

Efficiency Analysis of a Magnetic Resonance Coupled Wireless Power Transfer System

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Abstract. As the limitations of wired charging methods become more and more prominent, wireless charging as an emerging charging technology has been increasingly emphasized. Among these, resonant wireless charging technology has steadily advanced as circuit design and material research have progressed. This paper firstly introduces the background of wireless charging technology, its uses in daily life, and the significance of increasing wireless charging efficiency; then, this paper analyzes the major variables influencing the resonant wireless charging system's efficiency, including the circuit design, material selection, and system control strategy. By optimizing the coil design and adjusting the circuit parameters, the paper suggests multiple methods to raise the effectiveness of energy transfer. Finally, the paper verifies the effectiveness of these optimization strategies by establishing a simulation model, which offers theoretical justification for enhancing the wireless charging system's functionality in practical applications.

Keywords: Resonant wireless charging, transmission efficiency, coil.

1. Introduction

In modern life, electronic devices have become an integral part of people's daily lives. It is often necessary to plug and unplug the charger when using wired charging, and this operation inevitably affects the life of the charger, not only increasing the wear and tear of the interface, but also leading to poor contact and other problems. At the same time, plugging and unplugging operations are more likely to be incorrect at night or in low light conditions, which can also cause inconvenience to users. With the popularization of electronic devices and the increased demand for charging convenience, it has become especially important to find a more durable and convenient charging method.

Since the start of the Mobile World Congress 2018, wireless charging technology has become a major concern. Especially in recent years, power electronics technology has developed rapidly, and electronic products with wireless charging play an increasingly important role in daily life and work. In daily necessities, sweeping robots, cell phones, and electric toothbrushes have been added with wireless charging functions. In the field of medical devices, wireless charging plays an important role in hearing aids, blood glucose monitors and mobile ECG devices, which not only improves the portability but also the durability of medical devices [1].

However, the problem with wireless charging remains. During wireless charging, energy transfer typically has a lesser efficiency than connected charging, some energy is wasted as heat in the process of transitioning, which not only leads to longer charging time, but also may increase the heat generation of the device. Therefore, enhancing the effectiveness of wireless charging has emerged as a crucial concern for research and development specialists [2].

At present, significant results have been obtained from extensive domestic and international research on resonant wireless charging technology. Utilizing broad bandwidth semiconductors like silicon carbide (SiC) and gallium nitride (GaN) significantly increases the effectiveness of wireless charging; the high frequency characteristics and low on-resistance of GaN devices make the energy loss of wireless charging system under high power effectively reduced; SiC devices play an advantageous role in the high-power wireless charging system due to their excellent high temperature resistance and high voltage characteristics. In terms of coil design, the application of new coil materials such as Litz wire and multi-layer PCB coils effectively reduces AC resistance and eddy current losses. In terms of circuit optimization, the efficiency of wireless charging system is

dramatically improved by improving the resonant circuit and power management circuit. Liu T et al. (2016) constructed a switching circuit with parasitic elements and proposed a method to suppress the oscillation phenomenon during the switching process [3]. Riazmontazer H et al. (2015) enables the rate of change of voltage and current of SiC MOSFETs to be independently regulated by applying gate current (AGD) control technology to control gate current in a closed loop, optimized for reduced switching losses, reduced device stress, and reduced electromagnetic interference (EMI)[4]. Zhejiang University designed a novel SiC MOSFET driving circuit, which is able to utilize passive components such as diodes, capacitors, and resistors to suppress voltage spikes, improve circuit stability, and enhance EMI resistance [5].

In this paper, beginning with the resonant wireless charging system's circuit topology, the techniques to increase efficiency are outlined by examining the major variables influencing the charging efficiency. Firstly, in terms of the design and material selection of the transmission and reception coils, considering the existence of air gaps between the coils and between the coils and the magnetic core in the actual situation, 3D simulation of the square and round coils is required through Maxwell software in order to simulate the real scenario. The effect of the magnetic core addition on charging efficiency can be observed by using the magnetic field diagrams from the simulation results. These can be used to measure their self-inductance and mutual inductance values with and without the magnetic core. Second, this paper uses Simulink to build a circuit model of the resonant wireless charging system for the purpose of circuit optimization. Through iterative adjustments to the capacitance and inductance values in the circuit, the ideal combination of capacitance and inductance is discovered, thereby increasing the system's energy transfer efficiency. By optimizing the circuit parameters, this paper demonstrates that the reasonable design of inductor and capacitor values can effectively improve the system's operating performance and energy transfer efficiency.

2. The Basic Principle of Resonant Wireless Charging

2.1. Circuit Structure of Resonant Wireless Charging System

Fig 1 displays a basic schematic diagram of the resonant wireless charging system, which does not include the step of converting 220V AC power through a rectifier circuit into DC power after voltage conversion. The resonant wireless charging method transmits more effectively at high frequencies because the magnetic field between the coils changes more quickly and has a higher magnetic flux. The coupling coefficient between the coils rises as a result. Coupling coils are used to transport energy from the transmitter to the receiver after a high frequency converter transforms the rectified DC into high frequency AC. The received AC power must be rectified and regulated before being transmitted to the load side since the appliances require steady DC power [6].

