

Transmission characteristics of the mobile inductively coupled power transfer system for dual transmitters and pickups based on PSpice

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Abstract: In order to meet the application requirements of high-power mobile inductively-coupled power transfer (ICPT) equipment, the structure of the dual transmitter and pickup can be used to improve the transmission power of the ICPT system. However, this structure cannot easily describe the change of the mutual inductance parameter in the moving state, making the mathematical model difficult to establish. The change of load parameters during the movement will affect the current and voltage at the transmitter and pickup coils. Aiming at these problems, this paper proposes a dual transmitter and pickup ICPT system based on inductor-capacitor-inductor (LCL) compensation network, and analyzes its power transmission efficiency. By setting the shape and size of the coil, the influence of the change of the mutual inductance parameters on the system efficiency during the movement is reduced. The changes of the mutual inductance parameters of the ICPT system under the moving state are simulated by changing the coupling coefficient in the PSpice software. The results show that the structure of the ICPT system used in this paper can improve the output power and reduce the influence of the system when the load changes.

Key words: high power; ICPT, LCL compensation network, mobile, PSpice

1. Introduction

Inductively-coupled power transfer (ICPT) systems use loosely-coupled transformers to transfer energy between the transmitters and receivers contactless. Compared with the traditional power transmission mode, ICPT system does not generate sparks, has better insulation effect and higher



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security, and has lower maintenance cost. These advantages make the ICPT system widely used in transportation [1], medical equipment [2] and some special occasions, make it worth to be researched. In recent years, many domestic and foreign experts, scholars and research institutions have paid close attention to ICPT technology [3, 4]. Output power and transmission efficiency are two important performance indicators of the ICPT system. The compensation network [5, 6] and control method [7] of the ICPT system are the key factors affecting the performance index of the system. They are also hot topic for most scholars.

The ICPT system need to achieve stable and efficient transmission of energy when supplying power to high-power mobile devices [8]. In order to improve the transmission efficiency of the system, the ICPT system has been improved in terms of compensation structure, pick-up and transmitting coil. In the study of the mobile ICPT system, in order to improve the system transmission efficiency, the track length and edge correction are adjusted [9], the structure of the pickup coil is changed [10], and the compensation capacitor is optimized [11]. In the study of compensation structures, the LCL compensation structure is used to compensate for reactive power to improve the active power output [12–14]. By comparing the effects of LCL type compensation and S type compensation on the system output power, it is found that the LCL compensation structure can effectively increase the output power as the load resistance increases [14].

Affected by the capacity and price of semiconductor devices, multiple pick-up coils can be used to provide energy for one load. The structure and principle of the double pick-up coil ICPT system are studied [15]. The effect of mutual inductance between the pick-up coils is eliminated by adjusting the compensation capacitance, which effectively improves the output power and transmission efficiency at heavy load. The dual-pickup magnetic coupling resonant radio energy transmission system is studied [16]. The mathematical model is established by the equivalent circuit theory, and the transmission efficiency formula is derived. The chaotic particle swarm optimization algorithm is used to optimize the transmission efficiency of the system. In [17], the one-to-one coupled coil and the multi-receiving coupled coil are compared, and the results show that the multi-receiving coil can increase the transmission power. In addition, in the multi-coupling coil mode, the single-load and multi-load conditions are compared. Experiments show that the transmission efficiency is most obvious in single load mode. However, the compensation structures of these three references are basic series compensation structures, which can be further optimized.

In terms of the structure of the transmitting coil, a model of dual-transmitting coils is established [18]. By changing the coil length ratio to keep the sum of the mutual inductances when the load moves, and then, the transmission power is kept stable, but there is no comparative experiment on the structure, and the persuasive power is not enough. In [19], a parallel topology of the ICPT system was proposed. By connecting multiple low-power high-frequency inverters in parallel, the total current of the primary coil is increased, thereby increasing the output power of the ICPT system. At the same time, this topology has redundancy function and improved the reliability of the ICPT system. An ICPT system with a primary-side multi-coil structure is proposed [20]. Each coil is equipped with an independent high-frequency resonant inverter. By superimposing the magnetic fields generated by the coils, the total magnetic field generated by the coil is effectively increased, thereby increasing the output power. At the same time, the compensation structure is also relatively basic, and more in-depth research can be done on the compensation structure.

