Signal and Power Synchronous Transmission in WPT System Based on Capacitance Modulation

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Abstract. In inductive coupled power transmission system, at the same time of power transmission, signal transmission is necessary in order to realize the closed-loop control. Synchronous transmission of power and signal has advantages of high speed and stability. By using the method of capacitance modulation via changing capacitance, the working state of the resonator changes. The voltage across the coil appears certain changes. After step-down divider, demodulation, filtering, comparison and a series of signal processing, the transmitting signal will reproduce. The simulation and experiments show that the scheme is correct, the signal can be sent and extracted correctly, and the effect of power transmission is small. The synchronous transmission of signal in wireless power transmission system is realized.

1. Introduction
With the progress of science and technology, people desire more of the concept of convenience, high efficiency and environment protection. The purpose of getting rid of cable makes the wireless power transmission became possible. WPT(wireless power transmission) is a kind of technology that makes the power supply transmitted in wireless way instead of wired way [1]. At present, the WPT system commonly has the following kinds: Inductive coupled type, Magnetic resonance type, Microwave directional transmission, etc. From the point of present study situation, ICPT(Inductive Coupled Power Transmission) is most widely used, especially in the application of high power and small gap distance.

When used in the special scene, such as, EV charging system, solar charging system, power transmission only is not enough. Mature ICPT system shall have the function of collecting parameters of system every point in signal picking up point, and sending the signal to power sender to tell whether the charging complete [2]. Also, power sender should transfer signal to power picking up point. And then, signal can be transmitted between power sender and power picking up point in positive and negative way. While some WPT system also needs to achieve closed-loop control, which will lead to better effect of constant voltage output. Compared to Zigbee, bluetooth and other existing module, signal and power synchronous transmission technology has the advantages of high speed, no additional module [3]. Compared to the application of RFID, NFC technology, signal and power synchronous transmission technology has great superiority in power transmission without being limited by the signal transmission [4]. Characteristic all above provide a new research direction of signal and power synchronous transmission.

Article is organized as followings. Section II analyzes the structure model of capacitor series compensation, and gives the effect of WPT system under the circumstance of changing the resonant
capacitance. Section III shows the circuit of signal sending and signal picking up, and analyzes the circuit working state. Section IV shows the simulation results under high power and high voltage level. Section V is the experiment verification and result analysis. The conclusion will be put on the last section.

2. Principle analysis of signal and power synchronous transmission

2.1. Loosely coupled transformer series compensation modeling

ICPT system usually consists of DC bus, inverter, LCT (Loosely Coupled Transformer), rectifier bridge and load. Due to large air gap in loosely coupled transformer, the leakage inductance of the coil is large and the overall transmission efficiency is not high. Therefore, the capacitance to compensate for the LCT has to be used to eliminate the influence of the leakage inductance. The overall structure is shown in Fig.1. Series compensation (S-S compensation) is used in both transformer primary side and secondary side, which has advantages of resonance state stability and high system efficiency [5].

![Figure 1. Structure of ICPT system](image1)

When analyzing the leakage inductance of the series compensation, we should use T model to equivalent the LCT with the secondary parameter calculated to primary side, then, we get the circuit shown in Fig.2. Among the Fig.2, the \( L_M \) is LCT excitation inductance, the \( r_M \) is LCT losses, \( L_P \) and \( L_S' \) are LCT leakage inductance, \( C_P \) and \( C_S' \) are LCT compensation capacitance, \( r_P \) and \( r_S' \) are equivalent series resistance, \( R_L \) is equivalent load.

![Figure 2. T type equivalent circuit of loose coupled transformer](image2)

According to resonance principle, we have:

\[
C_s L_p = \frac{1}{\omega^2}
\]

\[
L_s' C_s' = \frac{1}{\omega^2}
\]

Circuit input impedance is:

\[
Z_{in} = \left( j \omega L_s' + r_s' + \frac{1}{j \omega C_s} + Z' \right) \left( r_M + j \omega L_{M} \right) + j \omega L_P + \frac{1}{j \omega C_p} + r_P
\]

(2)

Voltage transfer ratio is:
If the element values meets:

\[
L_p = L_q' = L
\]
\[
C_p = C_s' = C
\]

The voltage transfer ratio can be simplified as:

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{\omega^2 CL_m}{\omega^2 C (L_m + L) - 1} = 1
\]

Seen that the output voltage and input voltage ratio of 1 after reduction, which is nothing to do with the load. Thus, LCT with series compensation can be treated as variable ratio of N ideal transformer from voltage perspective.