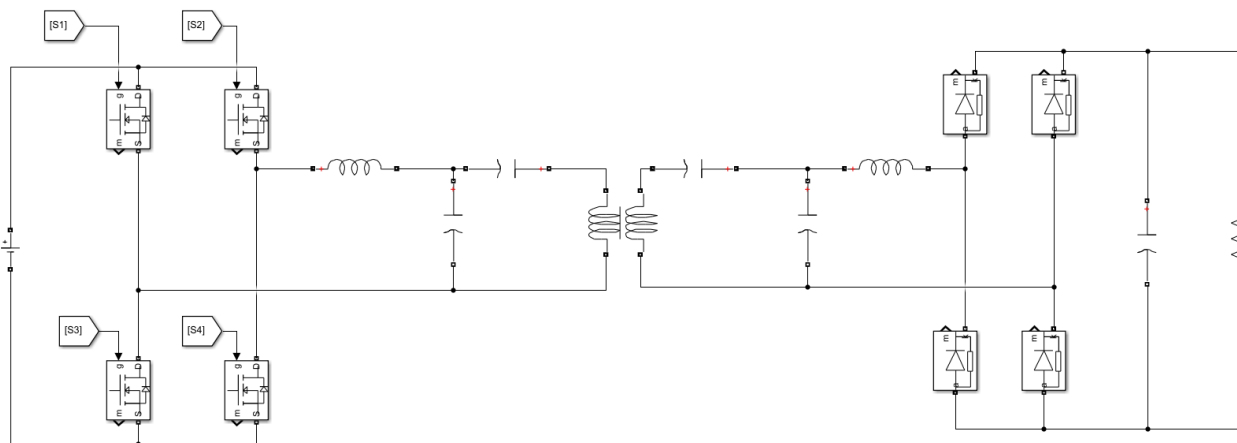


Figure 1. Block diagram of the basic structure of a resonant wireless charging system

Fig 2 shows the inverter control module, which is used to control the switching of the inverter MOS tubes at the transmitter side. The MOS tube can be turned on and off by the square wave's high-

and low-level signals. The MOS tube conducts and permits current to flow when the square wave is at a high level; it turns off and prevents current from flowing. The inverter transforms DC power into high-frequency AC power by quickly and repeatedly switching it on.

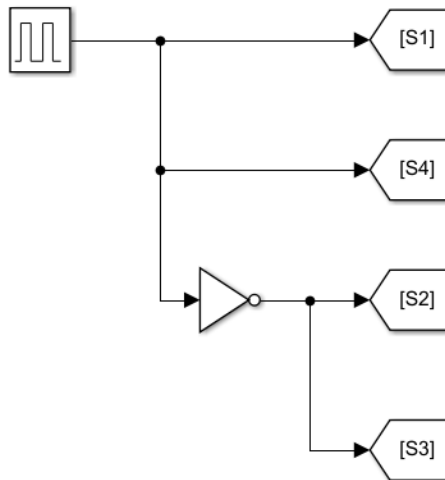


Figure 2. Inverter Control Module

2.2. Factors Affecting the Efficiency of Wireless Charging

Numerous elements influence a resonant wireless charging system's energy transfer efficiency. These factors can be categorized as follows: circuit design, material selection, and system control. The optimization of circuit design includes the coupling coefficient, resonant frequency matching, quality factor of the coil, load impedance, and the design of the primary and secondary coils; the selection of high-performance magnetic materials can improve the magnetic field strength and quality factor, and reduce the energy loss; and the system control strategy includes the optimization of the circuit topology and control strategy. By analyzing these factors, an effective approach for raising the system's energy transfer efficiency of the system can be found to ensure that the wireless charging technology achieves the best performance in practical applications.

In addition, the resonant wireless charging system's circuit model can be constructed for theoretical analysis. Electromagnetic resonant type can be regarded as a special case of electromagnetic induction type, and the difference with the induction type is that it relies on the resonance phenomenon of two coils for power transmission [7]. The circuit equivalent model of a wireless charging system with resonant LC series is displayed in Fig 3.

