2011; Li et al., 2012a, 2013; Dai and Sun, 2011; Tang et al., 2009). Moreover, in most industrial ICPT applications, only ac mains are available, so several research have been done to achieve AC output (Boys et al., 2008; Keeling et al., 2010; Sun et al., 2012).

Normally, in order to generate a high-frequency current on the primary side, an AC-DC-AC two-stage power conversion is employed in ICPT systems (Wang et al., 2010, 2011). However, extra semiconductor switches and large DC electrolytic capacitors can be costly and bulky (Safaee et al., 2012; Wu et al., 2011a) which also compromises system reliability. Meanwhile, for high power application, power factor correction circuitry is usually employed along with the rectification stage.

Recently, one of the options to design a direct AC-AC ICPT system is to generate a high-frequency current on the primary side based on free oscillation and energy injection control (Li et al., 2012b). The converter is simplicity but neglect the envelop characteristic of the track current and the design of the pickup. Moreover, it has been pointed out that a low energy storage power supply can be used to achieve AC-AC conversion (Wu et al., 2011b). Such technique can directly generate high frequency track currents whereas the AC-DC stage is still used because that such technique needs a small filter capacitor after the rectifier to reduce the energy storage of the power supply.

In this study, a novel direct sinusoidal input/output AC-AC ICPT system is presented without energy storage links. Compared with the traditional AC-DC-AC ICPT system, its structure and control are simple and the cost is lower. This technique combines the primary direct AC-AC converter with a secondary AC-AC converter based on energy injection control that converts the high frequency AC directly to a low frequency AC output. The expression for the steady load current based on impulse theorem has been discussed in detail. Simulations and experiments have been carried out to verify the theoretical results.

BASIC CIRCUIT OPERATION

The ICPT system can be classified by voltage-fed system and current-fed system. The voltage-fed system normally matches series tuned types of resonant tanks, while current-fed system matches parallel tuned types of resonant tanks. This study uses a typical voltage-fed resonant tank as an example. The main AC-AC topology of voltage-fed ICPT system can be shown in Fig. 1.

As shown in Fig. 1, the system has the symmetric circuit topology from primary part to secondary part. The series resonant network of the primary part consisting of a capacitor $C_p$ in series with an inductor $L_p$, such series resonant tank is assumed to be driven to produce a high-frequency sinusoidal current with low distortion directly from input AC supply. This sinusoidal current provide the Zero Current Switching (ZCS) conditions for IGBT switches ($P_1$–$P_s$).
Fig. 1: Symmetric AC-AC voltage-fed ICPT system

The secondary part consists the pick up coil $L_s$ which is completely tuned by the series capacitor $C_s$ and the $M$ is the mutual inductance between $L_u$ and $L_s$, such series resonant tank receives the high-frequency energy by the magnetic fields coupling. The symmetric AC-AC converter that includes four switches ($S_1$–$S_4$) converts the induced high frequency AC directly to a low frequency AC output to the load $R_L$.

**Primary AC-AC converter operation (the energy injection and free oscillation control method):** The four IGBTs ($P_1$–$P_4$) and four anti-parallel diodes ($P_{D1}$–$P_{D4}$) constitute two pairs bidirectional switch to convert the input AC supply into a series of the high frequency rectangular voltage waveform whose amplitude changed according to sinusoidal law (Fig. 2). The primary AC-AC converter operate based on energy injection mode and free oscillation mode: When the polarity of the input AC supply and the resonant current is positive, $P_1$ switched “on”, while other switches ($P_2$–$P_4$) be “off” and the energy is injected into the primary resonant tank, as the polarity of resonant current is negative then $P_1$, switched “on”, while other switches ($P_{D1}$, $P_{D3}$, $P_{D4}$) be “off” and the energy free oscillate in the resonant tank. The signals and waves corresponding to the principle are seen as Fig. 2.

**Impulse theorem:** There is a very important conclusion called impulse theorem in sample control theory which is the narrow pulses of equal impulse and different shape have the same effect when added to the inertia link. Impulse is the area of narrow pulses and the same effect means to get the same output response wave (Zheng et al., 2010).

Based on the impulse theorem (also called equivalent area principle), in order to make the output voltage waveform equivalent with the desired voltage waveform, the area sum of surrounded by sinusoid half wave with power grid frequency within the half output voltage period must be equal to the one of desired output voltage wave. It especially needs to be pointed that the wave of sinusoid half wave of the input supply is chopped by high frequency pulse signals based on energy injection and free oscillation principal (Fig. 3).

