Three Dimensional Radio Power Transmission

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Abstract. This paper systematically investigates the development history and simulation analysis of three-dimensional wireless energy transmission technology. Building upon previous research achievements in electromagnetic coupling mechanisms and spatial energy distribution optimization, this study proposes innovative improvements to existing system configurations. Through comprehensive modeling and simulation of 3D wireless energy transmission systems utilizing multidisciplinary simulation platforms including MATLAB/Simulink for system analysis and ANSYS Maxwell for electromagnetic field simulation, we demonstrate that a dual-coil structure exhibits significantly improved stability compared to conventional single-coil configurations in ideal transmission environments. The research further employs advanced electromagnetic simulation tools to visualize and analyze distinct magnetic field distribution patterns generated under varying phase modulation conditions within identical system parameters. A comparative study between 0° and 90° phase modulation strategies reveals substantial differences in spatial offset tolerance characteristics. Simulation results quantitatively demonstrate that 90° phase modulation enhances lateral displacement resistance by approximately 38% compared to conventional in-phase excitation, particularly in dynamic 3D wireless charging scenarios. These findings provide valuable theoretical guidance and technical references for the design of omnidirectional wireless power transfer systems, suggesting that optimized phase modulation combined with multi-coil configurations could effectively address spatial freedom challenges in practical three-dimensional wireless charging applications. The study establishes a foundation for future research directions in adaptive phase control algorithms and dynamic compensation mechanisms.

Keywords: Wireless Energy Transmmision, Phase Modulation, Three-Dimensional Phase, Finite Elements

1 Introduction

Three-dimensional wireless energy transmission is an emerging technology for electrical energy transmission. With artificial intelligence, logistics, and people's demand for convenience and freedom from wired charging, wireless energy transmission has emerged. In recent years, three-dimensional wireless energy transmission technology has been vigorously developed in the field of medical devices, mobile phones and automotive wireless charging. Compared with wired electrical

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energy transmission, which has safety problems such as circuit aging, tip discharge and electric sparks, wireless energy transmission has attracted the attention of academia and industry by virtue of its high spatial freedom, long transmission distance and other advantages. Conventional planar WPT systems face considerable challenges in maintaining a stable output due to lateral and angular deviations of the receiver (Rx). This instability severely limits their practical applications. Various omnidirectional WPT techniques have been developed to enhance the free positioning capability and to accommodate arbitrary orientations.

In 2021, a team from South Korea's Soongsil University proposed the first dual-frequency free-positioning transmitter coil (FPDB-Tx) model, which analysed the dual-frequency resonance conditions and power transfer function. The misalignment sensitivity and cross-coupling problems in multi-receiver WPT systems are solved with both high efficiency and spatial freedom through a 3D dual-inverted coil design and dual-frequency control strategy[1]. In 2022, Southwest Jiaotong University, China, proposed a double-layer orthogonal DD coil launch structure, which achieves self-decoupling (cross-coupling coefficient ≈ 0.00557) and avoids multi-coil cross-coupling loss through spatially orthogonal layout. The magnetic field distribution of different modes is analysed by finite element magnetic field simulation to determine the optimal coupling position (45°) and switching point. Through structural innovation and control strategy optimisation, the coupling failure problem of DD coils in rotational offset scenarios is solved, providing a solution for dynamic wireless charging system[2]. 2022 The Cho Chun Shik Graduate School of Mobility For a two-sided LCC topology WPT system, the optimal configuration of the shunt capacitors (CP1 and CP2) is deduced by the arithmetic-geometric mean inequality so that the coil current ratio (I1/I2) satisfies the loss minimisation condition. The method improves the coil-coil efficiency to 95.3% in an 85 kHz system, providing a parametric design guideline for high-power applications such as electric vehicles[3]. In 2024, the National Institute of Technology, Hakodate University, Japan, enhanced the coupling between the transmitting and receiving coils while suppressing the mutual coupling between the receiving coils by inverting the current phase of the two-sided receiving coils. An inductor is loaded at the frequency point where the kQ product is maximised (25 MHz) to enhance the system efficiency. The critical role of reverse-phase coil orientation in enhancing the coupling coefficient (kQ product) is revealed in a two-sided wireless energy transfer (WPT) system. Through resonant frequency optimisation (25MHz) and electromagnetic field analysis, it is demonstrated that the reverse-phase configuration can significantly improve the transmission efficiency compared to the same-phase, which provides a new idea for mutual coupling suppression in multi-coil systems[4].

