PSS Compensator Topology ICPT Transmission Performance Analysis

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In this paper, power transmission characteristics and main circuit phase angle characteristics of PSS type Inductively Coupled Power Transfer (ICPT) system are analyzed. In general, increasing the resonance frequency of the system can improve the power transmission capability of the system, but output power of PSS compensator topology is found to decrease with increasing resonance frequency. The PSS compensation topology has the feature that can transfer rated voltage with high variation of coefficient of coupling. This paper analyzes the system transmission efficiency and phase angle variation in the voltage range with a constant coupling coefficient. The feasibility of the design method is certified by experimental results.

Keywords: Inductive Coupled Power Transfer; PSS topology; Transmission power; Efficiency

1. Introduction

Inductively coupled power transfer is a contact-less method to transmit electrical energy without any mechanical contact between two magnetic coils. As the system does not have connector, it makes the system more flexible, and avoiding the inconvenience caused by regular plug. At the same time the power transmitting and receiving terminals are not electrically connected, thereby eliminating the common connector caused by arcing, sparks and other fundamental. It can be used at underwater, colliery, electricity, etc. [1-7]. In electric vehicle charging, which solve the requirements of the electricity supply for safety and reliability[8-12]. Thereby it becomes a hot research of domestic and foreign scholars in recent years.

There are still some problems in traditional SS, SP, PS, PP and other ICPT system topology. When the coupling distance changes, the core will offset which led to changes in the coupling coefficient load terminal voltage fluctuations, the stability of the output load is unable to guarantee. PSS compensator topology has a good behavior for the load voltage fluctuation because of the changing of coupling distance and core offset, which can ensure that the changing size of the coupling coefficient rate change at 30% while load voltage does not exceed 5%. PSS compensator topology has obtained more and more research in recent years, but there are not literature to study output characteristics, transmission efficiency and phase angle characteristics when the coupling coefficient change.

In this paper, we will study the ICPT system based on PSS [13,14] compensator topology, analyzes the system transmission efficiency and phase angle variation in the voltage range with a constant coupling coefficient. The feasibility of the design method is certified by the experimental results.

2. PSS adaptability analysis of topology load

Fig. 1 shows the structure of the proposed system using PSS topology. Lp represents the primary coil inductance. Ls represents the secondary coil inductance. M is the mutual inductance between the primary coil and the secondary coil. In primary side, the coil is compensated by two coils: Cps in series and Cpp in parallel. The capacitor Cps is adopted to compensate the leakage inductance. The parallel capacitor can reduce the current rating in main circuit. Lf and Cf are filter inductance and filter capacitor. Lf and Cf can eliminate the high order current harmonics. In secondary side, the capacitor Cs and secondary inductance Ls is connected in series. Capacitor Cs is fully resonance with inductance Ls, and then the reactance of secondary side is zero.

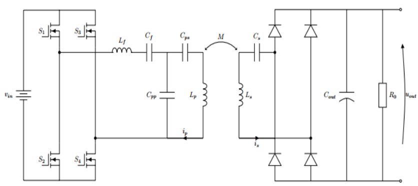

Fig. 1 PSS compensation ICPT system circuit structure

Supposing the resonance angular frequency of the system is ω, secondary pickup coil resistance can be ignored. Under this assumption, in order to achieve maximum power transfer system, the secondary side resonant capacitor selection meets [15,16]:

$$\omega^2 L_s C_s = 1 \tag{1}$$

Based on paper, the value of capacitor C_{ps} in conventional series-series compensation topology named Cpsis determined as follow:

$$C_{ps} = \frac{1}{L_p \omega_0^2} \tag{2}$$

In the proposed topology, we didn't choose Cps as the primary series compensation capacitor, instead, we chooseseries compensation capacitor using principles which can be called 'partly compensate'.

$$C_{ps} = \frac{1}{(1-a) L_p \omega_0^2} \tag{3}$$

where a is an auxiliary parameter and constrained by inequality $0 < a < 1$.Z_p is the winding impedance after partly series compensation. Z_p can be derivedas:

$$\begin{aligned} Z_p &= j\omega_0 L_p + \frac{1}{j\omega_0 C_{ps}} \\ &= j\omega_0 a L_p \end{aligned} \tag{4}$$

where r_p is the parasitic in primary side. It's obvious that Z_p is inductive when using partly compensation capacitor C_{ps}.

