

A Dynamic Tuning Method Utilizing Inductor Paralleled with Load for Inductive Power Transfer

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Abstract—The detuning of inductive power transfer (IPT) system which is usually caused by the component tolerance and aging of the inductors and capacitors can decrease the system efficiency. In order to tune the receiver circuit of IPT system, an inductor is paralleled with a diode full-bridge rectifier cascaded with a Buck converter and load serving as a tuning circuit. By changing the duty cycle of the buck converter, the impedance of the tuning circuit can be adjusted which can be used to compensate the reactance caused by detuning. The experimental results in a 400W prototype show that with 15% tolerance of the resonant capacitor in the receiver side, the system efficiency with the proposed method can reach 91% which has an improvement by 7.9% compared to the detuned system.

Keywords—inductive power transfer (IPT); dynamical tuning; impedance adjustment; Buck converter

I. INTRODUCTION

Overall system efficiency is one of the most important performances of an inductive power transfer (IPT) system, especially for the high-power level applications [1] for the ease of cooling. Due to the component tolerance and aging of the inductors and capacitors, the circuitry parameters may slightly drift away from the nominal one from time to time, and the system would detune afterward. The reactance mismatch caused by detuning can have great influence on the system output power and efficiency, so that the performance of the overall system will degrade accordingly. Therefore, it is important to maintain resonant condition in IPT system.

Many researches have focused on the dynamic tuning methods to improve system efficiency against detuning. The dynamic tuning method can roughly be divided into two categories: 1) frequency tracking [2-3]; 2) impedance adjustment [4-6]. For the frequency tracking method, the inverter operation frequency alters dynamically to track the resonant frequency point. Because no extra components are needed, and the topology of the circuit remains unchanged, this method is easy to be implemented. However, the frequency split phenomenon in some cases leads the system to fail to track the resonant frequency. For impedance adjustment method, the inverter frequency is fixed, and some impedance components are employed in the resonant tank of IPT systems, such as capacitor matrix [4] and variable inductor [5-6].

Because the switching of capacitor matrix is discrete, the solution of the tuning is limited. The variable inductor method can continuously regulate the impedance to tune the circuit by changing the conduction angle of the inductor. But the switches have to be synchronized with the high-frequency current/voltage in the resonant circuit which is highly determined by the measurement accuracy.

In this paper, an inductor is paralleled with a diode full-bridge rectifier cascaded with a Buck converter and the load serving as a tuning circuit in the receiver side. By changing the duty cycle of the buck converter, the equivalent resistance paralleled with the inductor is adjusted. As a result, the equivalent impedance of the tuning circuit is also varied which can be used to compensate the reactance caused by detuning. Because the buck converter is located in the DC side of the receiver, no synchronization is required for the switches of the buck converter. Besides, the switching frequency of the Buck converter can be much lower than the inverter frequency which can reduce the switching loss and control complexity.

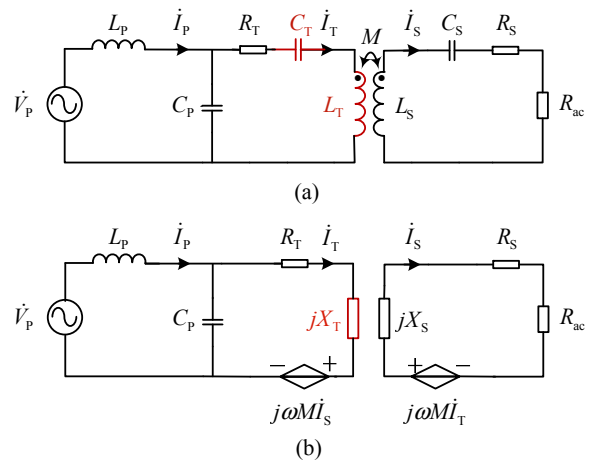


Fig. 1 Circuit topology of LCC-S compensation network. (a) Circuit topology. (b) Equivalent circuit.

II. THEORETICAL ANALYSIS

A common LCC-S compensation network is chosen as the resonant topology of the proposed system. The first-harmonic

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circuit model of the system is illustrated in Fig. 1. The LCC network in the transmitter side consists of compensation inductor L_p , compensation capacitors C_p and C_T , and the self-inductance of the transmitter coil L_T . The series resonant network in the receiver side consists of compensation capacitor C_S and the self-inductance of the receiver coil L_S . M is the mutual inductance between the transmitter coil and the receiver coil. R_{ac} is the equivalent load resistor.