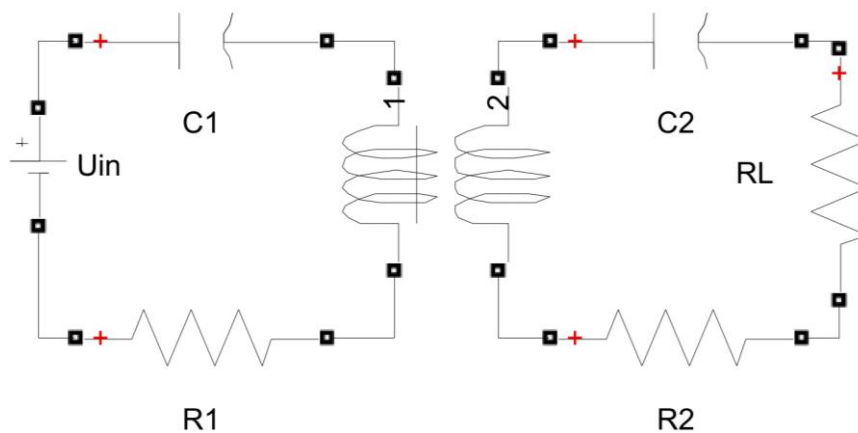


Figure 3. Circuit Equivalent Model of Resonant Wireless Charging System

Indicate the mutual inductance (M) and the angular frequency (ω) of the voltage in the resonant wireless charging system and by L_1 and L_2 the self-inductance of the resonant coil, it can be derived from Kirchhoff's voltage theorem:

$$U_{in} = i_1 R_1 + j(\omega L_1 - \frac{1}{\omega C_1})i_1 - j\omega M_{12}i_2 \quad (1)$$

$$j\omega M_{21}i_1 = (R_2 + R_L)i_2 + j(\omega L_2 - \frac{1}{\omega C_2})i_2 \quad (2)$$

The primary and secondary measurements' impedances are streamlined as follows to facilitate system analysis:

$$Z_1 = R_1 + j(\omega L_1 - \frac{1}{\omega C_1}) \quad (3)$$

$$Z_2 = R_2 + R_L + j(\omega L_2 - \frac{1}{\omega C_2}) \quad (4)$$

Furthermore, take note of the fact that because the resonant system comprises both the transmitting and receiving coils, their mutual inductance is the same:

$$M_1 = M_2 = M \quad (5)$$

From this, the above equation derived from Kirchhoff's voltage theorem can be simplified as follows:

$$U_{in} = i_1 Z_1 - j\omega M i_2 \quad (6)$$

$$j\omega M i_1 = Z_2 i_2 \quad (7)$$

Solving the above equations, the primary and secondary measured currents can be solved for:

$$i_1 = \frac{U_{in} Z_2}{Z_1 Z_2 + (\omega M)^2} \quad (8)$$

$$i_2 = \frac{U_{in} (\omega M)}{Z_1 Z_2 + (\omega M)^2} j \quad (9)$$

The wireless charging system's power transfer efficiency can then be calculated as follows:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\frac{U_{in}^2 (\omega M)^2 R_L}{(Z_1 Z_2 + (\omega M)^2)^2}}{\frac{U_{in}^2 Z_2}{Z_1 Z_2 + (\omega M)^2}} \times 100\% = \frac{(\omega M)^2 R_L}{Z_2 (Z_1 Z_2 + (\omega M)^2)} \times 100\% \quad (10)$$

The above equation shows that the wireless charging system's efficiency η in transferring energy is closely related to the impedance Z_1 and Z_2 of the system, the coil self-inductance M and the load impedance R_L . In order to carry out the study of wireless charging efficiency optimization, this paper will next carry out a detailed study in three aspects: material selection, coil design and circuit parameters. Firstly, the influence of different magnetic materials on wireless charging efficiency how high permeability and low loss materials can improve the energy transfer efficiency will be analyzed and explored. Then the coil design will be optimized through simulation experiments, including the effects of coil shape, size, and whether it has a magnetic core or not. Finally, methods to optimize the wireless charging efficiency will be further searched by changing the individual inductor and capacitor values in the simulation circuit.

3. Optimization Study of Resonant Wireless Charging Efficiency

3.1. Principle of Resonant Wireless Charging Efficiency Optimization

Resonant wireless charging efficiency can be greatly enhanced by raising the quality factor [8]. The corresponding model of the resonant wireless charging system's primary measurement is displayed in Fig 4.

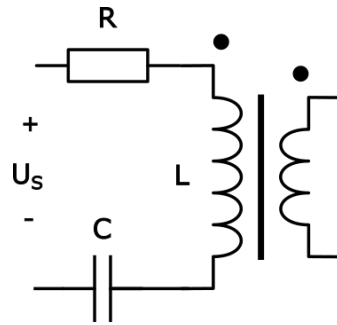


Figure 4. Equivalent model for primary measurement of resonant wireless charging system

Denote the angular frequency of the wireless charging system when it reaches the resonant state by ω_0 . Denote the self-inductance of the primary measurement coil by L . Calculate the primary measurement impedance to be $Z = R + j(\omega L - \frac{1}{\omega C})$. In a series resonant circuit, the inductive and capacitive impedances of the circuit cancel each other out, and the total impedance of the circuit is minimized, at which time the angular frequency of the resonance is $\omega_0 = \frac{1}{\sqrt{LC}}$.