By the same token, the current transfer ratio is:

\[
\frac{I_{\text{out}}}{I_{\text{in}}} = \frac{1}{1 - j \frac{Z'}{\omega L_m}}
\]

As a result, the leakage inductance of series compensation structure is not a constant current output. When analyzing self-inductance of series compensation structure, we should use mutual inductance model of LCT for equivalent. We can find the feature of constant current output.

2.2. Signal synchronous transmission principle

In the research at home and abroad, the realizing methods of signal and power synchronous transmission usually has the following kinds: (1) the main circuit increasing coding switch [6], (2) changing the inverter resonant frequency [7], (3) adding DC-DC circuit between DC bus and inverter [8], (4) two sets of transformer transmitting power and signal [9], (5) adding function switch [10], (6) loading and cutting out load, etc. Methods (1) (2) (3) can only transmit signal in positive way, however, method (4) (5) (6) can transmit in both positive and negative way. But the methods above on the transmission efficiency and the load voltage fluctuation has certain defects. This article use the method of changing compensation capacitance to influent resonance state in order to make both coil voltage to change. And transmitting signal can be reproduced via picking up the changing voltage information. The article takes 2ASK(Binary Amplitude Shift Keying) modulation for easier demodulation and higher accuracy rate.

Firstly we analyze signal transmitting from LCT primary side to secondly side. To simplify the derivation, on the basis of Fig.2, we take \(L_p=L_S=L_1\), \(C_p=C_S=C_1\), and dismiss the influence of \(r_m\), \(r_p\) and \(r_s\). When the resonance capacitance changes, primary series capacitance \(C_p\) changes for \(p^*C_1\) (\(p>0\), and \(p>1\)), as shown in Fig.3.
Input impedance is:

\[
R_{in} = \left( j\omega L_1 + \frac{1}{j\omega C_1} + R \right) / / \left( j\omega L_2 + \frac{1}{j\omega C_1} + j\omega L_4 \right)
\]

(7)

\[
R_{in} = \frac{j\omega L_4 R}{j\omega L_2 + R} + \frac{p - 1}{p} j\omega L_4
\]

(8)

Looking from DC bus:

\[
I_{in} = \frac{V_{in}}{R_{in}}
\]

(9)

The excitation inductance voltage on LCT is:

\[
V_1 = V_{in} - \frac{p - 1}{p} * j\omega L_4
\]

(10)

LCT secondary side coil voltage is:

\[
V_2 = \frac{L_4 + L_2}{L_2} V_{in} - \left( \frac{L_4 + L_2}{L_2} \frac{p - 1}{p} + 1 \right) j\omega L_4 - \frac{V_{in}}{j\omega L_4 + R} + \frac{p - 1}{p} j\omega L_4
\]

(12)

LCT secondary side coil voltage transfer ratio is:

\[
\frac{V_2}{V_{in}} = \frac{\omega L_2 \left( \omega L_4 + jR \right)}{j\omega (L_4 + L_2) \omega^2 L_4 \omega^2 L_2 - \frac{\omega L_2 \omega^2 L_4 - j\omega L_4}{p}}
\]

(13)

Secondly, when signal transmitting from LCT secondary side to primary side, equivalent circuit is shown as Fig.4. We also take \( L_p = L_S = L_1 \), \( C_p = C_S = C_1 \), and dismiss the influence of \( r_M \), \( r_P \) and \( r_S \). When the resonance capacitance changes, secondary series capacitance \( C_S \) changes for \( s^* C_S(s>0, \text{ and } s'>1) \),

\[\text{Figure 4. Equivalent circuit of signal transmitting from secondary side to primary side}\]

Input impedance is:

\[
R_{in} = \left( j\omega L_1 + \frac{1}{s^* j\omega C_1} + R \right) / / \left( j\omega L_2 + \frac{1}{s^* j\omega C_1} + j\omega L_4 \right)
\]

(14)

Looking from DC bus:

\[
I_{in} = \frac{V_{in}}{R_{in}}
\]

(15)

LCT primary side coil voltage is:

\[
V_1 = V_{in} \left( 1 - \frac{C_1}{R + \frac{1}{s^* j\omega C_1} + j\omega L_2} - \frac{C_1}{j\omega L_2} \right)
\]

(16)

Considering \( \omega^2 L_4 C_1 = 1 \), LCT primary side coil voltage transfer ratio is:
\[ \frac{V_1}{V_{in}} = 1 - \frac{C_1}{R + \frac{s-1}{s}} = \frac{C_1}{j\omega L} \quad (17) \]

Seen that LCT primary side coil voltage transfer ratio \( V_1/V_{in} \) is increasing with the parameter \( s \) increasing. Change of this state can be used to distinguish between digital signal sent "0" and "1".