The transmitter and the receiver are decoupled by adding two current-controlled voltage sources as shown in Fig. 2 (b). According to the mesh-current method, the system can be described by the following equations:

$$\begin{bmatrix} \dot{V}_p \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & 0 \\ Z_{21} & Z_{22} & Z_{23} \\ 0 & Z_{32} & Z_{33} \end{bmatrix} \cdot \begin{bmatrix} \dot{I}_p \\ \dot{I}_T \\ \dot{I}_S \end{bmatrix} \quad (1)$$

where

$$\begin{cases} Z_{11} = j\omega L_p + (j\omega C_p)^{-1} = 0 \\ Z_{12} = Z_{21} = -(j\omega C_p)^{-1} \\ Z_{22} = j\omega L_T + (j\omega C_T)^{-1} + (j\omega C_p)^{-1} + R_T = jX_T + R_T \\ Z_{23} = Z_{32} = -j\omega M \\ Z_{33} = j\omega L_S + (j\omega C_S)^{-1} + R_{ac} = jX_S + R_{ac} \end{cases}$$

\dot{V}_p is the first harmonic of the output voltage of the full-bridge inverters with angular frequency ω . The equivalent series resistors (ESRs) R_T and R_S of the transmitter coil and receiver coil are taken into account for analyzing the system efficiency. X_p and X_S stand for the reactance in the transmitter and receiver side separately, which indicate the non-resonant condition.

The currents in the transmitter side and the receiver side can be solved according to (1) as follows:

$$\begin{cases} \dot{I}_p = \dot{V}_p (N_{PR} + jN_{PI}) \\ \dot{I}_T = -j \frac{\dot{V}_p}{\omega L_p} \\ \dot{I}_S = \dot{V}_p (N_{SR} + jN_{SI}) \end{cases} \quad (2)$$

where

$$\begin{cases} N_{PR} = \frac{M^2 \omega^2 (R_S + R_{ac}) + R_T (R_S + R_{ac})^2 + R_T X_S^2}{\omega^2 L_p^2 (R_S^2 + 2R_S R_{ac} + X_S^2 + R_{ac}^2)} \\ N_{PI} = \frac{X_T (R_S + R_{ac})^2 - M^2 \omega^2 X_S + X_T X_S^2}{\omega^2 L_p^2 (R_S^2 + 2R_S R_{ac} + X_S^2 + R_{ac}^2)} \\ N_{SR} = \frac{M (R_S + R_{ac})}{L_p (R_S^2 + 2R_S R_{ac} + X_S^2 + R_{ac}^2)} \\ N_{SI} = -\frac{M X_S}{L_p (R_S^2 + 2R_S R_{ac} + X_S^2 + R_{ac}^2)} \end{cases}$$

The input power and output power of the system can be derived based on (2) as:

$$P_{in} = \text{Re}[\dot{V}_p \cdot (\dot{I}_p)^*] = \dot{V}_p^2 \cdot N_{PR} \quad (3)$$

$$P_{out} = \dot{I}_S \cdot (\dot{I}_S)^* \cdot R_{ac} = \frac{M^2 \dot{V}_p^2 R_{ac}}{L_p^2 (R_S^2 + 2R_S R_{ac} + X_S^2 + R_{ac}^2)} \quad (4)$$

$\text{Re}[Z]$ returns the real part of Z . By taking the ratio of P_{in} and P_{out} , the system efficiency can be derived as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{M^2 \omega^2 R_{ac}}{M^2 \omega^2 (R_S + R_{ac}) + R_T (R_S + R_{ac})^2 + R_T X_S^2} \quad (5)$$

According to (5), the system efficiency η has no relation to the reactance X_p in the transmitter side, but it is a function against X_S . As X_S is a part of the denominator of (5), it means that the existence of X_S will lower the system efficiency. Therefore, the receiver side should be tuned to suppress X_S for the purpose of improving the system efficiency. When M equals 82 μ H, and R_T and R_S equal 0.71 Ω and 0.5 Ω respectively, the system efficiency as a function against R_{ac} and X_S is plotted in Fig. 2.

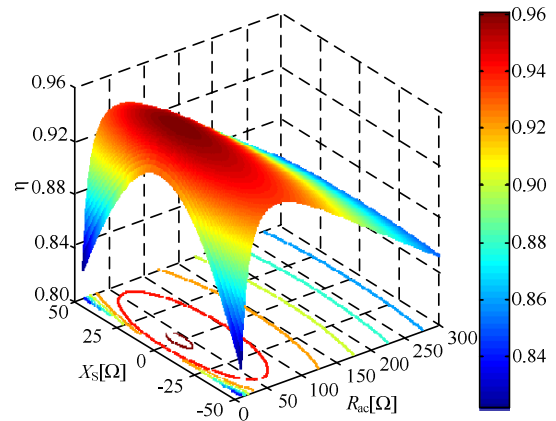


Fig. 2 System efficiency versus R_{ac} and X_S .

