A Dynamic Compensation Mechanism for Contactless Power Transfer Systems

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Abstract* - Inductively coupled power transfer (ICPT) systems are types of contactless energy transmission systems developed recently, which have been used for the in-line battery charging of autonomous underwater vehicles (AUV), for power supply of oil rigs and submarine mining operations, and for power supply of moving plat track vehicles in a container wharf. In an ICPT system, a primary capacitance is usually used to minimize the VA rating of power supply, and a secondary capacitance is adopted to maximize the power transfer. The changes of the secondary capacitance because of environmental temperature or other factors will alter the resonant frequency of the secondary side, and thus the power transfer capability is varied. In this study, the power transfer capability of ICPT systems is investigated in detail when the secondary capacitance changes. A dynamic compensation mechanism, named the resonant frequency control, is suggested to keep the system operation frequency to follow the secondary resonant frequency when the secondary capacitance varies. The performance of three frequency control methods, that is the resonant frequency control, the traditional variable frequency control, and the fixed frequency control, are compared when the secondary capacitance varies. Theoretical analysis and numerical simulations show that the power transfer capability of ICPT systems is an intricate function of the operational frequency, and thus resonant operations of the secondary side do not always guarantee maximizing the power transfer. A suitable control mechanism, such as the resonant frequency control, the variable frequency control, or the fixed frequency control, should be designed carefully according to the practical engineering requirement when the secondary capacitance varies.

***Keywords* - Inductively coupled power transfer systems, resonant frequency control, variable frequency control, dynamic compensation, drops of secondary capacitance.**

I. INTRODUCTION

Inductively coupled power transfer (ICPT) systems are types of contactless energy transmission systems developed recently, which have been used for the in-line battery charging of autonomous underwater vehicles (AUV) [1, 2], for power supply of oil rigs and submarine mining operations [3], and for power supply of moving plat track vehicles in a container wharf. The main feature of ICPT systems is contactless power supply that eliminates the electric spark of traditional electric sockets and current collectors and eliminates wear due to friction.

An ICPT system usually consists of two parts [4], the primary side and the secondary side, Fig. 1. A common AC power is rectified and inverted in high frequency to drive the primary side of the contactless transformer which transfers

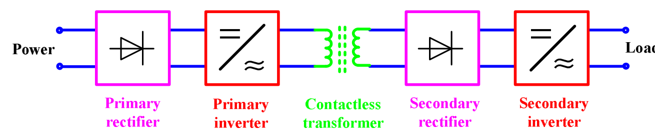

Figure 1. The structure of an ICPT system.

energy contactlessly to its secondary side. The secondary side pickup power might be rectified and inverted to drive loads. The air gap between the primary and secondary sides is typically 10cm [5], and the primary side might be a coil or a track which the secondary side may be moved on.

In an ICPT system, a primary capacitance is usually used to keep the zero phase angle operation of primary side in order to minimize the VA rating of power supply, and a secondary capacitance is adopted to produce resonance in the secondary side in order to maximize the power transfer. The system operation frequency is equal to the secondary resonant frequency [4-6].

In practice, the changes of the secondary capacitance because of environmental temperature or other factors will alter the resonant frequency of the secondary side, and thus the power transfer capability is changed. Wang et al. reported that a 5% drop in the secondary capacitance will result a 10% drop in the system power transfer [7].

In this study, the power transfer capability of ICPT systems is investigated in detail when the secondary capacitance changes. A dynamic compensation mechanism, named the resonant frequency control, is suggested to keep the system operation frequency to follow the secondary resonant frequency when the secondary capacitance varies.

The performance of three frequency control methods, that is the resonant frequency control, the traditional variable frequency control, and the fixed frequency control [4, 6], are compared.

Theoretical analysis and numerical simulations show that the power transfer capability of ICPT systems is an intricate function of the operational frequency, and thus resonant operations of the secondary side do not always guarantee maximizing the power transfer. A suitable control mechanism, such as the resonant frequency control, the variable frequency control, or the fixed frequency control, should be designed carefully according to the practical engineering requirement.

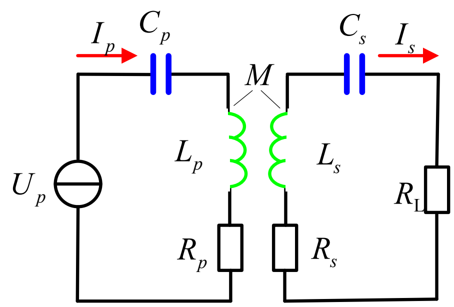

Figure 2. The topology of an ICPT system.

