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

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Abstract

In traditional Inductive Coupled Power Transfer (ICPT) systems, the determination of the optimal proportionality coefficient between the radius of the receiver coil Rx of a loosely coupled transformer and the distance h from the transmitter coil Tx to the receiver coil Rx, namely the radial-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 manpower and material resources, this paper proposes a design method for obtaining the optimal value of the proportionality coefficient between the radius of Rx and h by observing the variation patterns of current density in Rx through simulation. First, the decoupled equivalent circuit model of the system under the primary-parallel, secondary-parallel (PP) structure of a single-tube ICPT system is obtained, based on which the relationship between the current density on Rx and the mutual inductance M and system transmission power is derived; and through formula analysis, the values of the ratio a between the inductance L1 of Rx and the inductance L2 of Tx and the coupling coefficient of the system are determined to establish the values of L1 and L2 at different frequencies, thereby establishing a simulation model and utilizing 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 intuitive and visual, saving time and cost, and effectively improving design efficiency. The comprehensive simulation results determine the optimal radial-distance ratio for loosely coupled coils, and this parameter matches the empirical value summarized by enterprises through production practice.

Full Text

A Design Method for the Optimal Radius-to-Distance Ratio of Loosely Coupled Coils in ICPT Systems

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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) and the distance (h) between the transmitting coil (Tx) and receiving coil—known as the radius-to-distance ratio —is typically determined through system modeling to derive the mutual inductance between Tx and Rx, supplemented by extensive experimental validation. This approach lacks theoretical foundation and consumes significant manpower and material resources. To address this limitation, this paper proposes a design methodology that obtains the optimal radius-to-distance ratio by simulating and observing the variation patterns of current density in Rx.

First, a decoupled equivalent circuit model is established for a single-switch inverter ICPT system with primary-parallel and secondary-parallel (PP) compensation topology. Based on this model, the relationship among current density, mutual inductance M, and system transmission power is derived. Through formula analysis, the ratio a between Rx inductance L and Tx inductance L , along with the system coupling coefficient , are determined to establish the values of L and L at different frequencies. A simulation model is then constructed to investigate the optimal value of using finite element analysis 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 visualization, providing an intuitive and efficient means to reduce design time and costs while improving overall design efficiency. The comprehensive simulation results determine the optimal radius-to-distance ratio for loosely coupled coils, which aligns with empirical values derived from industrial production practice.

Keywords: Single-switch inverter, Inductively coupled power transfer, Radius-to-distance ratio, Current density, Finite element simulation

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1 Introduction

In recent years, inductively coupled power transfer (ICPT) technology has become a focal point of research and has been successfully applied in various fields, including wireless power supply for smart appliances, electric vehicle charging, and biomedical implantable devices. As a critical component in ICPT systems, the structure and parameters of loosely coupled transformers directly affect system volume and power transmission capability. However, current research both domestically and internationally lacks systematic investigation into the radius-to-distance ratio of loosely coupled transformers in inductive coupling systems, with existing parameters derived primarily from empirical production experience without theoretical analysis or validation.

To address this gap, this paper leverages the single-switch inverter ICPT system topology studied by our research group. The relationship between current density in Rx and mutual inductance magnitude is first derived, and the optimal radius-to-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 represent primary-side compensation capacitors, while Cs and Cs1 represent secondary-side compensation capacitors. When Cp is connected, 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 enables four compensation modes: primary-parallel secondary-parallel (PP), primary-parallel secondary-series (PS), primary-series secondary-parallel (SP), and primary-series secondary-series (SS).

This paper first investigates the optimal value using the PP compensation mode shown in [Figure 1: see original paper], with subsequent extension to the other three compensation modes and 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 input voltage, after full-bridge rectification and filtering by L1 and C1, can be considered a constant voltage source Ucp. Zf represents the impedance reflected from the secondary side to the primary side. In the secondary-side equivalent model shown in Figure 2b, Uoc represents the induced electromotive force in the secondary side. For other topologies such as full-bridge, half-bridge, and push-pull circuits, the equivalent circuit during switching transitions remains identical to that shown in [Figure 2: see original paper].

By deriving the steady-state equivalent model and applying decoupling equivalent principles, the primary-side impedance is Z1 = RP + j LP. The impedance reflected from the secondary side to the primary side is $^2M^2/Z2$, where Z2 represents the secondary-side impedance:

$$Z2 = RS + j\ LS + 1/(j\ CS) = RS + 1/(1+\ ^2CS) + j(\ LS -\ CSReq/(1+\ ^2CS))$$

Due to the high resonant angular frequency of the system, the internal resistance RS of the secondary-side coil can be neglected. The current density on Rx is given by:

$$= ILs/A = (URl/RLM)/A = (Uoc \cdot\ M/(\ LPLS -\ M^2) \cdot RLM)/A$$

where URl is the RMS output voltage, ULs is the RMS AC voltage after the resonant network, ILs 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. This expression demonstrates that is directly proportional to PPP, and consequently, 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 employed to investigate the optimal value for magnetically coupled coils.