On this basis, this paper discusses the basic topology of three-dimensional wireless energy transmission as well as the use of Matlab, ANSYS simulation software to verify the improvement of the magnetic field and output stability of three-dimensional wireless energy transmission.

2 Relevant Theoretical Framework

The theoretical architecture of the wireless energy transmission system is a multidisciplinary cross-complex system, covering a number of fields such as electromagnetic field theory, resonant coupling theory, circuit theory and control theory. Electromagnetic field theory provides the basis for energy transmission, which is achieved through electromagnetic induction or electromagnetic radiation to achieve wireless transmission of energy. Resonant coupling theory significantly improves transmission efficiency by matching the resonant frequencies of the transmitter and receiver. Circuit theory, on the other hand, optimises the energy conversion and management of the system through equivalent circuit models and impedance matching techniques. The control theory ensures the stability and adaptability of the system through frequency tracking, power control and feedback mechanisms.

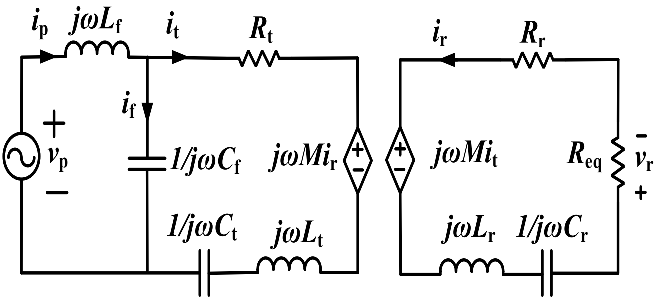

Fig. 1. Topology of LCC compensation for wireless energy transmission system.

As shown in Fig. 1, this is a topology of LCC compensation for wireless energy transmission system.

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% Defining the parameters of the system
L=49.2*10^-6;
Lp=L; Ls=L;
Lf=0.5*L;
Cf=1/(w^2*Lf);%Supplementary capacitance of the transmitter coil
Cp=1/(w^2*(Lp-Lf));
Cs=1/(w^2*Ls);
Rp=0.2;%ESR of the transmitting coil
Rs=0.2;%ESR of receiving coil
Req=10;%load resistance
Rf=0.1;
vp=10;%Input Voltage
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Fig. 2. Matlab code for LCC-S system parameters.

As shown in Fig. 2, this is the Matlab code for LCC-S system parameters.

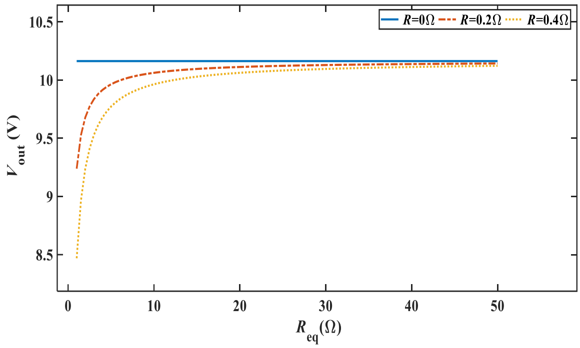

Fig. 3. LCC-S Constant Voltage Outputs.

As can be seen from Fig. 3, this is an image of the load resistance and the output voltage. In the ideal case, that is, with ESR equal to 0, the LCCS system will have a constant voltage output characteristic. From the graph, the load resistance is increased from 1 ohm to 50 ohms, and the output voltage is maintained between 10.1 and 10.2 volts. ESR is not able to ignore the resistance on the coil in the real case. When the coil resistance is 0.2 ohms, the output voltage cannot achieve the constant voltage output characteristic. It rises 10% from 9.2 volts to 10.1 volts. As the ESR continues to increase, its constant voltage output characteristics get worse.

