Design Method for Optimal Diameter-to-Distance Ratio of Loosely Coupled Coils in ICPT Systems (Postprint)

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Date: 2019-03-05T00:00:00+00:00

Abstract

In traditional Inductively Coupled Power Transfer (ICPT) systems, the optimal proportionality coefficient between the radius of the receiving coil Rx of a loosely coupled transformer and the distance h between the transmitting coil Tx and receiving coil Rx—namely, the determination of the radius-to-distance ratio —is obtained through system modeling to derive the mutual inductance value between Tx and Rx, supplemented by extensive experiments. To address this issue of lacking theoretical basis and wasting human and material resources, this paper proposes a design method to obtain the optimal value of the proportionality coefficient between Rx radius and h by observing the variation pattern of current density in Rx through simulation. First, the decoupled equivalent circuit model of the system under the primary-parallel, secondary-parallel (PP) configuration of a single-switch ICPT system is derived; based on this, the relationship between the current density on Rx, mutual inductance M, and system transmission power is derived; and through formula analysis, the values of the ratio a between Rx inductance L1 and Tx inductance L2 and the system coupling coefficient are determined to establish the values of L1 and L2 at different frequencies, thereby establishing a simulation model and using finite element simulation software to investigate the optimal value of . Compared with the method of optimizing coils through coil mutual inductance values, the current density in this paper can be directly observed through software, which is visual and intuitive, saving time and cost, and effectively improving design efficiency. The comprehensive simulation results determine the optimal radius-to-distance ratio for loosely coupled coils, which is consistent with the empirical value summarized by enterprises through production practice.

Full Text

Preamble

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Abstract

In traditional Inductively Coupled Power Transfer (ICPT) systems, the optimal ratio coefficient between the radius of the receiving coil (Rx) of a loosely coupled transformer and the distance (h) between the transmitting coil (Tx) and receiving coil (Rx)—known as the radius-center distance ratio —is typically obtained through system modeling to derive the mutual inductance value between Tx and Rx, supplemented by extensive experiments. This approach lacks theoretical foundation and wastes manpower and material resources. To address this problem, this paper proposes a design method that obtains the optimal radius-center distance ratio by simulating and observing the variation patterns of current density in Rx. First, the decoupled equivalent circuit model of a single-switch inverter ICPT system with primary-parallel and secondary-parallel (PP) compensation structure is derived. Based on this model, the relationship among current density, mutual inductance M, and system transmission power is established. Through formula analysis, the ratio of Rx inductance L to Tx inductance L (denoted as a) and the system' s coupling coefficient are determined to obtain L and L values at different frequencies, thereby establishing a simulation model to investigate the optimal value using finite element simulation software. Compared with coil optimization methods based on mutual inductance values, the current density approach proposed in this paper can be directly observed through software, providing vivid and intuitive visualization while saving time and cost and effectively improving design efficiency. The comprehensive simulation results determine the optimal radius-center distance ratio for loosely coupled coils, which aligns with empirical values summarized from production practice.

Keywords: Single-switch inverter, Inductively Coupled Power Transfer, radius-center distance ratio, current density, finite element simulation

1 Introduction

In recent years, Inductively Coupled Power Transfer (ICPT) technology has become a research hotspot among scientists and has been successfully applied in wireless power supply for smart appliances, electric vehicle wireless charging, and in-vivo biomedical charging [1-5]. As a key component in ICPT systems, the structure and parameters of loosely coupled transformers directly affect system volume and transmission power [6-9]. Currently, research on the radius-center distance ratio of loosely coupled transformers in inductive coupling systems is insufficient domestically and internationally, with parameters obtained only through empirical values from production practice lacking theoretical analysis and validation. Therefore, this paper builds upon the single-switch inverter ICPT system topology studied by our research group [10-12]. First, the corresponding relationship between current density in Rx and mutual inductance value is derived, and the optimal radius-center distance ratio of loosely coupled coils is investigated from the perspective of the relationship between mutual inductance and system voltage gain and transmission power.