$$Z_r = \frac{\omega_0^2 M^2}{R_{eq}} \tag{5}$$

When two coils are exactly in position, the main circuit should be working in ZPA (zero phase angle) condition. Selecting a suitable C_{pp}, we can guarantee that the reactance of Z_{source} is zero. According to (2), (3), (4), (5) C_{pp} will be given by

$$C_{pp} = \frac{aL_p}{(a\omega L_p)^2 + (\frac{\omega^2 M_{max}^2}{R_{eq}})^2} \tag{6}$$

M_{max} is the mutual coupling value (maximum coupling coefficient k). The output voltage is

$$u_{out} = \frac{j\omega_0 M}{\frac{\omega_0^2 M^2}{R_{eq}} + j\omega_0 L_p a} v_{in} \tag{7}$$

Using symmetrical coil $L_p = L_s = L$, coupling coefficient is $k = \frac{M}{\sqrt{L_p L_s}}$, system output power and input power ratio is :

$$P_{out} = \frac{V_{in}^{\ 2}}{\left(\left(\frac{a^2 L_p}{L_s}\right)\left(\frac{1}{k}\right)^2 + \left(\frac{\omega_0\sqrt{L_p L_s}}{\mathrm{R}_{eq}} k\right)^2\right)R} \tag{8}$$

The maximum value of the voltage is

$$G(k)\big|_{\max} = \frac{1}{\sqrt{2bq}} = \sqrt{\frac{\mathrm{R}_{eq}}{2a\omega_0 L_p}} \tag{9}$$

The maximum value of the output power is

$$P_{\max} = \frac{V_{in}^2 R_{eq}}{2\omega^2 L_s^2 k^2} \tag{10}$$

The output voltage out is proportional to G(k) when vin is fixed. Therefore, the ratio of output voltage to its maximum will be equal to the ratio of G(k) to G(k)|max. Through the ratio, output voltage drop when misalignment happens can be investigated. The ratio is defined as

$$H(k) = \frac{u_{out}}{u_{out}\big|_{\max}} = \frac{G}{G_{\max}} = \frac{\sqrt{2k^2}}{\sqrt{k^2 + \frac{k_0^4}{k^2}}} \tag{11}$$

For k < k0, H(k) increases monotonically with increasing in coupling coefficient k. H(k) peaks at k0. H(k) decreases slightly as the coupling coefficient increases continuously. By introducing an auxiliary parameter 0 < ζ < 1, output voltage uout can be designed to be always largerthan ζ · uout|max for a specific coupling range [kmin, kmax]. In this condition, the following inequality should be satisfied

$$\zeta < \sqrt{\frac{2k_0^2}{k^2 + \frac{k_0^4}{k^2}}} \tag{12}$$

$$\delta_k = \frac{k_{mi} - k_{ma}}{k_{ma}} = 1 - \sqrt{\frac{1-\sqrt{1-\zeta^4}}{1+\sqrt{1-\zeta^4}}} \tag{13}$$

To give a better understanding of this, we take k0 = 0.2, ζ = 0.95 as an example. When this set of parameters is given, kmin and kmax are calculated as 0.1588 and 0.2518. That means the output voltage drop will be less than 5% as k varies in [0.1588, 0.2518]. The variation interval of k can up to 36.9% of the total interval when voltageare guaranteed.

3. Characteristics of the phase angle

In this study, we employ a full-bridge as inverter topology and inductive circuit will result in soft switching inverter and better efficiency. The main circuit should be designed to achieve an inductive impedance which means that the AC voltage should lead the inverter current.

When using the compensation capacitors, the real part of Zsource can be calculated as:

$$\Re_{in} = \frac{\omega_0^2 M^2 / R_{eq}}{\left(1-\omega_0^2 a L_p C_{pp}\right)^2 + \left(\omega_0 C_{pp}\right)^2 \left(\omega_0^2 M^2 / R_{eq}\right)^2} \tag{14}$$

the imaginary of Zsource is:

$$\chi_{in} = j\frac{\omega_0 a L_p \left(1-\omega_0 a L_p C_{pp}\right) - \left(\omega_0^2 M^2 / R_{eq}\right)^2 \omega_0 C_{pp}}{\left(1-\omega_0 a L_p C_{pp}\right)^2 + \left(\omega_0 C_{pp}\right)^2 \left(\omega_0^2 M^2 / R_{eq}\right)^2} \tag{15}$$

The phase of the impedance which is given the symbol _x0012_ is determined through the following relations:

$$\theta = \frac{180^o}{\pi} \arctan \frac{\chi}{\Re} \tag{16}$$

Substituting (14) (15) to (16)

$$\theta = \frac{180^o}{\pi} \arctan\left(\frac{k_0^2}{k_0^4 + k_{\max}^4} \frac{k_{\max}^4 - k^4}{k^2}\right) \tag{17}$$

When k0 is equal to 0:2 and kmax is equal to 0:25, phase angle _x0012_ will result in Fig. 7. From the picture we can see that the angle of impedance has been always positive, then, providing a soft switching condition.