3 Research methodology and analysis

3.1 Simulation results and analysis

3.1.1 Self-inductance and mutual-inductance simulation: as shown in Fig.4, a three-dimensional wireless energy transmission model is built through Maxwell to simulate the size of self-inductance and mutual-inductance of the transmitting and receiving coils. The material of the two coils is set to be copper, the current is set to be 100mA, the number of turns is set to be 10, the diameter of the outer coil is set to be 100mm, the diameter of the inner coil is set to be 80mm, and the transmission distance between the two coils is set to be 50mm.

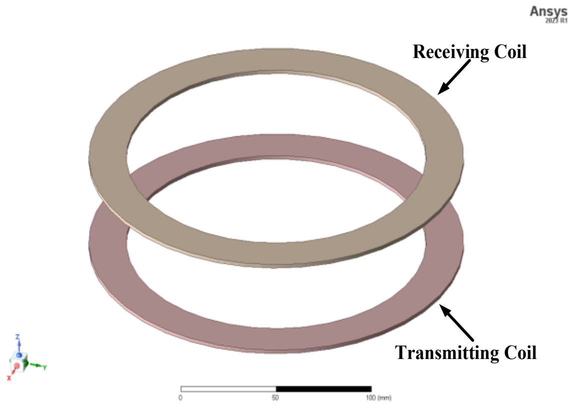

Fig. 4. Maxwell modelling of radio energy transmission system.

Table 1. Maxwell modelling coil self-induced mutual inductance simulation results

Freq(kHz)	Transmitting coil self-induction(uH)	Coil mutual inductance(uH)	Receiver coil inductance(uH)
100.0000	36.0906	7.9249	35.5494

As seen in Table 1, the magnitude of the self- and mutual inductance of the transmitting and receiving coils at this distance is derived from Maxwell simulations. When the frequency is 100k Hz, its coil self-inductance is roughly around 36 μ H. The self-inductance of the transmitting coil is basically the same as that of the receiving coil, also around 36 μ H. The mutual inductance of the two coils is also the same, which is about 7.8 μ H. When the self-inductance and mutual inductance of the transmitting coil are the same, the resonant frequencies of the two are the same, and the coupling conditions are symmetrical, the system is able to transmit the energy with maximum efficiency.

3.1.2 Simulation of three-dimensional wireless charging system with dual transmitting coils: two sets of transmitting coils are established to provide multi-dimensional magnetic fields with different directions as a way to achieve good offset resistance in a three-dimensional wireless charging system. As shown in Fig.5, Two sets of transmitting coils and one set of spinning receiving coils are modelled by Maxwell software. The outer coil diameter of the coil receiving coils is 100mm, the inner coil diameter is 80mm, and the coil material is set as copper. The two sets of transmitting coils are set as red and green, and the transmitting coil current is 100mA.

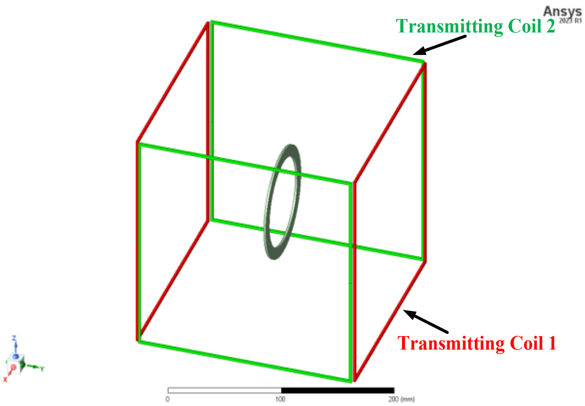

Fig. 5. Maxwell 3D wireless charging system model.

The transmitting coil is parallel to the receiving coil. Set up the receiving coil and the tangent plane to rotate 360 degrees at the centre of the circle and record data at 10 degree intervals. A 400 mm square air domain is set up and the programme is run to derive the coupling coefficient of the transmitting coil 1 and the receiving coil as well as the coupling coefficient situation between the transmitting coil 2 and the receiving coil.