III. TUNING METHOD

In order to tune the receiver circuit and improve the system efficiency under the non-resonance condition in the receiver side, a tuning circuit is proposed in this paper. A simplified equivalent tuning circuit is shown in Fig. 3. The tuning circuit consists of transformer M_C and resistor R_{Beq} . C_S is the compensation capacitor in the receiver side. The impedance Z_C of the tuning circuit can be altered by adjusting R_{Beq} . L_{CP} and L_{CS} are the self-inductance of the primary and secondary coil of the transformer M_C respectively. The impedance of the tuning component Z_C can be expressed as:

$$Z_C = \frac{\omega^2 M_C^2}{R_{Beq} + j\omega L_{CS}} + j\omega L_{CP} \quad (6)$$

The reactance X_S caused by the detuning in the receiver side is assumed to be:

$$X_S = \omega L_S - \frac{1}{\omega C_S} = \alpha \cdot \omega L_S \quad (7)$$

α indicates the non-resonant condition of L_S and C_S . R_{Beq} that adjusts the reactance of Z_C to compensate X_S can be derived as:

$$R_{Beq} = \frac{\omega \sqrt{(L_{CP} L_{CS} + \alpha L_S L_{CS})(M_C^2 - L_{CP} L_{CS} - \alpha L_S L_{CS})}}{L_{CP} + \alpha L_S} \quad (8)$$

In order to tune the receiver side in close loop, R_{Beq} should be adjusted automatically. In this paper, a tuning circuit that replaces R_{Beq} with Rectifier B and Buck converter B is proposed as shown in Fig. 4. By changing the duty cycle of the Buck converter B, the equivalent input resistance of the rectifier B can be adjusted. Consequently, the equivalent R_{Beq} is adjusted. Rectifier A and Buck converter A are the conventional power converter circuit connected to the load.

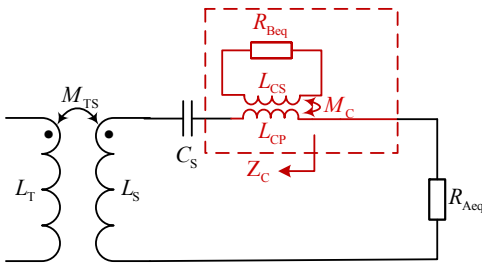


Fig. 3 Simplified equivalent tuning circuit in the receiver side.

IV. CONTROL STRATEGY

The control block of the proposed tuning method is shown in Fig. 4. A measurement coil with a corresponding decoupling transformer M_D is adopted to measure the resonant condition

as proposed in [7]. In the tuning control loop, the zero-cross signal of \dot{V}_{meas} and \dot{I}_s are measured, and the phase difference δ between \dot{V}_{meas} and \dot{I}_s is calculated. The control goal of the tuning loop is to keep δ to be zero. By adjusting the duty cycle D_B of Buck B, the reactance of the whole tuning circuit is changed. Finally, X_S caused by the non-resonance condition in the receiver side can be compensated with the controlled Buck converter B. Meanwhile, part of the active power flows to the load through rectifier B and Buck converter B. In the output voltage control loop, the output voltage is measured and another PI controller is adopted to regulate the output voltage by controlling the duty cycle D_A of Buck A.

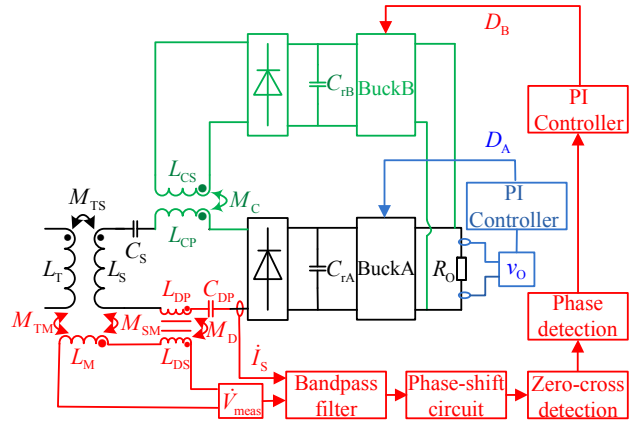


Fig. 4 Control block of the proposed method.

V. EXPERIMENTAL VALIDATION

A 400W prototype system is set up to verify the proposed control method as shown in Fig. 5. The input voltage of the system is 180V. The inverter frequency is chosen as 85kHz. The mutual inductance between the transmitter and the receiver is 82μH. The detailed circuit parameters are listed in TABLE I. The PI controllers for tuning the receiver circuit and regulating the output voltage are implemented in a DSP (TMS320F28335) in the receiver side. An electric load (IT8518B) serves as the adjustable load resistor. The waveforms are recorded by the oscilloscope (Agilent DSO-X 3034A) and the overall system efficiency is measured by the power analyzer (HIOKI PW6001).

