

High-Tolerance Inductive Power Transfer System Based on Parallel Dual-Channel Hybrid Topology

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To significantly enhance the misalignment resistance of the wireless charging system, a high-tolerance inductive power transfer (IPT) based on parallel dual-channel transmission hybrid topology is proposed. Firstly, LCC/S and LCC/LCC configurations are utilized to form an input-parallel-output-parallel hybrid topology, which constitutes the dual-channel constant current output of the system. The output currents are superimposed to improve the system's misalignment tolerance characteristics. Additionally, the adjustment factor is introduced to regulate the output gain of the LCC/S configuration. Then, the Velocity-Controlled Particle Swarm Optimization (VCPSO) algorithm is employed to optimize the fitness function and determine the optimal adjustment factor that minimizes the output current fluctuation under a misalignment of 140mm. Finally, the simulation and experimental results demonstrate that the maximum fluctuation of the output current does not exceed 7% when the system is misaligned by 50% of its dimensions.

Index Terms—Wireless power transmission, Hybrid topology, Constant current.

I. INTRODUCTION

Inductive power transfer (IPT), leveraging its technical strengths of high power and efficiency, is well-suited for electric vehicle (EV) charging^[1]. However, during the wireless charging of EVs, coil misalignment inevitably occurs, leading to significant reductions in output current and power. Traditional hybrid topologies can output currents with misalignment tolerance, but they only allow for a mutual inductance variation range of 0%-50% between coils, placing stringent requirements on coil parameters and hybrid compensation topology design^[2]. Therefore, this paper proposes an IPT system based on a dual-channel transmission hybrid topology. By introducing an adjustment factor to regulate the output gain of the LCC/S, the system achieves higher misalignment tolerance and constant current output characteristics, effectively solving the issue of output current fluctuation during system misalignment

and M_{s1s2} are nearly zero. Therefore, the hybrid topology proposed in this paper can be divided into two energy channels LCC/S and LCC/LCC discussed separately.

1) LCC/S Energy Transmission Channel

Using Kirchhoff's Laws, the currents in the LCC/S energy transfer channel under the conditions of satisfying $A_{cc}=0$ and $B_{cc}=0$ can be calculated as

$$I_{f1} = -\frac{U_{AB}R_{eq}(C_{f1}C_{p1}L_{p1}\omega^2 - C_{p1} - C_{f1})}{(\omega^2C_{f1}L_{f1} - 1)\omega^2C_{p1}M_{p1s1}^2} \quad (1)$$

$$I_{s1} = \frac{U_{AB}}{j(\omega^2C_{f1}L_{f1} - 1)\omega M_{p1s1}} \quad (2)$$

in which

$$A_{cc} = \alpha + \omega^2C_{p1}L_{f1} - \alpha\omega^2C_{p1}L_{p1} \quad (3)$$

$$B_{cc} = C_{p1}(1 - \omega^2L_{p1}C_{f1}) + C_{f1}(1 - \omega^2L_{s1}C_{s1}) + D_{cc} \quad (4)$$

$$D_{cc} = \omega^2C_{p1}C_{s1}(\omega^2M_{p1s1}^2C_{f1} - L_{s1} + \omega^2L_{s1}L_{p1}C_{f1}) \quad (5)$$

According to equation (2), the output current does not vary with changes in the load, achieving a constant current output independent of the load. Additionally, the output gain is inversely proportional to the variation in equivalent mutual inductance.

2) LCC/LCC Energy Transmission Channel

The currents can be calculated using Kirchhoff's Laws, when the LCC/LCC compensation topology satisfies as

$$\omega = \sqrt{\frac{C_{f2} + C_{p2}}{L_{p2}C_{f2}C_{p2}}} = \sqrt{\frac{L_{f2}C_{f2}}{L_{p2}C_{f2}C_{p2}}} = \sqrt{\frac{C_{s2} + C_r}{L_{s2}C_{s2}C_r}} = \sqrt{\frac{L_rC_r}{L_{s2}C_{s2}C_r}} \quad (6)$$

$$I_{f2} = \frac{M_{p2s2}^2R_{eq}U_{AB}}{\omega^2L_{f2}^2L_r^2} \quad (7)$$

$$I_r = \frac{M_{p2s2}U_{AB}}{j\omega L_{f2}L_r} \quad (8)$$

Obviously, as indicated by equation (8), the output current is independent of the load and is directly proportional to the equivalent mutual inductance M_{p2s2} .