In this paper, a dual transmitter and pickup ICPT system based on LCL compensation is established, and the influence of mutual inductance changes on the system under moving conditions is considered. Finally, the simulation proves that the proposed structure can achieve constant voltage at the transmitting end, constant current at the receiving end and can improve the output power.

2. Constant current characteristics and constant voltage characteristics of LCL circuit

Fig. 1 is an LCL compensation circuit diagram. The input impedance of the LCL compensation circuit in Fig. 1 is:

$$Z_{in} = \omega_0 L_2 \frac{1 - \omega_n^2 \lambda + j\omega_n Q [\lambda (1 - \omega_n^2) + 1]}{Q (1 - \omega_n^2) + 1\omega_n}, \quad (1)$$

where $\omega_0^2 = 1/(L_2 C_1)$, ω_0 is the resonant angular frequency of the system; $\omega_n = \omega/\omega_0$, ω_n is the normalized angular frequency of the system; $Q = \omega_0 L_2/R$, Q is the quality factor of the system; $\lambda = L_1/L_2$, λ is the ratio of the inductance in the topology circuit.

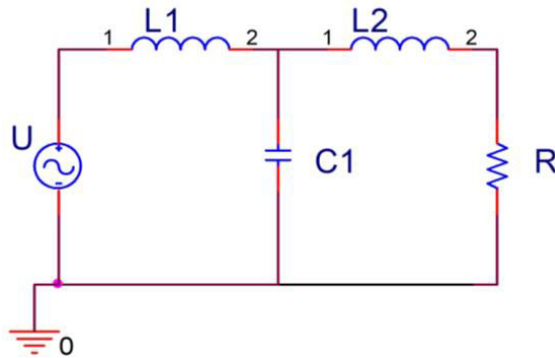


Fig. 1. LCL compensation circuit

The output current of the LCL compensation circuit is also the current on the inductor L_2 and the resistor R_L :

$$I_R = \frac{UQ}{\omega_0 L_2 \{1 - \omega_n^2 \lambda + j\omega_n Q [\lambda (1 - \omega_n^2) + 1]\}}. \quad (2)$$

The output voltage of the LCL compensation circuit is also the voltage on the resistor R_L :

$$U_R = \frac{U}{1 - \omega_n^2 \lambda + j\omega_n Q [\lambda (1 - \omega_n^2) + 1]}. \quad (3)$$

When $\omega_n^2 = 1/\lambda$, the load current is:

$$I_R = \frac{U}{j\omega_n L_2 \sqrt{\lambda}}. \quad (4)$$

It can be seen from the expression of the load current that the load current has no relationship with the magnitude of the load. At this time, the LCL circuit exhibits a constant current characteristic.

When $\omega_n^2 = 1 + 1/\lambda$, the load voltage:

$$U_R = \frac{U}{\lambda}. \quad (5)$$

It can be seen from the expression of the load voltage that the load voltage has no relationship with the magnitude of the load, and the LCL circuit exhibits a constant voltage characteristic.

In the special case of $\lambda = 1$, that is, $L_1 = L_2$, when $\omega_n = 1$, the LCL circuit exhibits a constant current characteristic, and when $\omega_n = \sqrt{2}$, the LCL circuit exhibits a constant voltage characteristic.

3. System principle and analysis

In this paper, the mobile ICPT system with two transmitting coils and two picking coils is taken as an example. The structure of the system is shown in Fig. 2. The system mainly consists of two parts: transmitting coils and receiving coils. The structure of the transmitting coils mainly includes: a voltage source, a high frequency inverter, a compensation circuit and a transmitting coil; the structure of the picking end mainly comprises: a picking coil, a compensation circuit and a load.