For signal transmitting from secondary side to primary side, we can analyze the reflection impedance. Due to the character of the full bridge inverter, we can think that the halfway point of the DC bus voltage after inverter is constant. If we only change the compensation capacitance of secondary side instead of other parameters, the system total impedance is variable, which can be appeared in primary side coil.

3. **Operating principles of the proposed topology**

3.1. **Topology and operation of signal sending circuit**

Topology of capacitive modulation circuit is shown in Fig.5. Taking signal transmitting from primary to secondary side for example, as shown in Fig.5-(a), \( Q_5, Q_6 \) and \( C_1 \) are additional control circuit. When Mosfet \( Q_5, Q_6 \) turns off, the compensation capacitance in primary side is \( C_P \), being completely resonance with \( L_P \), which lead to higher transmitting voltage. When Mosfet \( Q_5, Q_6 \) turns on, capacitance \( C_1 \) is connected into the circuit, primary compensation capacitance becomes \( C_P // C_1 \), which is not completely resonance with \( L_P \). Therefore, we can distinguish that sending signal is whether "1" or "0" via checking secondary side coil voltage.

![Figure 5. Circuit structure of capacitor modulation](image)

Signal transmitting from secondary side to primary side is in the same way with above. As shown in Fig.5-(b), secondary compensation changes from \( C_S \) to \( C_S // C_2 \), through changing the control switches \( Q_7, Q_8 \), which leads to voltage changing in primary coil. So the transmitting signal can be picked in the primary side.

3.2. **Topology and operation of signal picking up circuit**

Due to the transmitting signal is loaded into WPT carrier wave as modulating wave, the signal extraction needs a series of demodulation process. Contain the steps as follows: voltage division, isolation, envelope detection, LPF, and comparator. Structure diagram is shown in Fig.6.

![Figure 6. Block diagram of signal demodulation](image)

After the signal modulation, the coil voltage envelope the signal characteristics on both ends. In the demodulation process, firstly divide the coil voltage and isolate the front and back circuit. Then, signal
should be sent into voltage follower, which has influence in the function of isolation and buffer [11]. Detector is divided into synchronous detector and envelope detector, and synchronous detector is mainly used to suppress sideband amplitude modulation of carrier wave and single side band amplitude modulation wave demodulation.Envelope detector is a kind of vibration processing components based on filtering detection [12].

As shown in Fig.7-(a), the envelope detector, containing diode $D_1$, resistor $R_1$ and capacitor $C_1$, is widely used in ASK demodulation because it is cost effective and easy to implement [13]. There is a trade-off between ripple voltage $\Delta V$ and the time $T_{\text{drop}}$ that the output voltage falls a little when the discharge begins [14]. These two terms are expressed as follows:

$$ T_{\text{drop}} = \tau \ln \left( \frac{V_{\text{peak}}}{V_{\text{drop}}} \right), \quad \Delta V = \frac{V_{\text{peak}}}{f_C} \times \tau $$

$$ \tau = R_1 \times C_1 $$

Where $\tau$ is time constant, $f_C$ is the carrier frequency, and $V_{\text{peak}}$ is the peak voltage of the signal. As shown in Fig.7-(b), to decimate the high-frequency noise, time constant should increase to reduce $\Delta V$. In this way, $T_{\text{drop}}$ is increased, and the voltage falling edge becomes slow and cannot keep up with the transition of the data. Thus, selecting a proper time constant is very important to trade-off between ripple voltage $\Delta V$ and $T_{\text{drop}}$.

After obtaining the envelope characteristic containing digital signal, LPF should be used to filter out high frequency noise. Then the slowly varying part of the waveform is obtained, which is similar to square waveform. The waveform should be put into comparator in order to get clear and no-shaking wave signal that is transmitting signal, as shown in Fig.7-(a).