II. Methods

A. Circuits Analysis

The kernel circuits of ICPT systems are shown in Fig. 2 that neglects electric rectifiers and inverters for a series compensated primary and secondary topology. The subscript "p" and "s" represent the primary and secondary respectively.

The load impedance of the secondary side Z_s is

$$Z_s = jwL_s + \frac{1}{jwC_s} + R_s + R_L . \quad (1)$$

The reflected impedance Z_r that represents the loading effect of the secondary on the primary is [4, 6, 8]

$$Z_r = \frac{wM^2}{Z_s} . \quad (2)$$

Let $R = R_s + R_L$, the real and imaginary components of Z_r are

$$\operatorname{Re} Z_r = \frac{w^4 C_s^{\,2} M^2 R}{(w^2 C_s L_s - 1)^2 + w^2 C_s^{\,2} R^2} \quad (3)$$

and

$$\operatorname{Im} Z_r = \frac{-w^3 C_s M^2 (w^2 C_s L_s - 1)}{(w^2 C_s L_s - 1)^2 + w^2 C_s^{\,2} R^2} \quad (4)$$

respectively.

The total impedance Z_t seen from the power supply is

$$Z_t = jwL_p + \frac{1}{jwC_p} + R_p + Z_r . \quad (5)$$

Its real and imaginary components are

$$\operatorname{Re} Z_t = R_p + \operatorname{Re} Z_r \quad (6)$$

and

$$\operatorname{Im} Z_t = wL_p + \frac{-1}{wC_p} + \operatorname{Im} Z_r$$
$$= \frac{(w^2 C_p L_p - 1)\left[(w^2 C_s L_s - 1)^2 + w^2 C_s^{\,2} R^2\right] - w^4 C_p C_s M^2 (w^2 C_s L_s - 1)}{wC_p \left[(w^2 C_s L_s - 1)^2 + w^2 C_s^{\,2} R^2\right]} \quad (7)$$

respectively.

The primary and secondary currents are

$$I_p = \frac{U_p}{Z_t} \quad (8)$$

and

$$I_s = \frac{jwMI_p}{Z_s} \quad (9)$$

respectively.

The system input power P_{in} is

$$P_{in} = U_p I_p . \quad (10)$$

The load power P_{load} is

$$P_{load} = I_s^2 R_L . \quad (11)$$

The system energy transferring efficiency η is

$$\eta = \frac{P_{load}}{P_{in}} . \quad (12)$$

In general, the system operation frequency w is equal to the secondary resonant frequency w_0 which is predefined.

Z_s is simplified to

$$Z_s = R_s + R_L . \quad (13)$$

Z_r is now

$$Z_r = \frac{w_0^{\,2} M^2}{R_p + R_L} , \quad (14)$$

and its imaginary component is zero.

Z_t is

$$Z_t = R_p + Z_r . \quad (15)$$

The primary capacitance C_p is

$$C_p = \frac{1}{w_0^{\,2} L_p} . \quad (16)$$

The secondary capacitance C_s is

$$C_s = \frac{1}{w_0^{\,2} L_s} . \quad (17)$$

B. Fixed Frequency Control

In a fixed frequency control, the system operation frequency w is a constant that designed as the secondary resonant frequency w_0. A change of the secondary capacitance will alter the secondary resonant frequency w_0. The impedances Z_s, Z_r, and Z_t will lose their pure resistance characteristics. The ICPT systems will deviate from the zero phase angle operation, and the power supply efficiency will change.

C. Variable Frequency Control

In a variable frequency control, the system operation frequency w is adjusted automatically to keep the primary voltage and primary current in phase in order to minimize the VA rating of power supply.

D. Resonant Frequency Control

In an ideal ICPT system, the operation frequency w should follow the secondary resonant frequency w_0 to maximize the power transfer, while the primary capacitance C_p should be adjusted according to (16) to minimize the VA rating of power supply.

In another word, a two variables (w and C_p) control method should be used to complete two tasks, maximizing the power transfer and minimizing the VA rating of power supply.