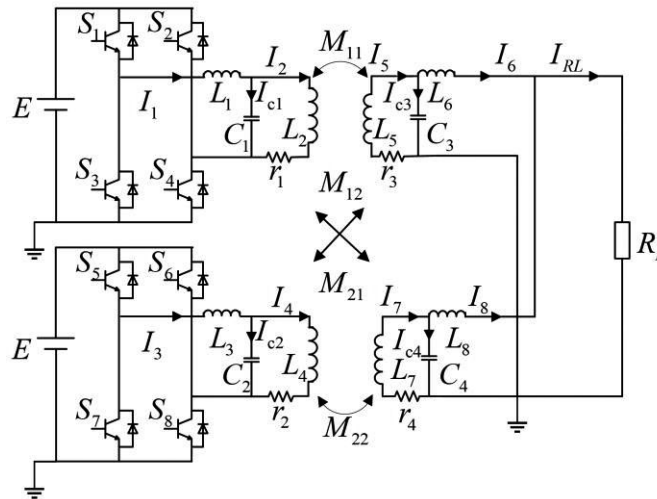


Fig. 2. Structure of dual transmitter and pickup ICPT system

In inductively coupled radio energy transmission, the transmitting coils and pick-up coils have a low coupling coefficient, similar to a loosely coupled transformer. The leakage inductance between the two coils is large, so a compensation circuit is needed at both the transmitting coils and the pick-up coils to reduce reactive power and reduce losses.

It can be seen from [21] that in the case where the inductances of both ends of the LCL compensation circuit are equal, the power factor of the resonant circuit is 1, and the maximum active power can be transmitted. In the LCL structure of the transmitting end and the picking end, let $L_1 = L_2 = L_3 = L_4$, the inductance is L_1 , $L_5 = L_6 = L_7 = L_8$, and the inductance is L_2 . $C_1 = C_2$, the capacitance is C_1 , $C_3 = C_4$, and the capacitance is C_2 . Let the internal resistance of the transmitting coil and the receiving coil be r_1 , r_2 , r_3 , and r_4 , respectively, and the internal resistance is R . The compensation structure at the transmitting end is the same LCL structure, and the two pickup ends also use the compensation structure of the same LCL, and ignore the internal resistance of the coil at the pickup end of the transmitting end. M_{11} , M_{12} , M_{21} , and M_{22} are mutual inductances between the transmitting coil 1, the transmitting coil 2, and the pick-up coil 1, and the pick-up coil 2, respectively. Fig. 3 is an equivalent circuit diagram of the dual-transmitting coil double-pickup ICPT system. Relational expressions can be obtained through circuit (6).

When the system resonates, that is, $j\omega L_1 + 1/j\omega C_1 = j\omega L_2 + 1/j\omega C_2 = 0$, the coil is in a self-resonant state. Then, the values of I_1 , I_3 , I_6 , and I_8 are obtained by solving the voltage current equations, and then the powers of the transmitting end and the picking end are obtained, thereby obtaining the transmission efficiency of entire ICPT System (7).

$$\left\{ \begin{array}{l}
 U = \left(j\omega L_1 + \frac{1}{j\omega C_1} \right) I_1 j\omega L_1 - \frac{1}{j\omega C_1} - I_2 \\
 U = \left(j\omega L_1 + \frac{1}{j\omega C_1} \right) I_3 j\omega L_1 - \frac{1}{j\omega C_1} - I_4 \\
 0 = \frac{1}{j\omega C_1} I_1 + \left(R + j\omega L_1 + \frac{1}{j\omega C_1} \right) I_2 + j\omega M_{11} I_5 + j\omega M_{12} + I_7 \\
 0 = \frac{1}{j\omega C_1} I_3 + \left(R + j\omega L_1 + \frac{1}{j\omega C_1} \right) I_4 + j\omega M_{21} I_5 + j\omega M_{22} + I_7 \\
 0 = j\omega M_{11} I_2 + j\omega M_{21} I_4 + \left(R + j\omega L_2 + \frac{1}{j\omega C_2} \right) I_5 - \frac{1}{j\omega C_2} I_6 \\
 0 = \frac{1}{j\omega C_2} I_5 + \left(j\omega L_2 + \frac{1}{j\omega C_2} + R_L \right) I_6 = R_L I_8 \\
 0 = j\omega M_{12} I_2 + j\omega M_{22} I_4 + \left(R + j\omega L_2 + \frac{1}{j\omega C_2} \right) I_7 - \frac{1}{j\omega C_2} I_8 \\
 0 = R_L I_6 - \frac{1}{j\omega C_2} I_7 + \left(j\omega L_2 + \frac{1}{j\omega C_2} + R_L \right) I_8
 \end{array} \right. , \quad (6)$$

$$\eta = \frac{\left[\frac{(M_{11} + M_{12} + M_{21} + M_{22}) \omega^3 C_1 C_2}{1 + 2RR_L \omega^2 C_2^2} \right]^2 R_L}{\omega^6 (M_{11} + M_{12} + M_{21} + M_{22})^2 C_1^2 C_2^2 R_L + 2\omega^2 RC_1^2 + 4\omega^4 C_1^2 C_2^2 R^2 R_L} \cdot \frac{1}{1 + 2\omega^2 C_2^2 RR_L} . \quad (7)$$