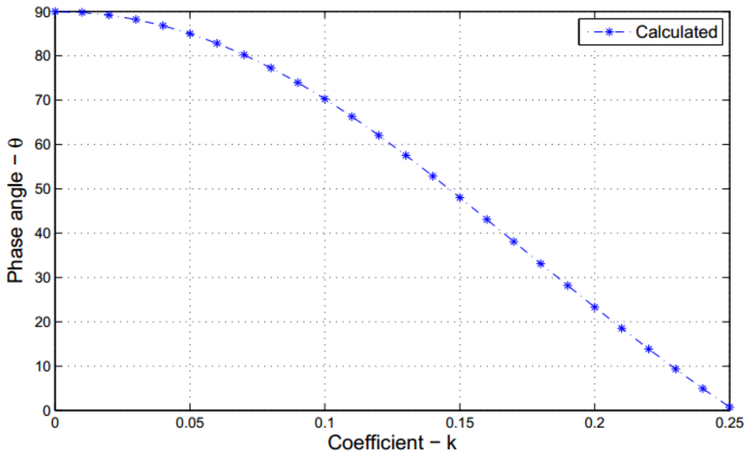

Fig. 2 Phase angle curve with the coupling coefficient

4. Efficiency analysis

System efficiency is a very important aspect of system design. Based on the above analysis, we designed a PSS compensation ICPT system, experimental apparatus are shown in Fig. 3.

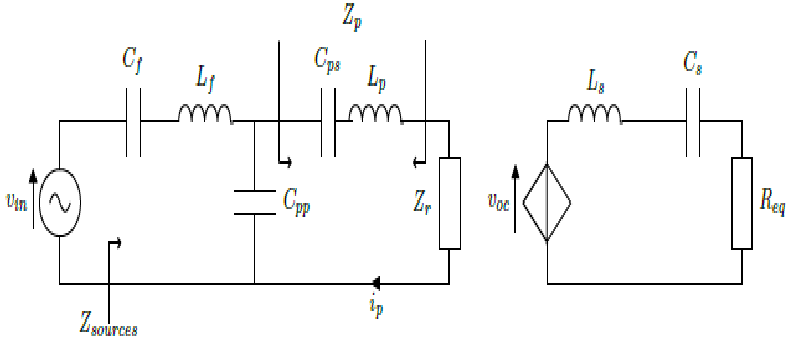

Fig. 3 System equivalent circuit

The total power losses caused by parasitic can be calculated as:

$$P_{loss} = I_0^2 r_0 + I_1^2 r_1 + I_p^2 r_p + I_s^2 r_s \tag{18}$$

The output power can be expressed as

$$P_{out} = I_s^2 R_{eq} \tag{19}$$

$$\left|\frac{I_1}{I_p}\right| \approx \left|\frac{Z_r + j\omega_0 a L_p}{\frac{1}{j\omega_0 C_{pp}}}\right| = \frac{k_0^2}{k_0^4 + k_{max}^4}\sqrt{k_0^4 + k^4} \tag{20}$$

$$\left|\frac{I_s}{I_p}\right| \approx kq \left|\frac{I_0}{I_p}\right| = \left|\frac{I_1 + I_p}{I_p}\right| \tag{21}$$

Considering only parasitic resistance loss, the efficiency of the system η can be calculated as

$$\eta = \frac{P_{out}}{P_{loss} + P_{out}} \tag{22}$$

$$\eta = \frac{(kq)^2 R_s}{(R_s + r_s)(\mathrm{kq})^2 + (\frac{k_0^2}{k_0^4 + k_{\max}^4}\sqrt{k_0^4 + k^4})^2 r_1 + r_p + (1 + \frac{k_0^2}{k_0^4 + k_{\max}^4}\frac{k_0^2}{k_0^4 + k_{\max}^4})^2 r_0} \tag{23}$$