2 Single-Switch ICPT System Structure

The topology of the single-switch inverter ICPT system is shown in [Figure 1: see original paper]. In the diagram, Cp and Cp1 are primary-side compensation capacitors, while Cs and Cs1 are secondary-side compensation capacitors. When Cp is connected to the circuit, the primary side employs parallel compensation; when Cp1 is connected, the primary side employs series compensation. Similarly, when Cs is connected, the secondary side employs parallel compensation; when Cs1 is connected, the secondary side employs series compensation. This configuration allows four compensation topologies: primary-parallel secondary-parallel (PP), primary-parallel secondary-series (PS), primary-series secondary-parallel (SP), and primary-series secondary-series (SS).

This paper first studies the minimum value of using the PP compensation method shown in [Figure 1: see original paper], then extends the analysis to the other three compensation methods and subsequently to half-bridge and full-bridge circuits. [Figure 2: see original paper] illustrates the equivalent circuit model for PP compensation, where Figure 2a shows the primary-side equivalent model and Figure 2b shows the secondary-side equivalent model. The AC220V/50Hz mains voltage, after full-bridge rectification and filtering by L1 and C1, can be regarded as a constant voltage source Ucp. Zf represents the impedance reflected from the secondary side to the primary side. In the secondary-side equivalent model, Uoc is the induced electromotive force in the secondary side. For other topologies such as full-bridge, half-bridge, and push-pull circuits [13], the equivalent circuit during switching processes remains the same as shown in [Figure 2: see original paper].

By obtaining the steady-state equivalent model and applying decoupling equivalent principles, the primary-side impedance is:

$$Z_1 = R_P + j\omega L_P$$

The impedance reflected from the secondary side to the primary side is:

$$\frac{\omega^2 M^2}{Z_2}$$

where Z is the secondary-side impedance:

$$Z_2 = R_S + j\omega L_S + \frac{R_{eq}}{1 + j\omega C_S R_{eq}} = R_S + \frac{1}{1 + \omega^2 C_S^2 R_{eq}^2} + j\left(\omega L_S - \frac{\omega C_S R_{eq}^2}{1 + \omega^2 C_S^2 R_{eq}^2}\right)$$

Since the system' s resonant angular frequency   is relatively large, the internal resistance of the secondary-side coil R can be neglected.

The voltage across the primary-side compensation capacitor is:

$$U_{Cp} = \frac{U_{oc}}{Z_1 + Z_f}$$

The current density on Rx is:

$$\rho = \frac{I_{Ls}}{A}$$

where U_{Rl} is the RMS output voltage, U_{Ls} is the RMS AC voltage after the resonant network, I_{Ls} is the RMS input current to the rectifier network from Rx, and A is the cross-sectional area of one turn of the Rx coil. The formula shows that   is directly proportional to P_{PP}, meaning   is directly proportional to M. Since   is positively correlated with M, and M directly affects system transmission power and efficiency, simulation of current density for Rx coils of different specifications can be used to investigate the minimum   value for magnetically coupled coils.

3 Minimum Value of

3.1 System Parameter Selection

The primary-side resonant angular frequency is:

$$\omega_1 = \frac{1}{\sqrt{L_P C_P}}$$

The secondary-side resonant angular frequency is:

$$\omega_2 = \frac{1}{\sqrt{L_S C_S}}$$

The voltage gain can be derived as:

$$M_v = \frac{j\omega M}{Z_2 - j\omega L_S} \cdot \frac{Z_2}{Z_1 + Z_f}$$

For analysis convenience, the load output power is approximated as equal to the system transmission power:

$$P_{PP} = \frac{R_{eq}M^2}{(\omega L_P L_S - \omega M^2)^2 + R_{eq}^2 M^2}$$

The system efficiency is:

$$\eta = \frac{Re(Z_2)I_P^2}{(Re(Z_2) + R_P)I_P^2} = \frac{1}{1 + \frac{R_P}{Re(Z_2)}} = \frac{1}{1 + \frac{Re(Z_f)}{R_P} \cdot \frac{R_P}{\omega^2 M^2}}$$

where Q is the system quality factor. Based on the characteristics of this system, Q = 0.9 is selected. Let a denote the ratio of Tx inductance L_P to Rx inductance L_S, i.e., a = L_P/L_S. Substituting a into the equations yields the variation curves of voltage gain M_v and power P with respect to a, as shown in [Figure 3: see original paper]. Since this system has high output power and requires high voltage gain, a = 4 is selected.