The ICPT system studied in this paper is an ICPT system under moving conditions. Under the mobile condition, the mutual inductance will change with the displacement. According to [18], the JMAG software is used to analyze the mutual inductance of the moving ICPT system. The sum

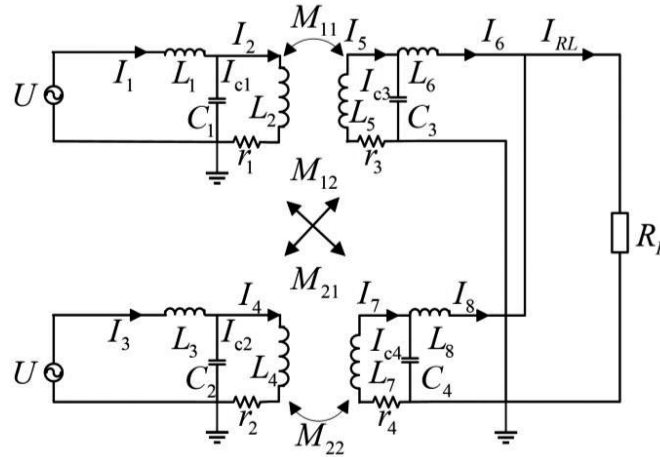


Fig. 3. Equivalent circuit diagram

of the mutual inductance between two coils of length 1 and one coil of length 2 is a constant value during the movement of the rectangular coil of ratio 1:2. In this paper, we assume that the length of the transmitting coil is twice the length of the pick-up coil and the coil is rectangular, then $M_{11} + M_{12}$ is a constant value and $M_{21} + M_{22}$ is a constant value. The expression that brings it into the transmission efficiency shows that the transmission efficiency is a constant value.

4. Simulation verification

Through the above analysis, the parameters are set. The series inductance L_1 and L_3 in the LCL structure of the transmitting end are 50 μH ; the LCL coil inductances L_2 and L_4 of the transmitting end are 50 μH ; the transmitting end LCL compensation capacitors C_1 and C_2 are 811 nF; the pickup end LCL The coil inductances L_5 and L_7 are 40 μH ; the series inductances L_6 and L_8 in the pickup LCL structure are 40 μH , and the pickup terminals LCL compensation capacitors C_3 and C_4 are 1.031 μF . The power supply U is 10 V. The load resistance R_L is a variable parameter. The system is verified by PSpice, where k_1 is the coupling coefficient between L_2 and L_5 , k_2 is the coupling coefficient between L_2 and L_7 , k_3 is the coupling coefficient between L_4 and L_5 , and k_4 is the coupling coefficient between L_4 and L_7 .

The effects of frequency and load on power and efficiency are analyzed by AC sweep under this simulation. At this point, we select five load parameters, 5 Ω , 10 Ω , 15 Ω , 20 Ω , 25 Ω , so that the effect of frequency on output power and system efficiency is more clearly seen.

It can be seen from Fig. 6 that the system resonance frequency is 25 kHz, and then the parameters of the respective components in Fig. 4 are brought into efficiency Formula (7) obtained above, where $\omega = 25000$ Hz, $M_{11} + M_{12} + M_{21} + M_{22} = 46.51 \times 10^{-6}$ H, $C_1 = 8.11 \times 10^{-7}$ F, $C_2 = 1.031 \times 10^{-6}$ F, $R = 0.0001$ Ω , the load resistance is 15 Ω , and the transmission efficiency of the system at the resonant frequency is: $\eta = 98.54\%$. The calculation results are similar to

