

A fast determination method for compensation of highly offset-resistant wireless energy transmission systems considering parasitic parameters

Yingying Wang, Yudong Wang, Jiahui Yu and Jindi Pang

School of Mechanical and Electrical Engineering, China University of Mining and Technology, Beijing, 10083 China

This paper focuses on constructing and analyzing an improved composite circuit for wireless power transmission with high misalignment tolerance. A method is proposed to simplify the circuit by incorporating a polygonal equivalent circuit, and the influence of parasitic capacitance on transmission performance was analyzed. It is recommended to consider parasitic capacitance when determining the compensation capacitance in resonance state. Furthermore, a composite equivalent circuit model is proposed, which helps to enable the efficient determination of the compensation circuit and enhance simulation efficiency of transmission systems.

Index Terms—Compensation capacitance, parasitic capacitance, polygonal equivalent circuit, wireless power transmission.

I. INTRODUCTION

IN PRACTICAL applications of Magnetic Coupling Resonant Wireless Power Transmission (MCR-WPT), parasitic capacitance significantly affects output stability and misalignment tolerance[1]. At present, parasitic capacitance parameters are usually ignored when determining the compensation capacitance value, which can affect the resonance state and thus affect efficiency. Moreover, the design of compensation capacitance and compensation circuits lacks an overall equivalent circuit. This paper studies the influence of parasitic capacitance on output current and voltage, and proposes an efficient composite equivalent circuit for wireless power transmission with high misalignment tolerance.

II. DESIGN OF MAGNETIC RESONANT COUPLER WITH HIGH OFFSET RESISTANCE

A. Simulation Parameters

This work proposes a compensation model combined with *S-S* (Series-Series) topology[2], with the structural topology shown in Fig 1. It consists of three parts: the inverter section, the coupler, and the rectifier section. The three-dimensional structure is illustrated in Fig 2. By employing series capacitors on both the input and output sides for compensation, a stable current output independent of load variations is achieved. Additionally, decoupling capacitors C_{X1}, C_{X2} are added on both sides. In the figures, C_P, C_S represents the compensation capacitors in the *S-S* topology, while C_{Pf}, C_{Sf} denotes series compensation capacitors for the auxiliary coil.

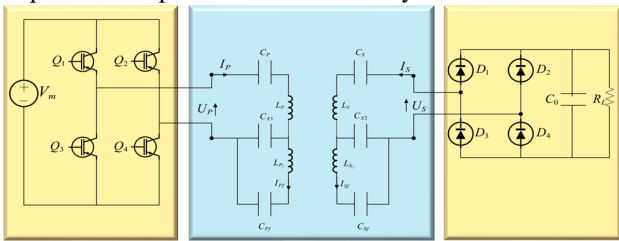


Fig. 1. Transmission system topology.

The two-port matrix equation and parameters were obtained as

$$\begin{bmatrix} U_P \\ U_S \\ 0 \\ 0 \end{bmatrix} = j\omega \begin{bmatrix} L'_P & M_{PS} & 1/\omega^2 C_{X1} & M_{PSf} \\ M_{PS} & L'_S & M_{PSf} & 1/\omega^2 C_{X2} \\ 1/\omega^2 C_{X1} & M_{SPf} & L'_{Pf} & M_{PfSf} \\ M_{PSf} & 1/\omega^2 C_{X2} & M_{PfSf} & L'_{Sf} \end{bmatrix} \begin{bmatrix} I_P \\ I_S \\ I_{Pf} \\ I_{Sf} \end{bmatrix} \quad (1)$$

where $L'_P = L_P - \frac{1}{\omega^2 C_P} - \frac{1}{\omega^2 C_{X1}}$, $L'_S = L_S - \frac{1}{\omega^2 C_S} - \frac{1}{\omega^2 C_{X2}}$,

$L'_{Pf} = L_{Pf} - \frac{1}{\omega^2 C_{Pf}} - \frac{1}{\omega^2 C_{Xf}}$, $L'_{Sf} = L_{Sf} - \frac{1}{\omega^2 C_{Sf}} - \frac{1}{\omega^2 C_{X2}}$.

In order to achieve magnetically coupled resonance it is necessary to satisfy $L'_P=0, L'_S=0, L'_{Pf}=0, L'_{Sf}=0$, we can find the value of C_P, C_S, C_{Pf}, C_{Sf} .