As the system reaches a state of resonance, the voltages of the inductor and capacitor are equal. In this way, the resonant circuit's quality factor is determined:

$$Q = \frac{U_{L0}}{U_s} = \frac{U_{C0}}{U_s} = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 RC} = \frac{1}{R} \sqrt{\frac{L}{C}} \quad (11)$$

As can be seen from the preceding calculation, the quality factor and the coil's self-inductance value L are directly proportional. Increasing the self-inductance value L is the easiest way to improve the energy transfer efficiency of the system. The next set of experiments was designed to improve the energy transfer efficiency of the wireless charging technology. In particular, the studies verified the influence of the magnetic core on the coil's self-inductance and the resonance condition of the commonly-used LCCL circuit configuration.

3.2. Coil Design Optimization

By optimizing the shape, size and core configuration of the coil, the coupling efficiency and overall performance of the system can be significantly improved. This section will concentrate on how modifying the coil design might maximize a wireless charging system's energy transfer efficiency.

Magnetic cores are usually made of materials with high magnetic permeability, such as ferrites. These materials are effective in concentrating and directing the magnetic flux, thus enhancing the magnetic field strength of the coil [9]. Since the self-inductance value is exactly proportional to the magnetic flux created by the coil, an increase in magnetic flux passing through the coil causes the coil's self-inductance to rise. At the same time, the core also causes the flux to be confined more inside the core than in the air between the two coils, somewhat isolating the flux coupling between the two coils, and the mutual inductance value may decrease.

The 3D simulation of square and circular coils can be performed using Maxwell software to measure their self-inductance, mutual inductance, and coupling coefficients with and without a magnetic core, respectively. The detailed comparison and analysis of these parameters can explore

the specific impact of the magnetic core on the system performance and find the optimal coil configuration to improve the efficiency and stability of the wireless charging system.

Fig 5 shows the circular coil structure without magnetic core built in Maxwell. In order to simulate the existence of an air gap for wireless charging in reality, the primary and secondary side coils are placed 10 cm apart in the simulation.

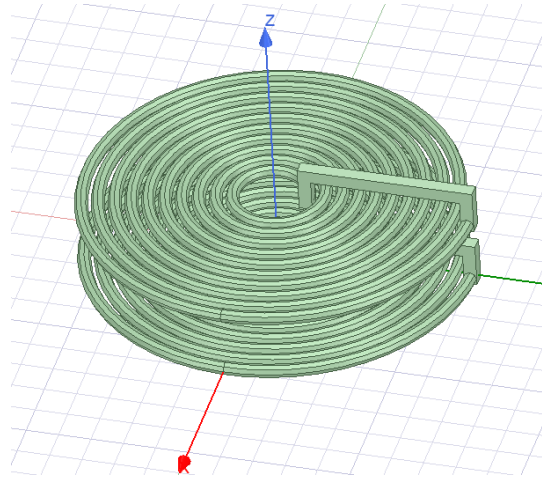


Figure 5. Circular coil structure without core

An excitation current of $I=1A$ is added to the primary and secondary side coils in the simulation in order to calculate their respective self-inductance, mutual inductance, and coupling coefficients, as shown in Table 1:

Table 1. Parameters of primary side and secondary side circular coils without cores

Parameter	Value
$L_1 / \mu H$	3.09
$M / \mu H$	1.53
$L_2 / \mu H$	3.15
K	0.77

Next, ferrite cores were added to the primary and secondary side coils, respectively, and the cores were placed 1 cm apart from the coils in the simulation in order to simulate the existence of an air gap between the coils and the cores in reality. The core placement is shown in Fig 6.

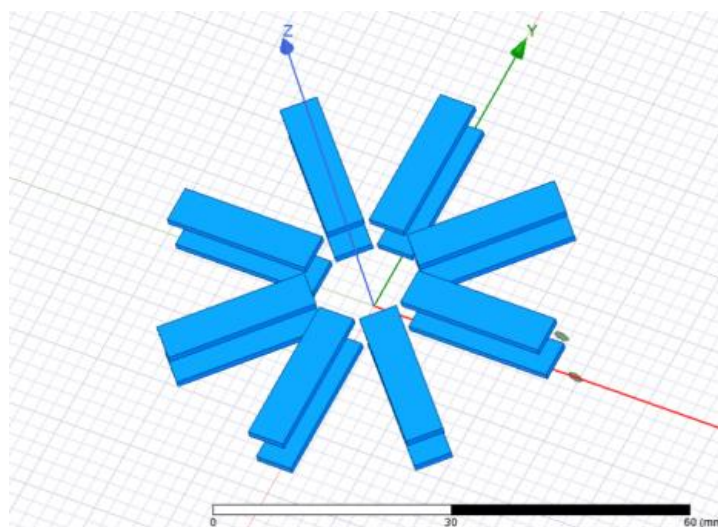


Figure 6. Core placement

As can be seen in Fig. 6, eight cores were set up for each coil, with each core placed at an angle of 45° apart. Fig 7 shows the coil structure after setting up the cores.