4. Simulation results
Parameters are taken as follows. DC bus voltage is 100V, output impedance load is 5.5Ω, system working frequency is 85KHz, air-gap is 3cm, compensation structure is series compensation. According to Maxwell Ansoft, coil self-induction is 22.008uH and compensation capacitance is 276.488nF. Because of the effect of resonant capacitance to voltage change is not instantaneous, LCT transmission has time delay. To make the change of working state obvious enough, we use 10 power
period to represent 1 signal period, namely $T_{info}=10T_{power}=117.65\mu s$. We use Cadence Pspice17.0 to simulate and Mosfet $Q_5,Q_6$ is driven by square power supply. When high voltage is supplied and Mosfet $Q_5,Q_6$ turns on, transmitting signal is “1”, vice versa. 

Fig.8-(a) shows the voltage of load, keeping about 82V, whose ripple wave is no more than 3V. Fig.8-(b) shows the coil voltage after division and isolation, which can be seen containing clear envelope feature. When Mosfet $Q_5,Q_6$ turns on, envelope voltage is higher, up to 10V. While Mosfet $Q_5,Q_6$ turns off, envelope voltage is lower, up to 7V.

![Figure 8. Simulation waveform](image)

5. Experiment verification

In order to prove the correctness of theoretical analysis, we make a set of ICPT system adopting series compensation, which mainly contains 7 parts: DC input source, TMS320F28335 DSP control board, primary side PCB, LCT, secondary side PCB, signal sending and picking up PCB, load. They are numbered from 1 to 7 in Fig.11. The main parameters adopted in system list in Table I.

Firstly we analyze the result of signal sending from primary side and extracting in secondary side. Signal being sent in primary side is controlled by Mosfet $Q_5,Q_6$, whose control waveform is shown in

![Figure 10. Simulation waveform](image)
Fig. 12. Here we take the alternant voltage of “1” and “0”, and the sending signal is also corresponding “1” and “0”. \( T_{\text{info}} = 10T_{\text{power}} = 117.65 \mu s \).

![Image of prototype](image)

**Figure 11.** Wireless power and signal synchronous transmission system adopting series compensation

**Table 1.** Some critical parameters employed in the prototype

| Parameter                     | Value     | Parameter                     | Value     |
|-------------------------------|-----------|-------------------------------|-----------|
| DC bus source                 | 32V       | Resistive load                | 40Ω       |
| Inverter frequency           | 85KHz     | Signal Mosfet                | FCA47N60  |
| Inverter Mosfet              | FDA20N50  | Signal transmitting frequency | Pros: 8.5 KHz |
| Primary coil self-inductance | 26.65μH   | Voltage follower amplifier    | Ti OPA1612 |
| Primary coil leakage inductance | 9.8μH  | Comparator                    | LM319     |
| Secondary coil self-inductance | 27.75μH  | Load voltage without signal sending | 31V |
| Secondary coil leakage inductance | 10.9μH | Load voltage with signal sending | Pros: 29.7V |
| Primary coil compensation capacitor | 357.75nF | Efficiency without signal sending | Cons: 30V |
| Secondary coil compensation capacitor | 321.64nF | Efficiency with signal sending | 90%       |
| Rectifier diode              | Sirectifier MBR30200PT | Signal transmitting speed | Pros: 8.5 Kbps |
|                              |           |                               | Cons: 21.25Kbps |

Clearly seen that LCT secondary side coil voltage contains signal envelope, secondary coil voltage is lower when Mosfet \( Q_5, Q_6 \) turns on, secondary coil voltage becomes higher when Mosfet \( Q_5, Q_6 \) cuts off from circuit. As shown in Fig. 12, secondary voltage passing diode envelope detector, we get the output waveform, which is the same as the ideal waveform in Fig. 7. When the amplitude of sine waveform is high, the envelope output fluctuates within a certain range. When the amplitude of sine waveform is low, the output waveform has an obvious falling stage, which clearly recognizes the “0” and “1”. To make the difference simple to read, we send the envelope detector output into comparator to compare with a DC input. As shown in Fig. 13, the signal has been extracted totally which has completely reversed phase relationship with sending signal.