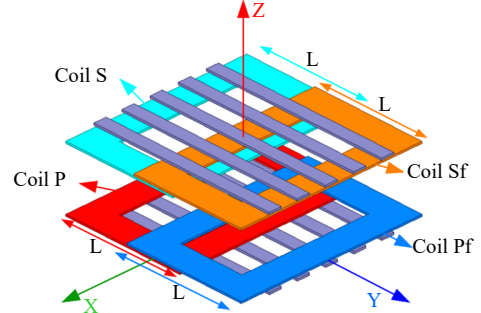


Fig. 2. Spatial structure of the four-coil coupler.

B. Coil decoupling on the same side

Decoupling of same-side coils was implemented after establishing port network equations and performing subsequent computations. Experimental simulations revealed that solely relying on overlap area design proved insufficient. Guided by literature review, C_{X1}, C_{X2} were designed to compensate coupling losses, with equivalent mutual inductance maintained through dual-variable regulation.

Parameters C_{X1} and C_{X2} were determined through analysis of the coupler system's equivalent mutual inductance to derive specific design values. This significantly improves the system's anti-deviation capability.

Based on geometric length and positional relationships, it can be deduced that existing studies assume mutual inductance cancellation when the overlapping area of two coils equals half the coil's cross-sectional area. However, our electromagnetic simulations demonstrate that due to structural parameters such

as coil width and thickness, the actual overlapping area must be reduced below half of the cross-sectional area.

III. A POLYGONAL EQUIVALENT CIRCUIT MODELING METHOD FOR COUPLERS

A. Equivalent circuit diagram of the coupler

Current values in the four-coil system under normal operating conditions were subsequently quantified. Analysis reveals that the four-coil coupled configuration exhibits steady-state currents with linear relationships amenable to quantitative characterization. We derived governing equations describing the linear current interdependencies as

$$I_P = aI_S + bI_{Pf} + cI_{Sf} \quad (2)$$

where $a=13.25517, b=49.95094, c=92.65486$. According to Fig.1, the expressions for the electromotive force and current of each coil can be derived as follows.

$$U_P = j\omega I_P L_P + j\omega I_S M_{PS} + j\omega I_{Pf} M_{PPf} + j\omega I_{Sf} M_{PSf} \quad (3)$$

$$U_S = j\omega I_S L_S + j\omega I_P M_{PS} + j\omega I_{Pf} M_{SPf} + j\omega I_{Sf} M_{SSf} \quad (4)$$

$$U_{Sf} = j\omega I_{Sf} L_{Sf} + j\omega I_P M_{PSf} + j\omega I_{Pf} M_{SPf} + j\omega I_S M_{SSf} \quad (5)$$

$$U_{Pf} = j\omega I_{Pf} L_{Pf} + j\omega I_S M_{PSf} + j\omega I_P M_{PPf} + j\omega I_{Sf} M_{PSf} \quad (6)$$

Subsequently, equivalent circuit analysis was performed on the model. Based on known data and constitutive equations, the following matrix was derived through systematic reduction.

$$\begin{bmatrix} U_S - U_P \\ U_{Pf} - U_{Pf} \\ U_{Sf} - U_P \end{bmatrix} = \begin{bmatrix} Z_{122} & Z_{123} & Z_{124} \\ Z_{132} & Z_{133} & Z_{134} \\ Z_{142} & Z_{143} & Z_{144} \end{bmatrix} \begin{bmatrix} I_S \\ I_{Pf} \\ I_{Sf} \end{bmatrix} \quad (7)$$

Where each element in the impedance matrix is obtained by a simple operation on the self-mutual inductance. The above equation can be obtained by inverse matrix transformation as:

$$\begin{bmatrix} I_S \\ I_{Pf} \\ I_{Sf} \end{bmatrix} = \begin{bmatrix} Z'_{122} & Z'_{123} & Z'_{124} \\ Z'_{132} & Z'_{133} & Z'_{134} \\ Z'_{142} & Z'_{143} & Z'_{144} \end{bmatrix} \begin{bmatrix} U_S - U_P \\ U_{Pf} - U_P \\ U_{Sf} - U_P \end{bmatrix} \quad (8)$$

According to equation (2) and (8) we can get the equation as:

$$I_P = \frac{U_P - U_S}{Z_{PS}} + \frac{U_P - U_{Pf}}{Z_{PPf}} + \frac{U_P - U_{Sf}}{Z_{PSf}} \quad (9)$$

This equation reflects the quantitative relationship between the current at one port and the voltage difference at three ports.