5. Experimental results and analysis

5.1 Experimental platform

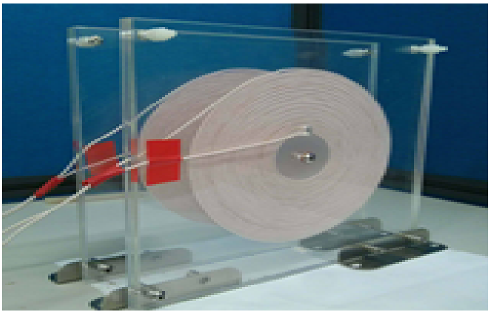

Fig. 4 Experimental Device

5.2 Efficiency analysis

The measured and simulated output voltage when lateral misalignment x varies are illustrated in Fig. 5. The air gap between two coils is maintained at 40mm for different lateral misalignment x. As shown in the experimental curves, the output voltage slightly increases and arrives its maximum value with a lateral misalignment of 30mm. It is worth nothing that the maximum lateral misalignment can be up to 30% of coil diameter D showing a good position tolerance and validating the applicability of the proposed concept.

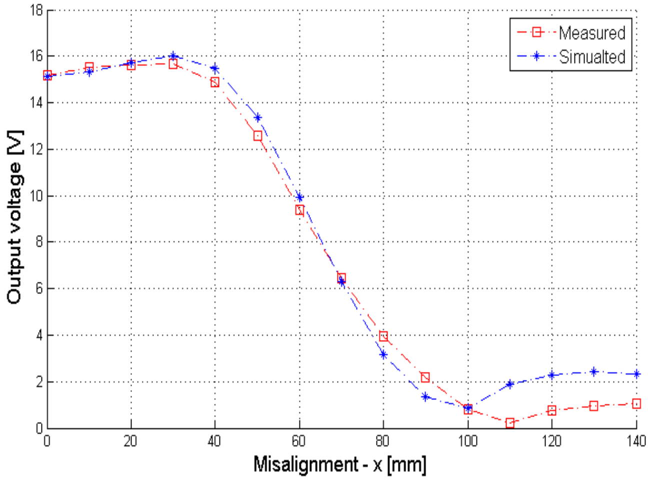

Fig. 5 Output voltage with different lateral misalignment

When the system input voltage is 48V, PSS compensation topology ICPT system efficiency curve under different coil distance is shown in Fig. 6. We can learn from the graph, when the coil distance is small, the system has high efficiency. When the eccentric distance of the coil is less than 20mm, the efficiency is always above 90%. When the coil eccentric distance continues to increase, the efficiency decreases quickly, as magnetic loss, resonant capacitor and the coil resistance loss are increasing.

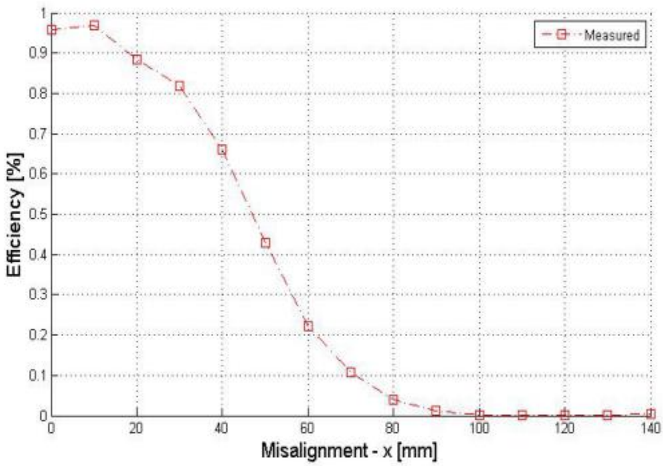

Fig. 6 Transmission efficiency with different lateral misalignment

6. Conclusion

In this paper, we studied the ICPT system based on PSS compensator topology, analyzes the system transmission efficiency and phase angle variation in the voltage range with a constant coupling coefficient. From our invitagation verified by experimental results, we are able to confirmed that

1) The maximum output is determined by compensation factor and resonance frequency;
2) Impedance phase angle is always positive when the coupling coefficientchanges within a certain range, providing a soft switching condition. It can reduce the loss of power devices, the resonance element and transformer coils.
3) Voltage gain increases with the resonant frequency decreasing, the transmission efficiency of the system increases with the resonance frequency increasing, and the system resonance frequency exists an optimal value.

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