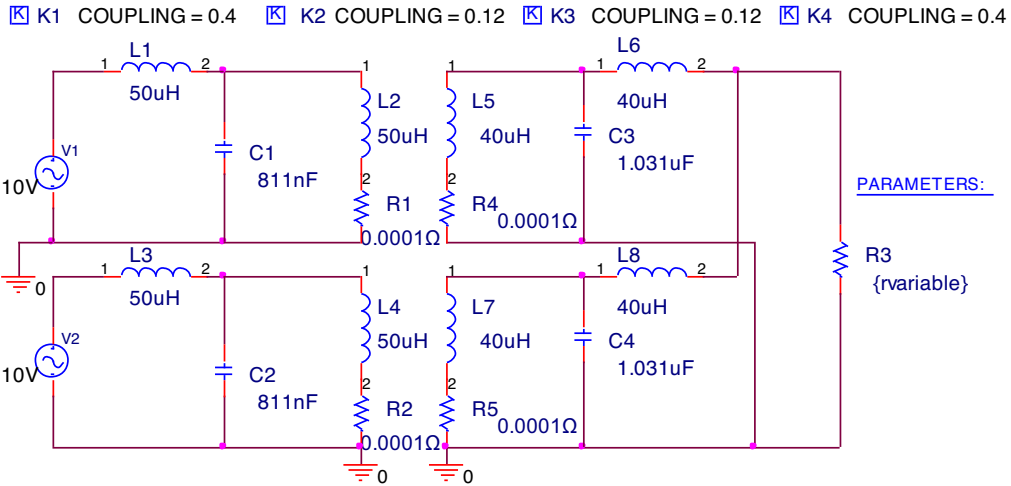


Fig. 4. ICPT circuit PSpice simulation diagram

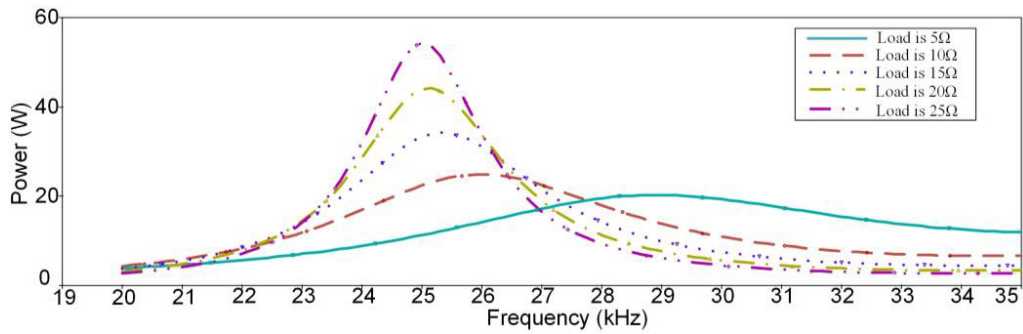


Fig. 5. System output power versus frequency

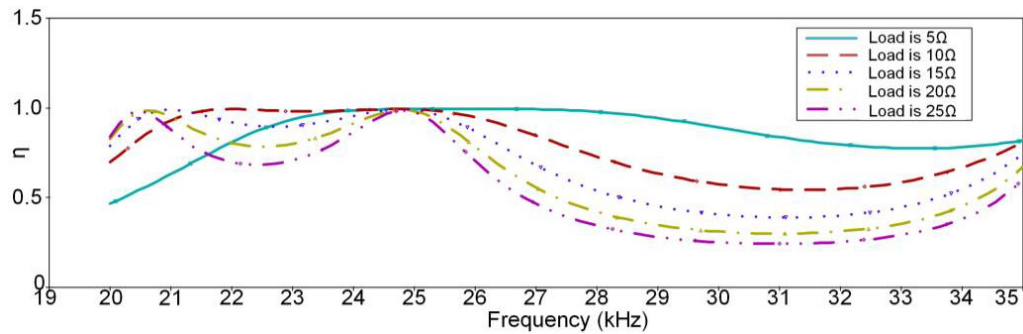


Fig. 6. System efficiency versus frequency diagram

the simulation results. In the process of calculation, it is found that the size of the efficiency is also related to the size of the internal resistance. The smaller the internal resistance, the greater the efficiency. If the internal resistance is small enough, the transmission efficiency at the system resonant frequency is close to 1.