In a fixed frequency control, the two variable w and C_p are both constant. In a variable frequency control, the operation

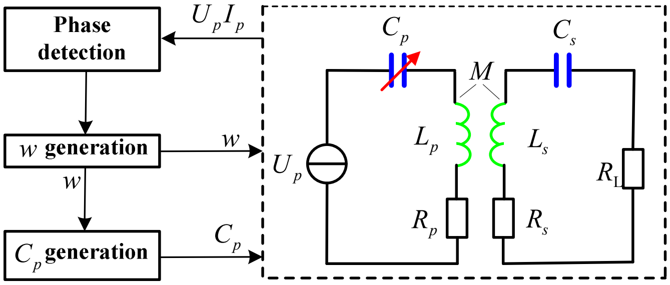

Figure 3. The resonant frequency control of an ICPT system.

frequency w is variable, while the primary capacitance C_p is a constant. In a resonant frequency control, both w and C_p are variable. In general, a more complex control method will get a more robust control performance.

In a resonant frequency control scene, focusing on the imaginary component of the total impedance Z_t in the (7), let

$$C_p = \frac{1}{w^2 L_p}, \tag{18}$$

then the first term in the numerator will be zero. Further, a traditional variable frequency control is used to find the root of (7), and the root is now

$$-w^4 C_p C_s M^2 (w^2 C_s L_s - 1) = 0 . \tag{19}$$

That is

$$w = \frac{1}{\sqrt{C_s L_s}} . \tag{20}$$

In a word, a two variables control method is designed to keep the ICPT system operating at the ideal state.

The resonant control strategy may be implemented by circuits shown in Fig. 3. The phase difference between the primary voltage and current is calculated by the Phase detection module, and then the operation frequency w is generated to reduce the phase difference. C_p is calculated according to (18). In the stable states, w will converge to the secondary resonant frequency w_0. A variable C_p may be implemented as a phase-controlled inductor [9, 10].

III. Results

Two ICPT systems reported in the literature are used to evaluate the performance of three control methods, the resonant frequency control, the variable frequency control, and the fixed frequency control. One ICPT system has a 200kW power [5]; the other system has a 250W power [8]. The parameters of two systems are shown in Table I. The simulation tool is Matlab/Simulink (Mathworks Inc, Natick, MA).

A. A 200kW ICPT System

In a fixed frequency control, the load power is almost unchanged at 200kW when the secondary capacitance changes, Fig. 4. However, the VA rating of power supply increases to 645kW and the system efficiency drops to 31% when the secondary capacitance has a 40% drop. A 645kW VA rating implies that the primary current will be 3.2 times the nominal value, and this current is too high compared to the maximum value that a wire could afford.

TABLE I
Parameters of Two ICPT Systems

Parameters	System A	System B
P_{load}	200kW	250W
f_0	18kHz	100 kHz
L_p	109μH	2800μH
L_s	50.7μH	60μH
M	11.9μH	123μH
C_p	0.72μF	905pF
C_s	1.5μF	42nF
R_p	3.9mΩ	5.7Ω
R_s	2.5mΩ	0.12Ω
R_L	1.25Ω	50Ω

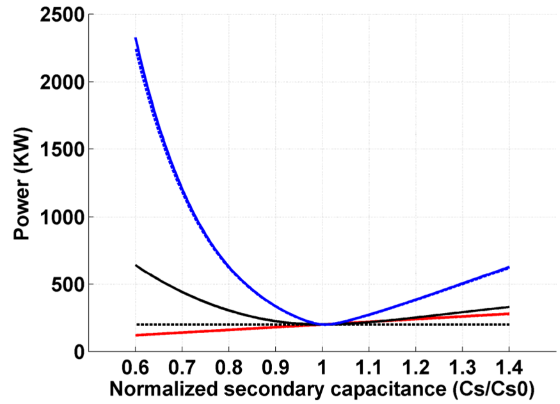

Figure 4. The power transfer capability of a 200kW ICPT system when its secondary capacitance changes. The red, blue, and black lines are simulations of resonant, variable, and fixed frequency control methods, respectively. The solid lines are the VA rating of power supply and the dashed lines are the load power.

A drop of the secondary capacitance C_s will first cause the load impedance Z_s to increase, then Z_r will drop, Z_t will drop further, I_p will increase, so the power supply VA rating will increase.