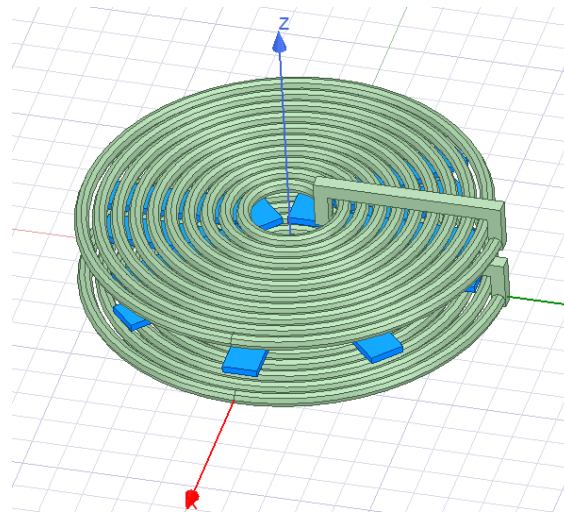


Figure 7. Circular coil structure with magnetic core

Similarly, as shown in Table 2, an excitation current of $I=1A$ is applied to the primary and secondary side coils' coupling coefficients, mutual inductance, and relative self-inductance.

Table 2. Parameters of primary side and secondary side circular coils with cores

Parameter	Value
$L_1 / \mu H$	3.96
$M / \mu H$	0.92
$L_2 / \mu H$	4.23
K	0.22

Comparison of the data in Tables 1 and 2 reveals that when a core is added to the coil, there is a significant increase in the self-inductance values L_1 and L_2 ; while the mutual inductance value M and the coupling coefficient K are significantly reduced.

Next, the same more commonly used square coil is used for simulation. Fig 8 shows the structure of the square coil without the added core. Again, the primary and secondary side coils are placed 10 cm apart in the simulation.

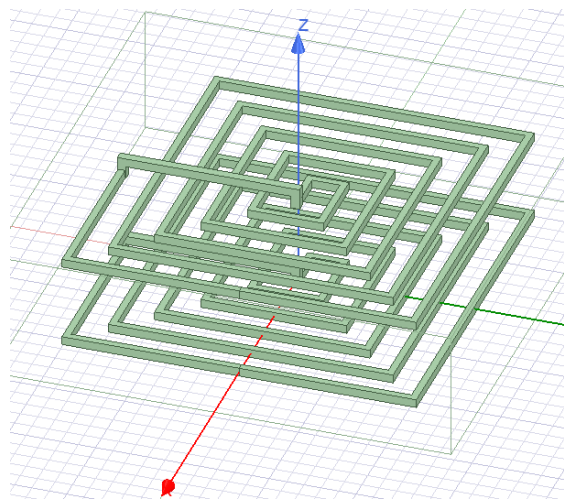


Figure 8. Square coil structure without core

Similarly, an excitation current of $I=1A$ is added to relative self-inductance, mutual inductance, and coupling coefficients of the primary and secondary side coils, as indicated in Table 3:

Table 3. Parameters of primary side and secondary side square coils without cores

Parameter	Value
$L_1 / \mu\text{H}$	0.24
$M / \mu\text{H}$	0.022
$L_2 / \mu\text{H}$	0.32
K	0.79

Eight cores were set for each coil in the same way. Fig 9 shows the coil structure after setting the cores.

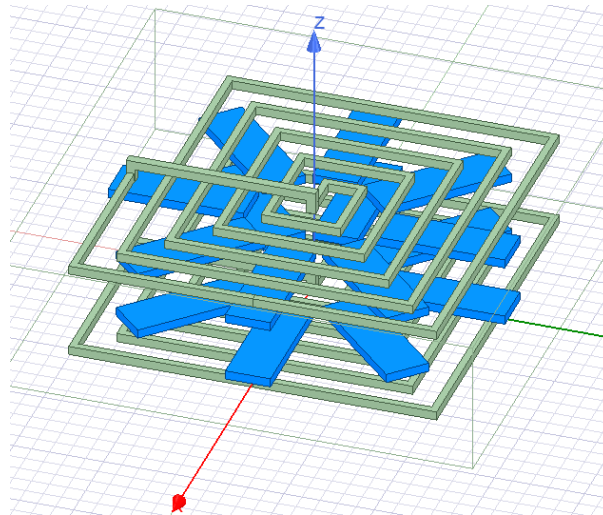


Figure 9. Square coil structure without core

Similarly, an excitation current of $I=1\text{A}$ is added to relative self-inductance, mutual inductance, and coupling coefficients of the primary and secondary side coils, as indicated in Table 4:

Table 4. Parameters of primary side and secondary side square coils with cores

Parameter	Value
$L_1 / \mu\text{H}$	0.25
$M / \mu\text{H}$	0.0068
$L_2 / \mu\text{H}$	0.368
K	0.22

Comparison of the data in Tables 3 and 4 leads to similar conclusions as for the circular coil.