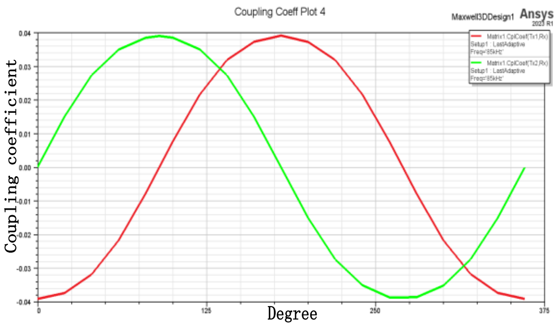

Fig. 6. Mutual inductance of two transmitting and receiving coils at 90° phase difference.

When only one transmitting coil is designed, the mutual inductance of the transmitting coil and the receiving coil becomes the green or red image in Figure 6, that is, the equivalent mutual inductance fluctuates up and down in the function interval, and this system does not have a good offset resistance.

3.1.3 Equation derivation: it is assumed that the inductance of the coils and compensation capacitors in the two transmitters are the same. Therefore, the parameters of the 3D wireless charging system can be expressed as:

$$L_{f1} = L_{f2} = L_f, L_{t1} = L_{t2} = L_t$$
$$C_{f1} = C_{f2} = C_f, C_{t1} = C_{t2} = C_t \qquad (1)$$
$$R_{t1} = R_{t2} = R_t$$

The capacitor is compensated at the resonant corner frequency (i.e., ω0 = 2 π f0), which satisfies:

$$\frac{1}{\sqrt{L_f C_f}} = \frac{1}{\sqrt{(L_t - L_f)C_t}} = \frac{1}{\sqrt{L_s C_s}} = \omega_0 \qquad (2)$$

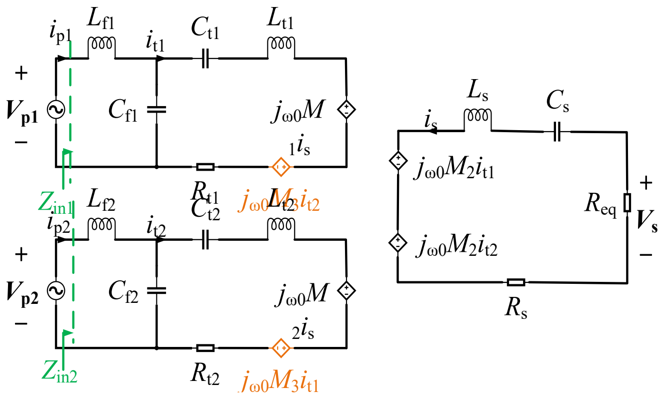

Fig. 7. Equivalent circuit of the system at fundamental frequency.

According to (1) and (2), the excitation currents (it1 and it2) of the transmitter coil can be expressed as:

$$i_{t1} = \frac{v_{p1}}{j\omega_0 L_f} \qquad (3)$$

$$i_{t2} = \frac{v_{p2}}{j\omega_0 L_f} \qquad (4)$$

A rotating magnetic field can be generated by introducing a phase difference in the excitation currents of the individual emitters. In this study, a phase difference of 90 degrees between it1 and it2 is achieved by adjusting the input voltages vp1 and vp2 to meet:

$$v_{p1} = V_p \angle 0^\circ \qquad (5)$$

$$v_{p2} = V_p \angle -90^\circ \qquad (6)$$

Where Vp denotes the root mean square (rms) value of the input voltage. According to Faraday's law, the excitation current in the Tx coil induces a controlled voltage source in the Rx circuit as shown in Figure 7. Through the resonance of Ls and Cs, the voltage on the Rx side is affected by Req and Rs. Therefore, the rms value of the output voltage can be expressed as:

$$V_s = \frac{V_p M_{eq} R_{eq}}{L_f (R_s + R_{eq})} \quad (7)$$

Where denotes the equivalent mutual inductance [5]. As can be seen in Figure 6, when the phase difference is equal to 90° using the modulation method, the mutual inductance M1 of the transmitting coil 1 and the receiving coil shows a cos function image as the angle changes; the mutual inductance M2 of the transmitting coil 2 and the receiving coil shows a sin function image as the angle changes. Again, since sin2 + cos2 is equal to 1 at the same angle, it follows that the equivalent mutual inductance Meq of the system is a fixed value when the phase difference is equal to 90°. Therefore, in this ideal wireless energy transmission system, the dual transmitting coils with a phase difference of 90° are more stable compared to the single transmitting coil. Thus, this three-dimensional wireless charging system produces a good resistance to offsets.