Following the same operation yields expressions for the other three currents. The equivalent circuit of the four-coil coupler is shown in Fig. 3.

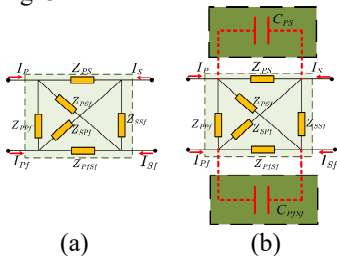


Fig. 3. Equivalent circuit diagram of the coupler: (a) disregarding parasitic capacitance. (b) Consider some parasitic capacitance.

B. Calculation of parasitic capacitance

Parasitic capacitance takes into account the voltage distribution on the coil windings, and the parasitic capacitance between

the coils can be obtained by the calculus obtained from the total electric field energy equal to the energy represented by the total dynamic capacitance of the set. An accurate equation for calculating the capacitance between coils has been given by some researchers and after our analysis[3], we decided to use this calculation method. The capacitance value is obtained by the following equation

$$C_{AB} = \frac{\epsilon_0 \epsilon S}{3L_{AB}} \left(\frac{n_1}{n_2} + 1 \right)^2 \quad (10)$$

where ϵ is the relative dielectric constant of the insulating material, S is the overlap area of the two coils facing each other, L_{AB} is the distance between the two coils, and n_1/n_2 is the ratio of the number of turns of the secondary side to that of the primary side. The data $C_{PS}, C_{PSf}, C_{PSf}, C_{PSf}$, can be calculated.

IV. SIMULATION RESULTS INCORPORATING PARASITIC CAPACITANCE

The four stray capacitances were connected within the circuit for computational simulation. Initial post-integration results which were shown in Fig.4 exhibited substantial fluctuations and errors, revealing inadequate performance of the compensation design. By reapplying the compensation component design methodologies outlined in Sections II and III, revised compensation capacitance values were obtained. Subsequent simulation analysis with the updated compensation design yielded the output current and voltage waveforms shown in Fig. 5.

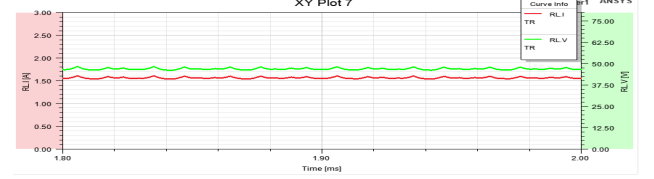


Fig. 4. Simulation results without re-optimized compensation parameters

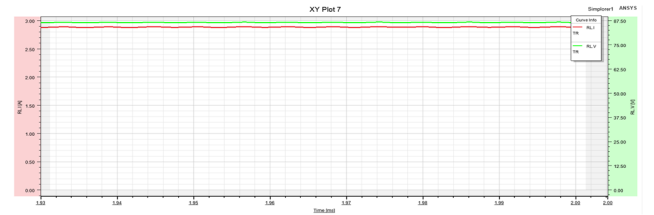


Fig. 5. Simulation results with re-optimized compensation parameters.

By comparing Figs. 4 and 5, it is evident that the re-optimized compensation parameters lead to increased RMS values of output voltage and current, effectively suppress ripple components, and enhance system output stability.

REFERENCES

- [1] G Lee, BH Waters, Schen. Design Considerations for Asymmetric Magnetically Coupled Resonators used in Wireless Power Transfer Applications[J]. Power Amplifiers for Wireless & Radio Applications, 2013, 12(9):157-159.
- [2] MAI Ruikun, YANG Bin, CHEN Yang, et al. A misalignment tolerant IPT system with intermediate coils for constant-current output[J]. IEEE Transactions on Power Electronics, 2019, 34(8):7151-7155.
- [3] Y. L. Li, "Analysis and Calculation of Winding Loss and Distribution Parameters in High-Frequency Transformers," Master's thesis, Hebei Univ. Technol., Tianjin, China, 2015.