It can be concluded that when the core is added to the coil, there is a significant increase in the self-inductance values L_1 and L_2 ; while the mutual inductance value H and the coupling coefficient K are significantly reduced. This verifies the derivation of the effect of the magnetic core on the coil parameters before simulation.

Fig 10 and 11 show the magnetic fields near the circular and square coils after the addition of the magnetic core.

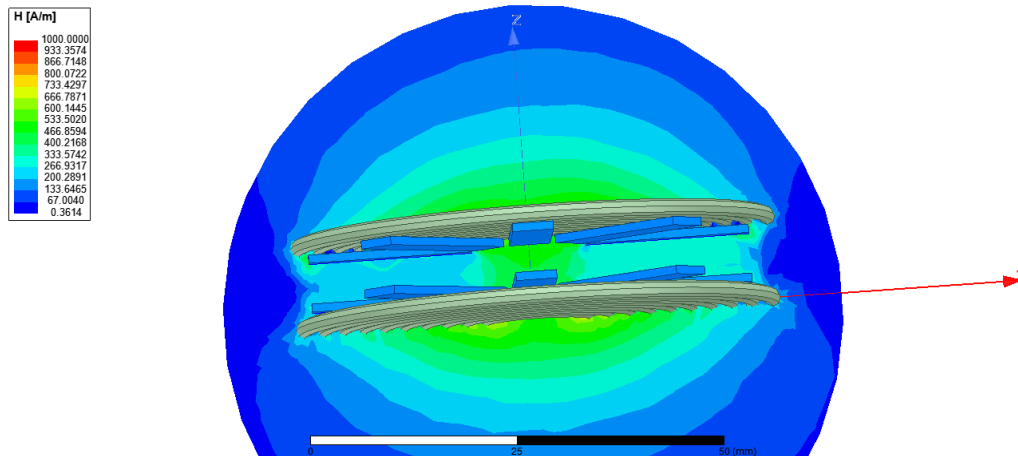


Figure 10. Magnetic field in the vicinity of a circular coil with a magnetic core

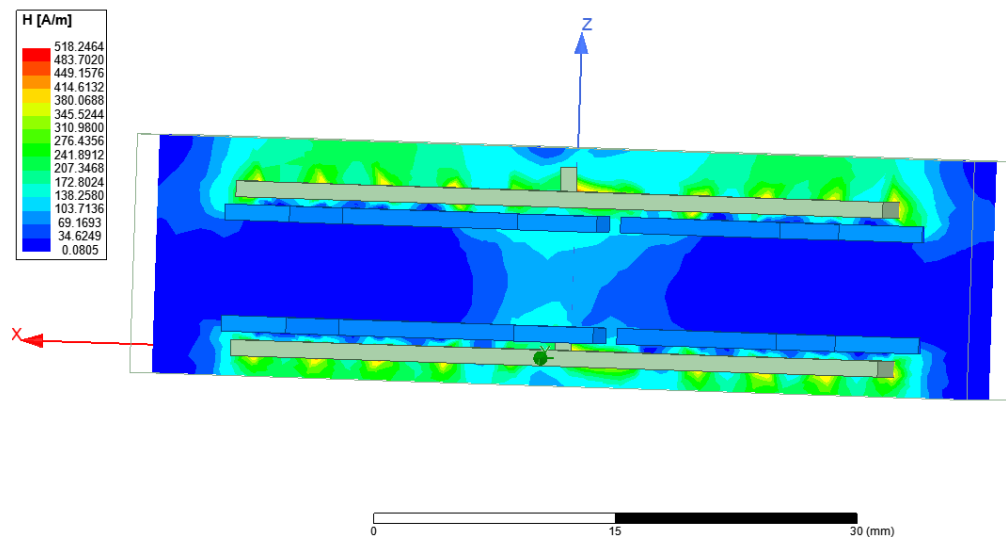


Figure 11. Magnetic field in the vicinity of a square coil with a magnetic core

As can be seen from these two graphs above, the magnetic field near the coil is significantly enhanced with the addition of the core. This indicates that high permeability materials such as ferrite can effectively concentrate and direct the magnetic flux. The presence of the magnetic core improves the coupling coefficient of the coil, making energy transfer more efficient. This also verifies the important role of magnetic core materials in wireless charging systems: the energy transfer efficiency of the system can be significantly improved by optimizing the core material and design. All these simulation results prove that using high permeability materials such as ferrite can help wireless charging systems function better.

3.3. Circuit Optimization

Certain circuit characteristics are critical to the energy transfer efficiency of resonant wireless charging devices [10]. A typical topology is the LCCL resonant circuit, where the system's stability and efficiency can be maximized by judiciously varying the quantities of capacitance and inductance. Thus, this chapter will study how to modify the inductance and capacitance values in the LCCL resonant wireless charging system in order to increase the overall energy transfer efficiency and examine the specific implications on the system's functioning.