It can be seen from the comparison in Fig. 7 to Fig. 10 that under the premise that the values of $k_1 + k_2$ and $k_3 + k_4$ are constant, when the coupling coefficient changes, the load current and the load voltage change little, indicating the ICPT system in this paper. In the change of mutual inductance, the fluctuation of the load current and voltage will not be caused, and the system can be stabilized under the condition of moving. It can be seen from the current diagrams of the load

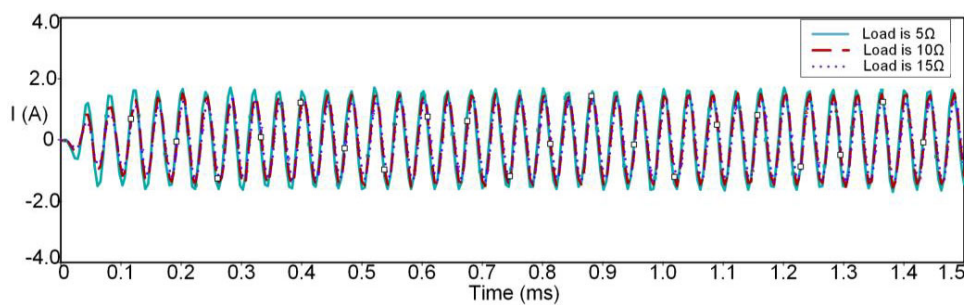


Fig. 7. Load current diagram for $k_1 = 0.26, k_2 = 0.26, k_3 = 0.26, k_4 = 0.26$

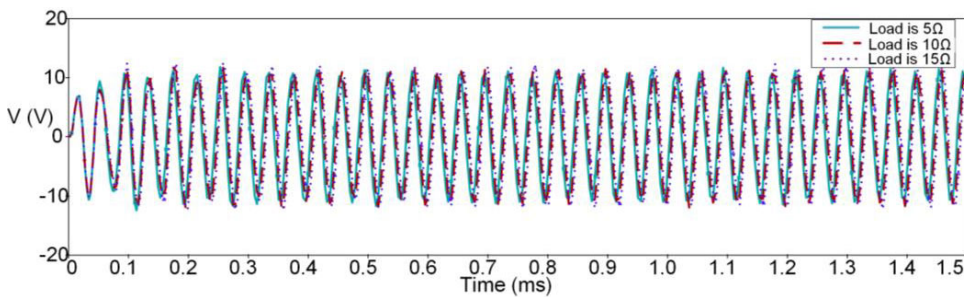


Fig. 8. Transmitting coil voltage diagram for $k_1 = 0.26, k_2 = 0.26, k_3 = 0.26, k_4 = 0.26$

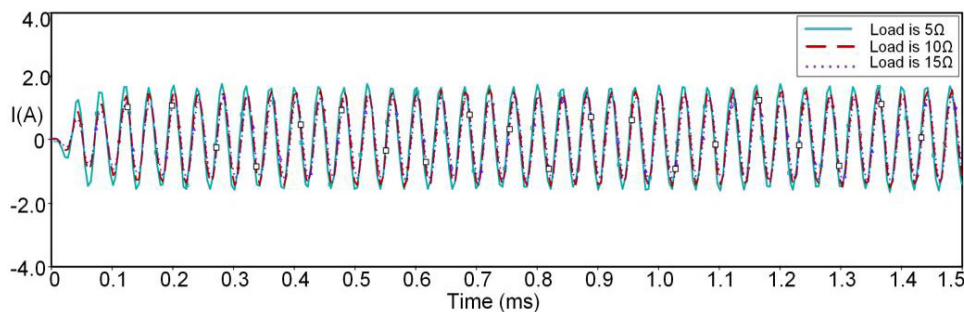


Fig. 9. Load current diagram for $k_1 = 0.4, k_2 = 0.12, k_3 = 0.12, k_4 = 0.4$

that the load current is very stable with the change of the load, and remains basically unchanged, indicating that the system has a constant current at the pickup coil. The voltage of the transmitting coil also does not change due to the change of the load, indicating that the system has a constant voltage at the transmitting end. When the load changes, the current is constant. According to the power formula, $P = I^2 R$, it can be seen that as the load increases, the output power also increases. In addition, if the load changes suddenly during the movement, the system output current does not change. Can improve system stability.