To determine the optimal value, the transmission distance h should be optimized. According to ICPT system characteristics, the coupling coefficient typically ranges from 0 to 0.5, but in practical applications, is typically 0.2 to 0.3. Therefore, this paper calculates system parameters at frequencies of 200 kHz, 500 kHz, 800 kHz, 1000 kHz, and 1500 kHz for = 0.2 and = 0.25 to investigate the optimal value, as shown in .

3.2 Relationship Between and Mutual Inductance M

The radius-center distance ratio of the loosely coupled coils in the system is:

$$\gamma = \frac{D}{h}$$

where D is the radius of Rx. Applying Neumann' s formula:

$$M = \mu_0 N_1 N_2 \sqrt{D_1 D_2} \left[\left(\frac{2}{b} - b \right) K(b) - \frac{2}{b} E(b) \right]$$

where D is the radius of Tx, D is the radius of Rx, and b, K(b), and E(b) are defined as:

$$b = \frac{2\sqrt{D_1 D_2}}{(D_1 + D_2)^2 + h^2}$$

$$K(b) = \int_0^{\pi/2} \frac{d\theta}{\sqrt{1 - b^2 \sin^2 \theta}}$$

$$E(b) = \int_0^{\pi/2} \sqrt{1 - b^2 \sin^2 \theta}\, d\theta$$

Substituting these into the mutual inductance equation yields the variation curve of M with respect to , as shown in [Figure 4: see original paper]. The results indicate that to achieve maximum mutual inductance and system power, the value corresponding to maximum mutual inductance approaches 1.3 to 1.5 as the switching frequency increases. This suggests that the optimal radius-center distance ratio should be in the range of 1.3 to 1.5.

4 Simulation Results

4.1 Relationship Between and M

To analyze and verify the correspondence between current density on Rx and mutual inductance M, the mutual inductance value between coils can be obtained using the calculation tool in finite element simulation software. The simulation results are shown in [Figure 5: see original paper]. Figures 5a and 5b illustrate the variation of and M on an Rx coil with outer diameter 9 cm and inner diameter 7 cm as Tx dimensions change. In Figure 5b, redder colors indicate larger mutual inductance values, and the Tx dimensions corresponding to the red region represent the optimal Tx size matched with Rx. To further verify the relationship between coil current density and mutual inductance, an additional comparison was made for an Rx coil with outer diameter 9 cm and inner diameter 5 cm, as shown in Figures 5c and 5d. The variation trends remain consistent. By comparing the current density on the Rx coil and the mutual inductance of the magnetically coupled coils with changing Tx coil dimensions, it is found that the Tx dimensions corresponding to both the minimum and maximum values of current density and mutual inductance are identical. This confirms that as Tx dimensions change, the current density on Rx and the mutual inductance variation trends are consistent, thereby verifying the proportional relationship between and M through simulation.

4.2 Relationship Between and M

For the value, under a fixed coupling coefficient, when is constant, the transmission distance h varies with coil radius D while maintaining a constant ratio . To determine the minimum value, the coil radius D is fixed and the distance between coils is varied until the system operates normally at the farthest transmission distance. At this point, reaches its minimum value. Using finite element simulation software with parameters from , where the Rx coil has an outer diameter of 11 cm, inner diameter of 9 cm, and average radius of 10 cm, the farthest transmission distance at which the inter-coil mutual inductance meets the required value for normal system operation was obtained, and was calculated.

As shown in , for the same coupling coefficient, the transmission distance h increases while decreases with increasing frequency. Under the same frequency, a smaller coupling coefficient results in a longer transmission distance. The optimal value is approximately 1.33, which basically matches the values obtained in [Figure 5: see original paper].

5 Conclusions

This paper proposes a design method to obtain the minimum value by simulating and observing the variation patterns of current density in Rx. The conclusions are as follows:

1. This method is applicable to various primary-secondary compensation structures in full-bridge, half-bridge, push-pull, and single-switch inverter ICPT systems.
2. For ICPT systems, under the condition of Rx radius and transmission distance, the farthest transmission distance between the two coils is 1.33 times the Rx radius.
3. The optimized parameters obtained by the proposed design method basically match the results summarized from enterprise experiments and have been successfully applied in a Qingdao-based enterprise producing wireless charging products, demonstrating promising prospects for broader application.

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Note: Figure translations are in progress. See original paper for figures.