To verify and visually inspect how the circuit parameters affect the system's energy transfer efficiency, a simulation model can be created in Matlab/Simulink. The circuit schematic for the Simulink-built resonant wireless charging system is displayed in Fig 12.

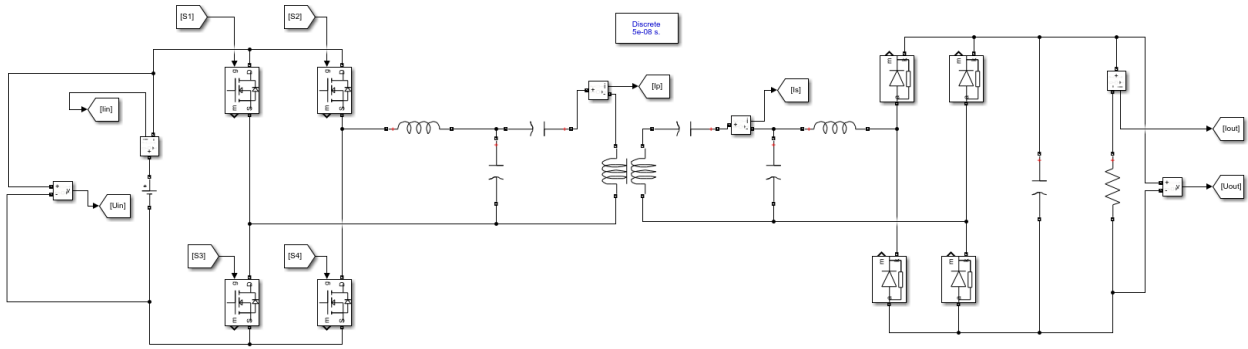


Figure 12. Magnetic field in the vicinity of a square coil with a magnetic core

In order to verify the performance of the LCCL resonant wireless charging system the currents of the primary and secondary transmitting coils need to be captured to confirm that the current waveforms are stable sinusoidal curves. The system's input and output voltages and currents were also measured, and these values were used to compute the system's output power and energy transfer efficiency. Fig 13 shows the acquisition and calculation of various types of data of the system. By analyzing and calculating these data, the actual working effect of the system under different inductance and capacitance configurations can be evaluated to ensure that the outcomes of the simulation match what is predicted theoretically.

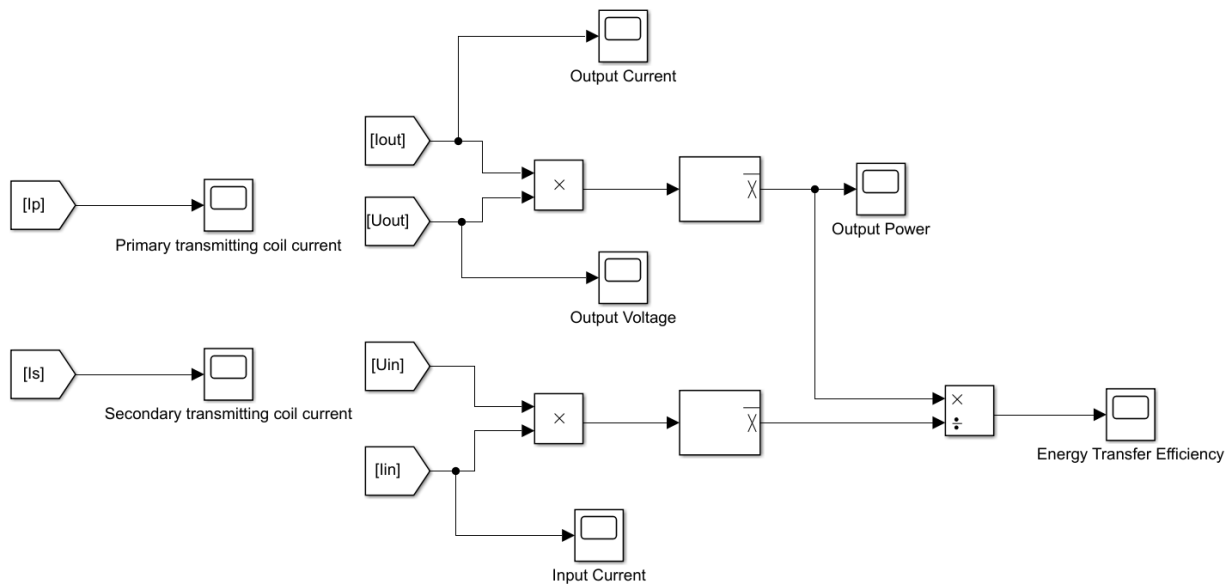


Figure 13. data acquisition and arithmetic

Fig 14 illustrates a circuit equivalent model of the primary measurement of the resonant wireless charging system.