I_s is related to $Z_t Z_s$. Z_t drops, and Z_s increases, their product is almost unchanged, so the load power is almost unchanged.

In a variable frequency control, the load power is slightly smaller than the power supply, and the system power transfer efficiency is close to 100% when the secondary capacitance changes. However, the VA rating of power supply increases to 2326kW when the secondary capacitance has a 40% drop. A 2326kW VA rating implies that the primary current will be 11.6 times the nominal value, and this current is too high that should be avoided. In this example, the operation frequency w has a 3% change when the secondary capacitance changes. I_p increases because Z_t drops.

In a resonant frequency control, the system power transfer efficiency is also close to 100% when the secondary capacitance changes. However, the VA rating of power supply increases to 281kW when the secondary capacitance has a 40% increase. A 281kW VA rating implies that the primary current will be 1.4 times the nominal value that in general a wire can afford.

A distinguish feature of a resonant frequency control is that the power transfer is an approximately linear function of the secondary capacitance change.

For $R_p << Z_r$ in this example, Z_t is

$$Z_t = R_p + Z_r \approx Z_r \,. \tag{21}$$

The secondary current I_s is

$$I_s = \frac{jwMI_p}{Z_s} = \frac{jwMU_p}{Z_s Z_t} \approx \frac{jwMU_p}{Z_s Z_r} \propto \frac{1}{w} \,. \tag{22}$$

The load power is

$$P_{load} = I_s^2 R_L \propto \frac{1}{w^2} = C_s L_s = kC_{s0} \,. \tag{23}$$

This linear characteristics facilitate a voltage control strategy being used to keep the load power unchanging when the secondary capacitance changes [8].

In this example, the operation frequency w has a 29% change when the secondary capacitance changes.

B. A 250W ICPT System

The key features of three frequency control methods are similar to the 200kW ICPT system mentioned above.

In a fixed frequency control, the load power is almost unchanged at 250W when the secondary capacitance changes, Fig. 5. However, the VA rating of power supply increases to 294W and the system efficiency drops to 85% when the secondary capacitance has a 40% drop.

In a variable frequency control, the system power transfer efficiency is close to 95% when the secondary capacitance changes. However, the VA rating of power supply increases to 340W when the secondary capacitance has a 40% drop. In this example, the operation frequency w has a 1.4% change when the secondary capacitance changes.

In a resonant frequency control, the system power transfer efficiency is also close to 95% when the secondary capacitance changes. However, the VA rating of power supply increases to 361W when the secondary capacitance has a 40% increase. Its power transfer is an approximately linear function of the secondary capacitance change. In this example, the operation frequency w has a 29% change when the secondary capacitance varies.

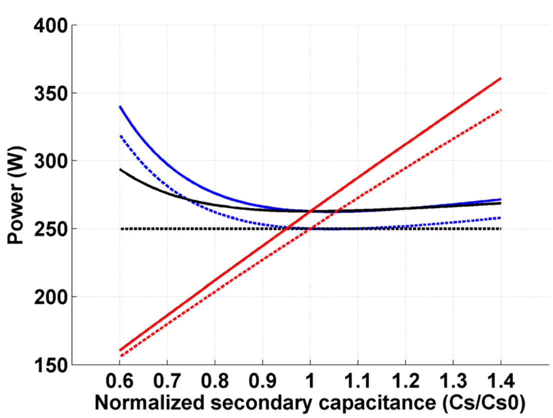

Figure 5. The power transfer capability of a 250W ICPT system when its secondary capacitance changes. Other conventions are the same as Fig. 4.

IV. CONCLUSIONS

The power transfer capability of ICPT systems of three frequency control methods is investigated in detail when the secondary capacitance changes. A distinguish feature of a resonant frequency control is that the power transfer is an approximately linear function of the secondary capacitance change. This linear characteristics facilitate a voltage control strategy being used to keep the load power unchanging when the secondary capacitance varies. One ICPT system adopting a fixed or variable frequency control method shows that the primary current will be three times of nominal values that should be avoided when the secondary capacitance alters.

The power transfer capability of ICPT systems is an intricate function of the operational frequency, and thus resonant operations of the secondary side do not always guarantee maximizing the power transfer. A suitable control mechanism, such as the resonant frequency control, the variable frequency control, or the fixed frequency control, should be designed carefully according to the practical engineering requirement when the secondary capacitance varies.

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