A novel composite coupling mechanism base on nested wrapped for dual excitation IPT system

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Abstract. The traditional research based on dual-excitation wireless power transfer system (DES), its theoretical analysis is mostly based on the situation that the mutual inductances of the two primary coils and the secondary coil are equal. When the secondary coil is mismatch, the output powers of the inverters are different due to the difference of the mutual inductances between the two primary coils and the secondary coil, which affects system reliability. This paper designs a coupling mechanism with internal and external nesting, no matter where the secondary coil is located, the mutual inductances between the secondary coil and both the primary coil are the same. Compared with the single excitation system (SES), in the case of the same input voltage, the output power is increased by 4 times, and the stress of the switching component can be effectively reduced under the same output power. The feasibility of the proposed method is verified by simulation and experiment.

1. Introduction
With the development of wireless power transfer technology, it is widely applied on the high power and high efficiency field\cite{1-4}. In practical applications, coupling coefficient and switching component capacity limit the output power of the system. The multi-excitation wireless power transfer system can not only improve the output power of the system but also reduce the voltage and current stress of the switching component, which has a great application prospect.

In order to balance the relationship between system output power and stress, more and more scholars have begun to engage in the research of dual excitation wireless power transfer system\cite{5-6}, but there are few studies on the consistency of the mutual inductances between the two primary coils and the secondary coil. When the position of the secondary coil changes, the mutual inductance between the two primary coils and the secondary coil is different, this results in difference of the each excitation input power, which can make the system unstable. In order to solve this problem, this paper designs a kind of internal and external nested coupling mechanism, compared with the traditional coupling mechanism, when the secondary coil is mismatch, the change of mutual inductance between the two primary and secondary coils of the coupling mechanism is synchronized. Finally, a model is built based on the LCC-S topology and the effectiveness of the proposed method is verified through simulation and experiments.

2. System modeling and theoretical analysis

2.1. Coupling mechanism model
This paper proposes a coupling mechanism with internal and external nesting, and its winding method is shown in figure 1. Formula (1) is the calculation method of mutual inductance between the primary
and secondary coils, N1, N1′, N2 is the coil turns. From equation (1), the mutual inductance of the two primary coils and the secondary coil is approximately equal. The performance of the coupling mechanism will be analyzed in section 3.

\[ M_{\alpha'\beta'} = \frac{N_1 N_1' \mu_0}{4\pi} \int_0^{2\pi} \int_0^{2\pi} \frac{r_{12} \cos \beta d\beta}{r_1} \frac{r_{12} \cos \beta d\beta}{r_2} \quad (1) \]

2.2. Equivalent model of dual excitation system.

Figure 2 is the equivalent model of the dual excitation system (DES). To simplify the analysis, assuming the two topological parameters of the primary side are the same. \( u_1 = u_2 = u_{\text{ab}} \), \( L_{c1} = L_{c2} = L \), \( C_{p1} = C_{p1}', C_{p2} = C_{p2}' \), \( L_{p1} = L_{p2} = L \), \( r_{p1} = r_{p2} = r_p \). When the system resonance frequency satisfies formula (2), the coil current can be derived as [7]: \( i_{p1} = i_{p2} = i_p = u_{\text{ab}}/j\omega L \).

\[ \frac{1}{\sqrt{L_{c1}C_{p1}}} = \frac{1}{\sqrt{L_{c2}C_{p1}'}} \quad (2) \]

According to KVL law, the relationship between system voltage and current can be derived as:

\[
\begin{align*}
\frac{u_{\text{ab}}}{j\omega} &= jwL_1i_{\text{ab}} + \left( jwL_2 + \frac{1}{jwC_1} \right) i_p + jwM_{1\beta}i_{\beta} + jwM_{1\gamma}i_{\gamma} \\
\frac{u_{\text{ab}}}{j\omega} &= jwL_{\beta}i_{\beta} + \left( jwL_{\gamma} + \frac{1}{jwC_2} \right) i_p + jwM_{\beta\beta}i_{\beta} + jwM_{\beta\gamma}i_{\gamma} \\
0 &= jwM_{\gamma\beta}i_{\beta} + jwM_{\gamma\gamma}i_{\gamma} + i R_{eq}
\end{align*}
\]

\( R_{eq} \) is equivalent resistance, \( R_{eq} = 8R(\pi^2)^{-1} \). The current equation can be obtained as:
From formula (4), it can be seen that the difference between Ms1 and Ms2 leads to differences of the input current, when Ms1 = Ms2 = M, the input impedance of the primary side of the system can be derived as:

\[
Z = \frac{w^2 L^2}{(jwLp + jwM_{12} - jwL + \frac{1}{jwC_p}) + \frac{2w^2 M^2}{R_{eq}} + r_p}
\]  

(5)

In order to reduce the reactive power of the system, the imaginary part of the system input impedance should be zero, the system impedance can be simplified as:

\[
Z = \frac{w^2 R_{eq} L^2}{2w^2 M^2 + R_{eq} r_p}
\]  

(6)

In order to analyze the advantages of the dual excitation system, table 1 compares the output characteristics of the single excitation and dual excitation system.