II. DESIGN OF HIGH-TOLERANCE IPT SYSTEM

A. Design of Parallel Dual-Channel Hybrid Topology

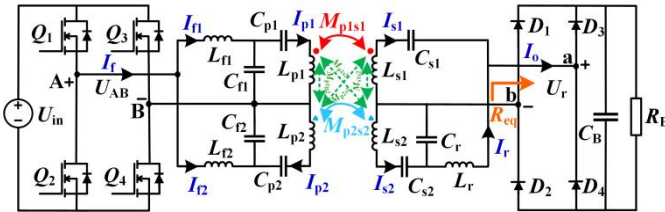


Fig. 1. Schematic diagram of the proposed hybrid topology circuit

The schematic diagram of the proposed parallel dual-channel hybrid topology is shown in Fig. 1. The input of the primary-side compensation topology and the output of the secondary-side compensation topology both adopt parallel connection forms. Two mutually perpendicular electromagnetic coils are adopted on both the primary and secondary sides. Since mutually perpendicular electromagnetic coils do not pass magnetic flux through each other, the equivalent mutual inductances M_{p1p2} , M_{p1s2} , M_{p2s1} ,

Therefore, the output current of the hybrid topology shown in Figure 1 can be expressed as

$$I_o = \frac{U_{AB}}{j(\omega^2 C_{fl} L_{fl} - 1)\omega M_{p1s1}} + \frac{M_{p2s2} U_{AB}}{j\omega L_{f2} L_r} \quad (9)$$

If the coils are misaligned in the secondary side, the output gains of the two compensation topologies will be directly and inversely proportional to the equivalent mutual inductance, respectively. Compared with traditional hybrid topologies, the output gain of the LCC/S can be mitigated using $(\omega^2 C_{fl} L_{fl} - 1)$ to slow down the change in output gain when the coil misalignment is excessive. Therefore, the proposed parallel dual-channel hybrid topology can prevent the output gain of the LCC/S from becoming too large and losing its high misalignment tolerance.

B. The Optimization of magnetically coupled structures

To eliminate the impact of equivalent mutual inductances M_{p1p2} , M_{p1s2} , M_{p2s1} , and M_{s1s2} on the system, parametric optimization of the magnetically coupled structure was conducted, as shown in Fig. 2.

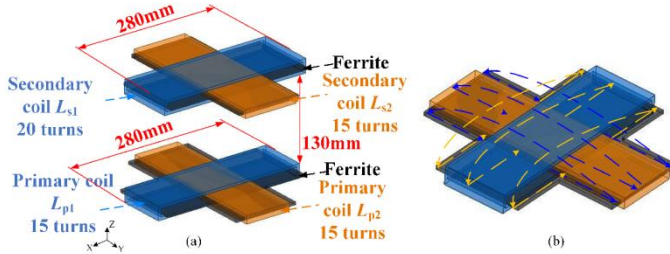


Fig. 2. (a) The proposed magnetic coupled structure with decoupling characteristics (b) Magnetic flux distribution of two mutually perpendicular solenoid coils.

To effectively regulate the output gain of the LCC/S compensated topology and enhance the system's output misalignment tolerance, the adjustment factor ρ is introduced as

$$\rho = \omega^2 C_{fl} L_{fl} - 1 \quad (10)$$

Then the output offset current can be set as

$$\Delta I_o = \frac{\Delta M_{p2s2} U_{AB}}{\omega L_{f2} L_r} - \frac{\Delta M_{p1s1} U_{AB}}{\rho \omega M_{p1s1} (M_{p1s1} - \Delta M_{p1s1})} \quad (11)$$

To obtain a suitable adjustment factor ρ and make (11) as small as possible, the VCPISO algorithm is used to optimise ρ , the flow chart is shown in Fig. 3.