3 Minimum Value of

3.1 System Parameter Selection

The primary-side resonant angular frequency is $= 1/\sqrt{}(LpCp)$, and the secondary-side resonant angular frequency is $= 1/\sqrt{}(LsCs)$. The voltage gain is:

$$Mv = j\ M(Z2 - j\ LS)/[Z2(Z1 + Zf)]$$

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

$$PPP = ReqM^2/(\ LPLS -\ M^2)^2$$

The system efficiency is:

$$= Re(Z2)Ip^2/[(Re(Z2) + Rp)Ip^2] = 1/[1 + Rp/Re(Z2)] = 1/[1 + Re(Zf)Rp/(\ ^2M^2)]$$

where Q represents the system quality factor, which is taken as Q = 0.9 based on system characteristics. Letting a denote the ratio of Tx inductance Lp to Rx inductance Ls (a = Lp/Ls), and substituting a into the equations for voltage gain and power yields the variation curves shown in [Figure 3: see original paper]. Given the high output power requirement of this system and the need for high voltage gain, the parameter a is selected as 4.

To determine the optimal radius-to-distance ratio , the transmission distance h should be optimized. According to ICPT system characteristics, the coupling coefficient typically ranges from 0 to 0.5, though practical applications require

0.2–0.3. Therefore, this paper investigates the optimal value at frequencies of 200 kHz, 500 kHz, 800 kHz, 1000 kHz, and 1500 kHz for values of 0.2 and 0.25, as summarized in .

3.2 Relationship Between and Mutual Inductance M

The radius-to-distance ratio for loosely coupled coils in the system is defined as = D/h, where D is the radius of Rx. Applying Neumann’ s formula, the mutual inductance is:

M = N N √(D D)[(2/b - b)K(b) - (2/b)E(b)]

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

b = 2√(D D)/√((D + D)^2 + h^2)
K(b) = ^{ /2} (1 - b^{2}sin^2)^{-1/2} d
E(b) = ^{ /2} (1 - b^{2}sin^2)^{1/2} d

Substituting these expressions yields the mutual inductance M as a function of , as shown in [Figure 4: see original paper]. The results indicate that to achieve maximum mutual inductance and system power, the optimal value corresponding to maximum mutual inductance approaches 1.3–1.5 as the switching frequency increases, suggesting that the optimal radius-to-distance ratio should be in the range of 1.3–1.5.

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4 Simulation Results

4.1 Relationship Between Current Density and Mutual Inductance M

To analyze and verify the correspondence between current density on Rx and mutual inductance M, the mutual inductance between coils is obtained using the built-in calculation tool in finite element simulation software. The simulation results are presented in [Figure 5: see original paper]. Figures 5a and 5b show the variation of and M with Tx dimensions for an Rx coil with outer diameter 9 cm and inner diameter 7 cm. In Figure 5b, redder colors indicate larger mutual inductance values, with the red region corresponding to the optimal Tx size matching the Rx coil. To further validate the relationship, an additional comparison is made for an Rx coil with outer diameter 9 cm and inner diameter 5 cm, as shown in Figures 5c and 5d, revealing consistent variation trends. The comparison demonstrates that the Tx dimensions corresponding to minimum and maximum current density on Rx coincide with those for minimum and maximum mutual inductance, respectively. This simulation validates the proportional relationship between and M.

4.2 Relationship Between and M

For 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 established and the distance between coils is varied to find the maximum transmission distance at which the system operates normally. This yields the 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 maximum transmission distance achieving required mutual inductance for normal system operation is obtained, and is calculated.

As shown in , for a given coupling coefficient, the transmission distance h increases with frequency while decreases. At the same frequency, a smaller coupling coefficient results in greater transmission distance. The optimal value is approximately 1.33, which aligns well with the range indicated in [Figure 5: see original paper].

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5 Conclusion

This paper proposes a design methodology for determining the minimum value by simulating and observing current density variation patterns in Rx, yielding the following conclusions:

1. The proposed 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, the maximum transmission distance between coils is approximately 1.33 times the radius of the Rx coil.
3. The optimized design parameters obtained through this method align with empirical results from industrial experiments and have been successfully implemented by a wireless charging product manufacturer in Qingdao, demonstrating significant potential for broader application.

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