Fig. 2(a–g): Control sequence of the AC-AC resonant soft-switched converter of primary part, (a) Input voltage waveform, (b) Control pulse waveform of $P_1$, (c) Control pulse waveform of $P_2$, (d) Control pulse waveform of $P_3$, (e) Control pulse waveform of $P_4$, (f) Output voltage waveform of the primary inverter and (g) Resonant current waveform of the $L_P$

Fig. 3: Output voltage waveform of primary AC-AC inverter

From Fig. 3, let the amplitude of the input AC supply be $V_{in}$ frequency be $f_n$ period be $T_n$, then the
voltage waveform of the input AC supply can be expressed as follow:

\[ V_{ac} = V_{m} \sin 2\pi f_{c} t \]  

(1)

In order to facilitate analysis of the circuit and highlight the main issues, supposed the resonant frequency \( f_{c} \) is large enough, then the area of each trapezoidal curve (\( S_{ABC} \)) can be replaced by the rectangle area (\( S_{ABCD} \)), then each area of the voltage \( S_{j} \) can be expressed as:

\[ S_{j} = 0.5T_{r} V(j) \]  

(2)

where, \( V(j) \) is the length of the rectangle (\( S_{ABCD} \)) that is replaced by the instantaneous voltage (\( t = j \)) and the width of the rectangle is the half resonant period (0.5\( T_{r} \)). The zero phase frequency must be equal to the secondary resonant frequency so that the maximum output power could be achieved (Wang et al., 2004). Therefore, the resonant period \( T_{r} \) should be:

\[ T_{r} = \frac{1}{f_{c}} = \frac{2\pi}{\omega_{0}} = 2\pi \sqrt{L_{r}C_{p}} = 2\pi \sqrt{L_{c}C_{s}} \]  

(3)

where, the \( \omega_{0} \) is the zero phase angular frequency of the system, as shown in Fig. 3, the area of surrounded by every sinusoid half wave with the input power after inverted by the high frequency control pulse (\( S \)) is expressed as follow:

\[ S = \sum_{j=1}^{N} S_{j} = \sum_{j=1}^{N} \frac{V_{m}}{2f_{c}} \sum_{j=1}^{N} 2\pi \sin 2\pi f_{c}(j - 0.5) \frac{1}{f_{c}} \]  

(4)

where, the \( N \) is:

\[ N = \frac{0.5T_{r}}{f_{c}} = \frac{0.5}{f_{c}} \]  

(5)

Then the voltage injected into the primary resonant tank should be:

\[ V = \sum_{j=1}^{N} \frac{S_{j}}{0.5T_{r}} = \frac{f_{c}V_{m}}{f_{c}} \sum_{j=1}^{N} \sin 2\pi f_{c}(j - 0.5) \frac{1}{f_{c}} \]  

(6)

The resonant current of primary part \( i_{L_{s}} \) can be derived as:

\[ i_{L_{s}} = \frac{V}{R_{L}} = \frac{f_{c}V_{m}}{R_{L}} \sum_{j=1}^{N} \sin 2\pi f_{c}(j - 0.5) \frac{1}{f_{c}} \]  

(7)

where the reflected impedance \( R_{r} \) that is dependent on the transformer coupling and operating frequency is given by:

\[ R_{r} = \frac{\epsilon_{b}^{2}M^{2}}{Z_{s}} \]  

(8)

where, \( Z_{s} \) is the impedance of the secondary part and \( M \) is the mutual inductance between primary coil and secondary coil.

**Secondary AC-AC converter operation:** Similarly, the working principle of the secondary part is also based on the energy injection and free oscillation mode, it is the inverse process of the primary part. The high frequency resonant current induced from the primary part is converted into low frequency current waveform whose amplitude changed according to sinusoidal law, the signals and waves corresponding to above principle are seen as Fig. 4.

The equivalent circuit of the secondary part based on the mutual inductance model is shown in Fig. 5.

According to the AC impedance model of system resonant tank, the induced voltage \( V_{m} \) of the secondary resonant inductance \( L_{s} \), can be:

\[ V_{m} = \epsilon_{m} M_{m} \]  

(9)

Then, the current of the secondary inductance \( i_{L_{s}} \) should be:

\[ i_{L_{s}} = \frac{V_{m}}{Z_{s}} = \frac{V_{m}}{\epsilon_{m}M_{m} f_{c} \sum_{j=1}^{N} \sin 2\pi f_{c}(j - 0.5) \frac{1}{f_{c}}} \]  

(10)

where, \( R_{m} \) is the equivalent resistance of the output port of the secondary resonant link and \( R_{s} \) is the inherent resistance of inductor \( L_{s} \). Substituting Eq. 7-9 into Eq. 10, the secondary inductance current \( i_{L_{s}} \) is derived as:

\[ i_{L_{s}} = \frac{V}{\epsilon_{m}M_{m}} = \frac{f_{c}V_{m}}{\epsilon_{m}M_{m} f_{c} \sum_{j=1}^{N} \sin 2\pi f_{c}(j - 0.5) \frac{1}{f_{c}}} \]  

(11)

It can be seen from Eq.11 that the \( i_{L_{s}} \) is independent of the load \( R_{L_{s}} \); in addition, the on-and-off period of the switch \( S_{k} \) is equal, suppose the working time of the circuit is \( \sigma \), the expression of the equation as follow can be given according to energy conservation principle:

\[ i_{L_{s}}^{2}R_{L_{s}}\sigma = i_{L_{s}}^{2}R_{L_{s}}\sigma = i_{L_{s}}^{2}R_{L_{s}}\sigma \]  

(12)

Then substituting Eq.12 into Eq.11, the load current \( i_{L} \) can be obtained as follow:
From Eq 13, it can be obviously seen that the load current $i_L$ is completely independent of the load $R_L$. In other words, the system exactly has the constant current characteristic.