Next, we analyze the result of signal sending from secondary side and extracting in primary side. Signal being sent in secondary side is controlled by Mosfet \( Q_7, Q_8 \), whose control waveform is shown in Fig. 14. The communication speed should increase to satisfy the close-loop control under the condition of signal being extracted correctly. Here we set \( T_{\text{info}} = 4T_{\text{power}} = 47.06 \mu s \). During the period of signal sending, the primary side coil voltage contains signal envelope.
After the coil voltage waveform pass the envelope detector, we can get the output in Fig.15. Since the voltage amplitude difference in sending “1” and “0” is not obvious, the envelope voltage output waveform reflects the voltage falling to a certain extent. With the reduction of voltage amplitude, envelope detector output voltage has gradually decreasing trend. In the stage of recovery of voltage amplitude, envelope detector output has a jump increase. The high increase can be used as a way of picking up sending signal “1”. As shown in Fig.15, comparator output waveform is similar to sending signal, which only has delay of 11.4μs. This is resulted by the capacitance changing process shown after a period of time. Furthermore, the delay time is smaller than a power transmitting period, which has achieved an ideal result.

![Waveform diagram](image1)

**Figure 12.** Waveform of positive transmission  

![Waveform diagram](image2)

**Figure 13.** Waveform of positive transmission

![Waveform diagram](image3)

**Figure 14.** Waveform of negative transmission  

![Waveform diagram](image4)

**Figure 15.** Waveform of negative transmission

6. Conclusion  
The paper proposes a signal and power synchronous transmission method in ICPT system. Compared with other methods, the proposed method has the advantages of small effect in power transmitting and not affected by power transmitting. In this method, the signal sending and extracting are completed in compensation capacitance between two side, which has less influence on the before and after system. Therefore, in the load side, filter capacitance value properly selected can eliminate the ripple wave introduced by signal transmitting. Through the simulation and experiment verification, the proposed method has high accuracy and high speed in signal reverse transmitting, which lays a foundation for system close-loop control.

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References
[1] Su Yugang, Zhou Chuan, Lv Lin, et al. Reviews on wireless power transmission technique based on electrical-field coupled mode[J]. World Sci-Tech R&D, 2013, 35(2): 1-2.
[2] Deng Qijun, Liu Jianguo, Zhou Hong, et al. Design and development of measuring & control system for wireless power transfer system[J]. Electric Power Automation Equipment, 2015, 35(7): 147-148.
[3] Liang Hao, Chen Xinrong. Solar cell monitoring system based on wireless sensor network[J]. Electric Power Automation Equipment, 2010, 30(9): 125-126.
[4] Dong L, Meigen S, Jiang T, et al. Wireless sensing system-on-chip for near-field monitoring of analog and switch quantities[J]. IEEE Transactions on Industrial Electronics, 2012, 59(2): 1288-1294.
[5] Mo Hanqiu, Tang Houjun, Lan Jianyu, et al. Design of wireless power transmission system based on LCL-SS resonant network[J]. Power Electronics, 2015, 49(10): 34-36.
[6] Wang Chencheng. Study on inductively coupled power and data transfer system[D]. Chongqing: Chongqing University, 2010.
[7] Sun Yue, Wang Chencheng, Tang Chunsen, et al. Study on inductively coupled synchronous transmission of power and signal[J]. Advanced Technology of Electrical Engineering and Energy, 2010, 29(4): 10-13.
[8] Zhang Aiguo. Study on synchronous transmission of inductive power and signal[D]. Harbin: Harbin Institute of Technology, 2010.
[9] Thierry B, Marc P, Valerie N, et al. Contactless power and information transmission[J]. IEEE Transactions on Industry Applications, 2002, 38(5): 1266-1272.
[10] Atsuo K, Kzauzki I, Junjh H. Wireless transmission of power and information through one high-frequency resonant AC link inverter for robot manipulator applications[J]. IEEE Transactions on Industry Applications, 1996, 32(3): 503-508.
[11] Urvashi S. Wideband voltage followers with improved performance and high-frequency analog electronic circuits[C]// IEEE 5th India International Conference on Power Electronics. India: IEEE, 2012.
[12] Du Lingyan, Wang Zhenhao, Wang Gang, et al. Design of real-time operating state monitoring system for HV breaker[J]. Electric Power Automation Equipment, 2006, 26(1): 58-61.
[13] Yuh-shyan H, Ho-cheng L. A New CMOS Analog Front End for RFID Tags[J]. IEEE Transactions on Industrial Electronics, 2009, 56(7): 2299-2307.
[14] Rui Y, Theng-tee Y, Hwa-SENG Y. A low-power UHF/13.56MHz/2.4GHz multi-standard RFID reader transceiver SoC in 90nm CMOS[C]// IEEE Radio and Wireless Symposium. Phoenix, Arizona: IEEE, 2011: 255-258