**Table 1. Performance comparison between single excitation and dual excitation systems.**

| Parameter | \(i_{in}\) | \(i_p\) | \(i_s\) | \(P_{out}\) | \(\eta\) |
|-----------|-----------|----------|----------|-------------|--------|
| DES       | \(\frac{u_a(2w^2 M^2 + R_{eq} r_p)}{w^2 R_{eq} L^2}\) | \(\frac{u_{ab}}{wL}\) | \(\frac{2wM_{12}}{R_s}\) | \(\frac{4u_a^2 M^2}{R_{eq} L^2}\) | \(\frac{2w^2 M^2}{2w^2 M^2 + R_{eq} r_p}\) |
| SES       | \(\frac{u_a(w^2 M^2 + R_{eq} r_p)}{w^2 R_{eq} L^2}\) | \(\frac{u_{ab}}{wL}\) | \(\frac{wM_{12}}{R_s}\) | \(\frac{u_a^2 M^2}{R_{eq} L^2}\) | \(\frac{w^2 M^2}{w^2 M^2 + R_{eq} r_p}\) |

3. Simulation and experimental results

3.1. Simulation results
Figure 3 shows the coupling mechanism model of the DES. Type1 and type2 are currently commonly used models, type3 is the model designed in this paper. A comsol simulation model is built to analyze the performance of the coupling mechanism. In order to compare the performance of the three types of coupling mechanisms, table2 shows the mutual inductance between the two primary coils and the secondary coil when the secondary coil is in different positions. It can be seen from table2, type3 mutual inductance difference is smaller when the distance changes. Through the parametric scanning of the coupling mechanism of type2 and type3, the variation of mutual inductances with moving distance is obtained. Figure 4(a) shows the magnetic field of the primary coil, it can be seen from figure 4(b)(c) that the coupling mechanism of type 3 has better mutual inductance consistency when the distance changes.

![Figure 4](image)

Table 3. Simulation parameters.

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| DES       |       | IPT       |       | SES       |       |
| $f$       | 100kHz| $L_s$     | 82uH  | $C_p$     | 20.1nF|
|           |       | $L$       | 20uH  | $M_s$     | 11uH  |
|           |       | $C_1$     | 126.6nF| $R_s$     | 0.2Ω  |
|           |       | $R_p$     | 0.15Ω | $M_{12}$  | 71.8uH|
|           |       | $R$       | 10Ω   | $U_{ab}$  | 30V   |
|           |       |           |       |           |       |

Based on the parameters in table 3, build a simulation model in MATLAB. Figure 5 shows the current simulation results of SES and DES in different operating modes. From figure 5(a)(b), it can be seen that under the same input voltage and load, the output current and voltage of the DES is about twice that of the SES. In order to compare the system performance when the output power is the same, increase the input voltage of the SES by 2 times or reduce the load by 1/4. Figure 5(c) shows the simulation results when the input voltage of the SES is 60V and the input voltage of the DES remains unchanged (30V), the inverter output currents of the two systems are equal, but the coil current of the SES is twice that of the DES. Figure 5(d) compares the current simulation results of the two systems when the load of the SES is reduced to 1/4 (2.5Ω) of the original, at this time, the coil currents of the two systems are equal, but the inverter current of the SES is twice that of the DES.
3.2. Experimental results

Figure 6 shows the experimental setup of the system, the coupling mechanism is wound by means of inner and outer nesting. In this way, the mutual inductances between the two primary coils and the secondary coil are consistent. Figure 7 is the experimental waveform of the DES, system output power is 91.2W, when the parameters of the dual excitation system are the same, the input power of each excitation is the same.

Figure 8 shows the experimental waveform of the SES. When the input voltages of the SES and the DES are the same, the experimental result is shown in Figure 8(a). Compared with the DES, the SES output voltage and inverter current are only half, and the coil current is the same. System output power is 23.7W. In order to analyze the advantages of the DES under the same output power, the input voltage of the single excitation system is increased by 2 times (60V), the experimental result is shown in figure 8(b), compared with the dual excitation system, the coil current is increased by 1.81 times and the inverter current is the same.
4. Conclusion
This paper designs a kind of inner and outer nested coupling mechanism suitable for dual excitation system. Compared with traditional dual excitation coils, the coupling mechanism has better mutual inductance consistency. The theoretical model of the system is derived based on the LCC-S topology. The simulation and experimental results show that the output power of the dual excitation system is increased by 3.85 times under the same conditions, and the voltage and current stress of the switch component can be effectively reduced at the same output power.

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References
[1] Li,S.F,Wang,L.F, Guo,Y.J, Tao,C.X. (2020) Power Stabilization With Double Transmitting Coils and T-Type Compensation Network for Dynamic Wireless Charging of EV. IEEE Journal of Emerging and Selected Topics in Power Electronics,8(2):1801-1812.
[2] Li,X.F,Hu,J.F,Wang,H.S, Dai,X.(2020) A New Coupling Structure and Position Detection Method for Segmented Control Dynamic Wireless Power Transfer Systems.IEEE Transactions on Power Electronics,35(7):6741-6745.
[3] Chen,Z.Y, Xu,A.Q, Yi,C.H.(2020) Range-Adaptive Wireless Power Transfer Based on Differential Coupling Using Multiple Bidirectional Coils. IEEE Transactions on Industrial Electronics,67(9):7519-7528.
[4] Qu, X.H, Jing,Y.Y. (2017) Higher Order Compensation for Inductive-Power-Transfer Converters With Constant-Voltage or Constant-Current Output Combating Transformer Parameter Constraints. IEEE Transactions on Power Electronics,32(1):394-405.
[5] Dai ,X , Jiang , J.C, Li, Y.L. (2017) Topology optimization and phase shift control for inductive power transfer with dual excitation units. In: Wireless Power Transfer (WoW). Chongqing,pp.300-304.
[6] Yan,Z.T, Liu,Y.B, Chen,H.(2020) Efficiency Improvement of Wireless Power Transfer Based on Multitransmitter System. IEEE Transactions on Power Electronics,35(9):9011-9023.
[7] Wei,Z, Mi,C.(2016) Compensation Topologies of High-Power Wireless Power Transfer Systems. IEEE Transactions on Vehicular Technology,65(6):4768-4778.