**Frequency stability:** From Eq. 13, it can be seen that the constant current characteristic of the system depend on the resonant frequency $f_0$. In order to ensure there is only one zero phase angle frequency, parameters of the system should be satisfied as follow (Zhang et al., 2013):

$$i_L = i_{L_o} = \frac{\sqrt{2}U_{rms} \sum \sin 2\pi f_0 (j - 0.5)}{2\Phi c f_0}$$

**Simulation and Experimental Results**

**Simulation analysis:** On the basis of the analysis discussed above, the simulation model in MATLAB/SIMULINK software of the proposed AC-AC ICPT system can be easily built with the parameters shown in Table 1.

The simulation waveforms of the system are as shown in Fig. 6 and 7. It can be seen from Fig. 6b that the primary resonant current $i_{L_o}$ can be directly generated by the input AC supply that is shown in Fig. 6a. The steady-state waveform is achieved after 5 msec and the envelope of the resonant current is in good quality by using the energy injection and free oscillation control method, the current amplitude of $i_{L_o}$ is 20 A. The enlarged drawing of the resonant current (39.5–40.5 msec) shown as Fig. 6c shows that the frequency of current $i_{L_o}$ is 20 kHz and made to be a low distortion sinusoidal shape, the system operates at ZCS condition because the control pulse waveform of P1 is in phase with $i_{L_o}$.
The resonant current waveform of primary part and load current waveform of secondary part with dynamic load switching is shown as Fig. 7.

Current waveform of secondary part with dynamic load switching (a) Primary resonant current waveform with the load \( R_{L1} = 400 \, \Omega \) varying from \( R_{L2} = 200 \, \Omega \) and (b) Load current waveform with the load \( R_{L1} = 400 \, \Omega \) varying from \( R_{L2} = 200 \, \Omega \).

From Fig. 7a, as the load \( R_{L1} \) varies from \( R_{L2} = 400 \, \Omega \) to \( R_{L2} = 200 \, \Omega \) the primary resonant current \( i_{L1} \) varies from 20 to 10 A, simultaneously, the load current \( i_L \) shown as Fig. 7b keeps at 2 A, this proves that the symmetric AC-AC ICPT system exactly has the constant current characteristic.

It also can be seen from Fig. 7b that the load current \( i_L \) is 50 Hz and made in good quality by the low-pass filtering tank followed of the inverter.

**DISCUSSION**

The symmetric AC-AC ICPT system shown in Fig. 1 has been implemented in a laboratory scale. The inverter consists of four IGBTs (International Rectifier IRGBC40K). The zero-crossing points of inductance current are detected by the current sense transformers.
Phase-locked loop (CD4046) is selected to achieve the ZCS operation for the converter with variable frequency. According to the parameters in Table 1. The experimental results of the proposed ICPT system are shown below.

Figure 8 shows the experimental waveforms of the symmetric AC-AC ICPT system, the primary resonant current \(i_p\) is controlled based on the energy injection and free oscillation mode, it can be seen from Fig. 8 that the peak resonant current \(i_p\) decreases from 8 to 14.9 A as the load \(R_2\) is switched from 400 to 200 \(\Omega\), while the amplitude of the output load current \(i_3\) still remains at 1.86 A and the frequency keeps at 49.8 Hz. Considering the coil resistance and conduction loss in actual system, the experimental results are lower than the simulation value which is obtained under ideal situation. In addition, the load current \(i_3\) shown in Fig. 8 (CH3) has slight ripple which is caused by the output filter capacitor \(C_b\) whose discharge time is affected by the sudden change of the load resistance. However, compared with the fact that the power of the system decreased by 50\% under dynamic load switching condition, such slight current ripple will not affect our conclusion that the system does have the constant current characteristic.

From Fig. 9, it can be seen that the system has achieved ZCS as the resonant current \(i_p\) is in phase with control pulse of \(P\). It also can be seen that the experimental curve of the current \(i_p\) deviates by about 0.8 kHz from the theoretical value. This is caused by deviations in actual component values from the nominal values. The theoretical results are based on the simplifications in the model that ignores losses in the capacitors and electromagnetic structure. Therefore, this error in practice doesn’t affect the analyzed results above this section.

CONCLUSION

This study put forward a symmetric AC-AC ICPT system without requiring energy storage links. The expression for the steady load current based on impulse theorem has been discussed in detail under dynamic load switching condition. Simulations and experiments have been carried out to validate the constant current characteristic of the system and it realizes 50 Hz sinusoidal mains input and generates 50 Hz sinusoidal mains output without any large filter capacitor and rectifier, this could save cost and volume of the ICPT system and the system complexity is also been reduced.

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REFERENCES