As shown in Fig. 8, the fluxes at 0° and 180° are in opposite directions along the y-axis, those at 90° and 270° are in opposite directions along the x-axis, and those at 45° and 225° are in opposite directions along the x- and y-axis diagonals.

As seen in Fig. 9, if the 3D wireless charging system is modulated with a 90° phase difference, then its magnetic field becomes a 360° rotating magnetic field. When no modulation is applied, the main magnetic flux of the 3D wireless charging system is in the same direction. By simulating out the magnetic field situation of the system at different angles, it is found that a rotating magnetic field is generated when the phase angle is 90° and compared with 0° phase, it is found that 90° phase angle is the most stable in transmission.

3.2 Magnetic field simulation

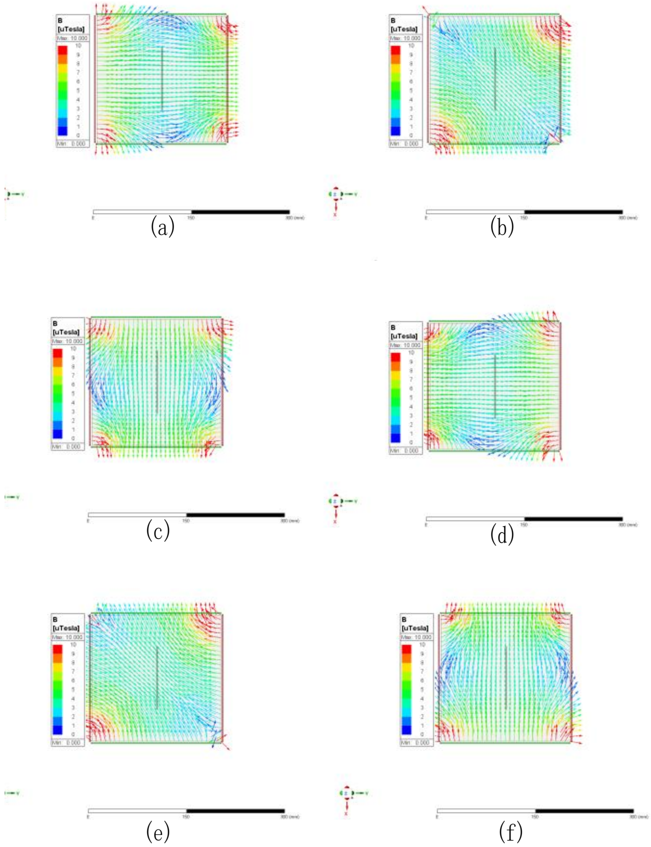

Fig. 8. Magnetic field distribution at different phases (a) 0°, (b) 45° (c) 90°, (d) 180°, (e) 225° (f) 270°.

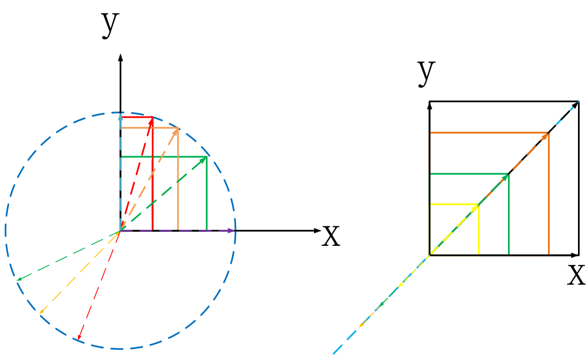

Fig. 9. Schematic representation of the synthetic magnetic field at 90° and 0° phase difference.

4 Conclusion

This paper investigates the effect of mutual inductance of LCC-S wireless energy transmission system under different phase differences. A simulation model based on the mutual inductance theory is developed to analyse both the mutual inductance of the transmitting and receiving coils as well as the magnetic field distribution of the wireless energy transmission system. The results of simulation and experiment show that the system stability is best when using dual transmitter coils with 90° phase modulation in an ideal case 3D wireless transmission system, which produces a good offset resistance. This design is suitable for three-dimensional dynamic wireless charging scenarios provides a basis for the design of the control strategy of the system.

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