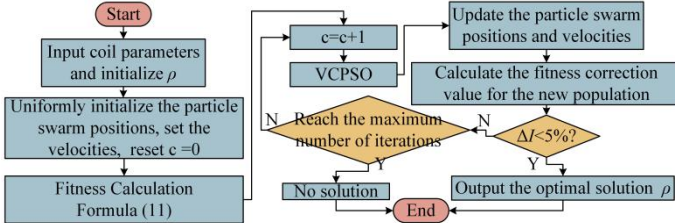


Fig. 3. Flowchart for optimization of adjustment factor based on VCPISO

III. RESULTS AND DISCUSSION

To verify the misalignment-resistant property of the proposed high-tolerance IPT system, the experimental platform is constructed with the coil misalignment range of 0 mm to 140 mm, as shown in Fig. 4.

From Fig. 5(a) and Fig. 5(b), the output current changes by 4.28% when the mutual inductance of the system coil changes by 79.6%. From Fig. 5(c), the output current fluctuates by 4.12% and the maximum fluctuation is 6.57%, with system misalignment of 140 mm and 79.6% variation in mutual inductance M_{p1s1} and M_{p2s2} . Additionally, the output current fluctuates by 7.82% when the load R_B changes from 3Ω to 15Ω. Therefore, the proposed high-tolerance IPT system achieves constant current output with high misalignment tolerance.

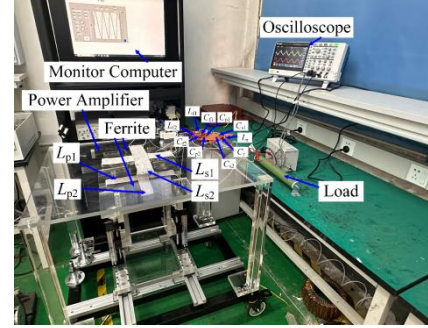


Fig. 4. The experimental prototype of IPT system proposed in this paper

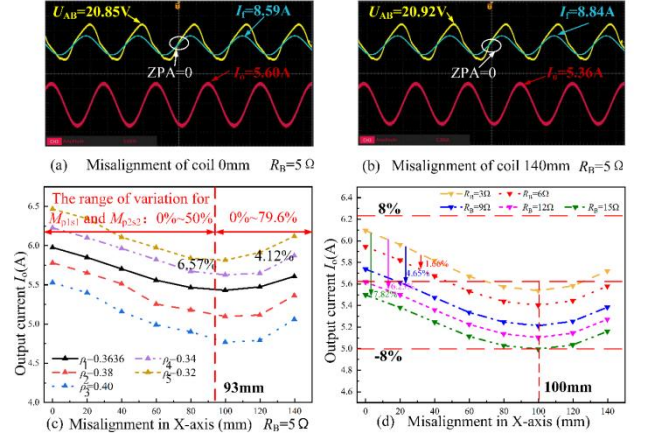


Fig. 5. (a) System voltage and current values for 0% change in M_{p1s1} , M_{p2s2} (b) System voltage and current values for 79.6% change in M_{p1s1} , M_{p2s2} (c) Output current of different adjustment factors during coil misalignment (d) Output current of different loads during coil offset.

IV. CONCLUSION

This paper proposes a parallel dual-channel hybrid topology that adjusts the output current gain of the LCC/S topology by incorporating an adjustment factor. This enhancement expands the allowable range of equivalent mutual inductance variation in the system from 50% to 79.6%, achieving a high degree of tolerance to variations in coupling and load. Simulated and experimental results demonstrate that the proposed topology can maintain a maximum output current fluctuation of only 6.57% within a misalignment range of 140mm along the X-axis and under conditions of a 79.6% change in equivalent mutual inductance.

REFERENCES

- [1] G. A. Covic and J. T. Boys, "Inductive Power Transfer," in Proceedings of the IEEE, vol. 101, no. 6, pp. 1276-1289, June 2013.
- [2] G. Ke, Q. Chen, L. Xu, X. Ren and Z. Zhang, "Analysis and Optimization of a Double-Sided S-LCC Hybrid Converter for High Misalignment Tolerance," in IEEE Transactions on Industrial Electronics, vol. 68, no. 6, pp. 4870-4881, June 2021.