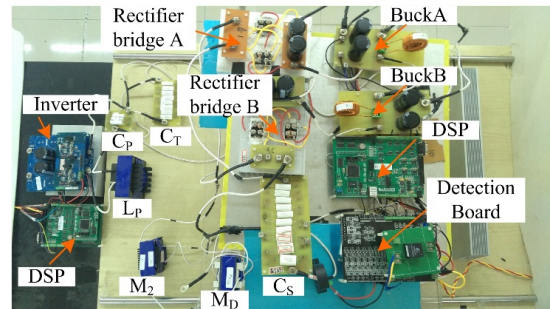


Fig. 5 Experimental prototype.

TABLE I PARAMETERS OF THE PROPOSED IPT SYSTEM FOR EXPERIMENTS

Symbol	Parameter	Value	Unit
U_{dc}	input voltage	180	V
f	inverter frequency	85	kHz
L_P	Inductance of LCL network	95	μ H
C_P	transmitter resonant capacitor	36.9	nF
L_T	transmitter coil inductance	384	μ H
C_T	coil compensation capacitor	12.13	nF
L_S	receiver coil inductance	294	μ H
C_S	receiver resonant capacitor	11.93	nF
L_M	measurement coil inductance	7.84	μ H
L_{DP}	inductance of the transformer in the receiver side	11.157	μ H
C_{DP}	compensation capacitor	314.24	nF
L_{DS}	inductance of the transformer in the measurement side	165.72	μ H
M_{TS}	mutual inductance of transmitter and receiver side coils	82	μ H
M_{SM}	mutual inductance of receiver and measurement side coils	34.07	μ H
M_{TM}	mutual inductance of the transformer	12.12	μ H
L_{CP}	inductance of the transformer in the measurement side	45.07	μ H
L_{CS}	inductance of the transformer in the receiver side	115	μ H
M_C	mutual inductance of the transformer	72	μ H

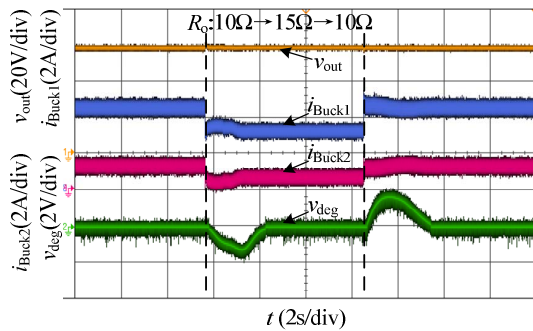


Fig. 6 Time domain response when the load resistor changes.

The time response when the load resistor changes from 10Ω to 15Ω and then back to 10Ω is shown in Fig. 6. The measured phase difference δ of \dot{V}_{meas} and \dot{I}_s is converted to the analog signal v_{deg} by a peripheral digital to analog converter module. As the load resistor is altered from 10Ω to 15Ω, the impedance of the tuning circuit is changed and v_{deg} deviates away from zero. The amplitude of i_{BuckA} and i_{BuckB} decreases because the output power is decreased. With the proposed method, v_{deg} is gradually adjusted to be zero.

In Fig. 7, the overall system efficiency with load resistor ranging from 10Ω to 20Ω are shown for α equals 0.15. In

detuning cases, the system efficiency decreases when the load resistor becomes smaller. By applying the proposed method, the receiver side can be tuned, and the system efficiency is improved dramatically. The maximum system efficiency reaches 91.5%.

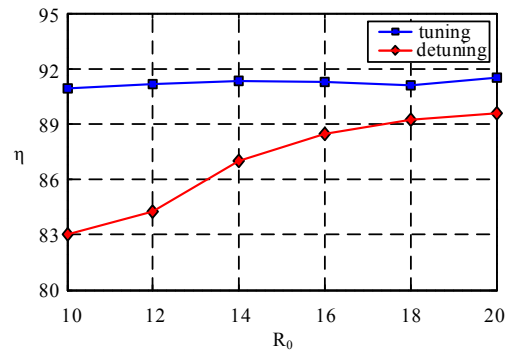


Fig. 7 Overall system efficiency under the tuning and detuning conditions.

VI. CONCLUSION

An inductor is paralleled with a diode full-bridge rectifier cascaded with a Buck converter and the load serving as a tuning circuit in this paper to tune the receiver circuit of IPT system dynamically and to improve the system efficiency. The impedance of the tuning circuit can be adjusted by changing the duty cycle of the Buck converter to compensate the reactance caused by detuning. With 15% tolerance of the resonant capacitor in the receiver side, the system efficiency can reach 91% with proposed method which is 7.9% higher than the detuned condition in a 400W experimental prototype.

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