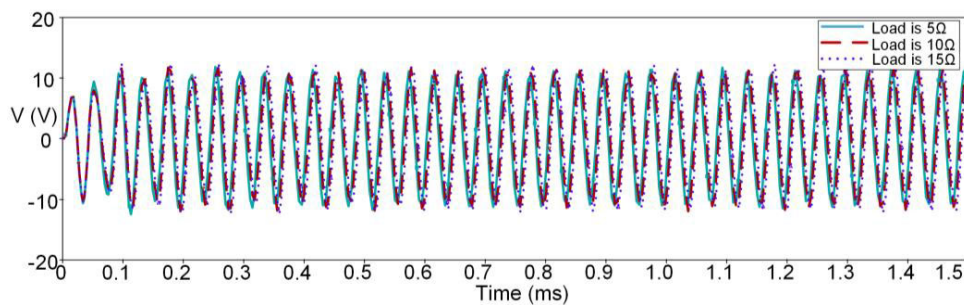


Fig. 10. Transmitting coil voltage diagram for $k_1 = 0.4, k_2 = 0.12, k_3 = 0.12, k_4 = 0.4$

In addition, under the same parameters, we simulate the ICPT system with dual transmitter and single pickup, and the ICPT system with single transmitter and single pickup. As shown in Fig. 11 and Fig. 12, the previous theory is verified by simulation.

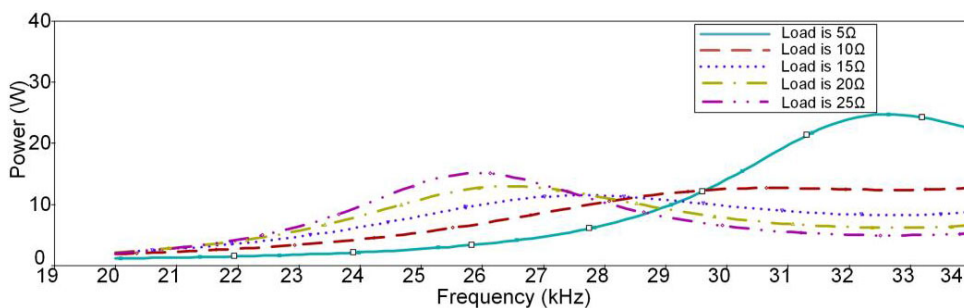


Fig. 11. Dual transmitter, single pick-up ICPT output power diagram

Comparing the output power map of the ICPT system with dual-transmission single pick-up structure and the ICPT system with single-transmitter single pick-up structure with the output power of the dual-transmission dual pick-up structure of the ICPT system proposed in this paper, it can be found that the resonant frequency of different structures is also different. When the system is in resonance, the dual-transmitter single-pick-up ICPT system has a larger output power than the single transmitter single pick-up ICPT system, while the dual transmitter and pickup structure has a larger output power than the dual-transmission single-pick-up ICPT system. The proposed dual-transmission dual pick-up ICPT system can effectively increase the output power and is suitable for some scenarios that require high power.

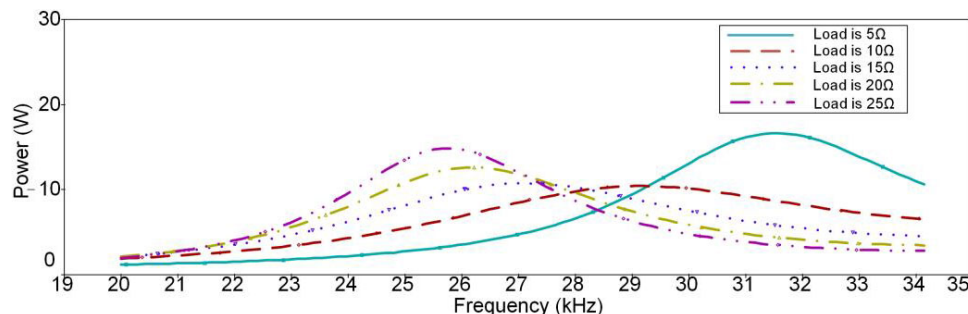


Fig. 12. Single transmitter, single pick-up ICPT output power diagram

5. Conclusion

This paper analyzes the constant current and constant voltage characteristics of the LCL compensation structure and the structure and compensation network of the mobile dual transmitter and pick-up ICPT system. The dual-transmitter dual pick-up ICPT system is analyzed in a resonant state to determine the system transmission efficiency. Simplifying the change of mutual inductance in the moving state by setting the coil so that the mutual inductance changes with certain rules. The voltage and current waveforms of different loads under different mutual inductance conditions are simulated by PSpice software. The characteristics of the constant voltage and the constant current at the pick-up end of the LCL compensation structure are verified by simulation. Finally, by comparing the output power of the dual transmitter dual pick-up ICPT system and the dual-emission single-pickup ICPT system and the single-shot single-pickup ICPT system, it is found that the structure of the ICPT system proposed in this paper can effectively improve the output power.

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