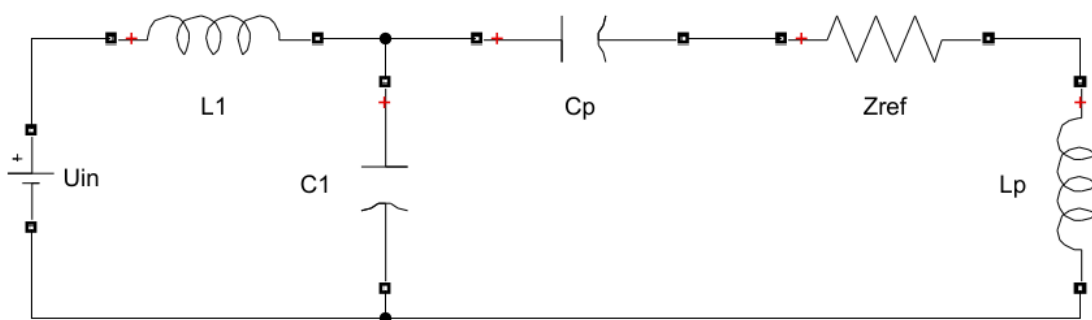


Figure 14. Circuit equivalent model for primary measurement of resonant wireless charging system

Since the primary measurement LCCL structure has low-pass and high-resistance characteristics, its equivalent model is shown in Fig 14, where Z_{ref} is the reflected impedance of the secondary side.

When the secondary side is resonantly compensated, Z_{ref} is purely resistive. At this time, the system operating frequency is $\omega_0 = \frac{1}{\sqrt{L_1 C_1}}$

The impedance can be analyzed and calculated by Kirchhoff's voltage theorem to obtain the resonance conditions at the transmitter side:

$$\omega_0 L_p - \frac{1}{\omega_0 C_p} - \frac{1}{\omega_0 C_1} = 0 \quad (12)$$

Similarly, the secondary side can be analyzed to obtain the resonance condition of the bilateral wireless charging system as:

$$L_1 C_1 = \frac{1}{\omega_0^2} \quad (13)$$

$$L_2 C_2 = \frac{1}{\omega_0^2} \quad (14)$$

$$L_p - L_1 = \frac{1}{\omega_0^2 C_p} \quad (15)$$

The capacitance values of C_1 , C_2 , C_p , and C_s under resonant conditions can be derived by varying a set of L_1 and L_2 values. During the simulation process, by repeatedly adjusting the capacitance values of L_1 and L_2 and evaluating the performance under each configuration the optimal combination of inductance and capacitance can be found, which can significantly improve the energy transfer efficiency of the system.

A set of system parameters is designed after experimental simulation with multiple sets of data. The maximum system efficiency and output power can be realized under this set of system parameters, as shown in Table 5.

Table 5. Wireless charging system parameters

Parameter	Value
Frequency/Hz	85000
V_{DC} / V	540
$L_1 / \mu H$	27
$L_2 / \mu H$	72
$C_1 / \mu F$	0.130
$C_2 / \mu F$	0.0487
$C_p / \mu F$	0.0165
$C_s / \mu F$	0.0449

Fig 15 shows the system output voltage. As can be seen through fig 15, the transition time of the system is 0.08 s. The transition time is short, the response time is fast, and it meets the basic requirements of the system design. The system enters the steady state after 0.08s, basically no fluctuation, smooth output, the output voltage is always stabilized at about 642V, which meets the control requirements of the system discharge.

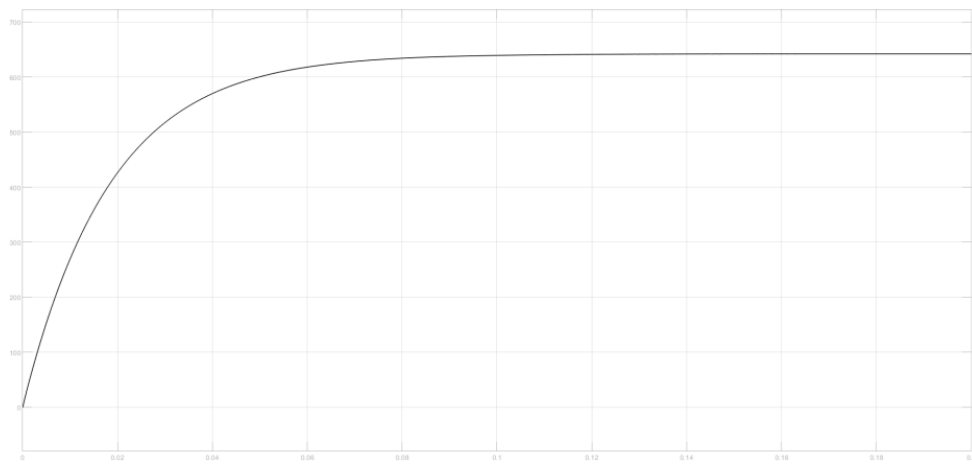


Figure 15. Wireless charging system output voltage

The system energy transfer efficiency is displayed in fig 16. The system parameters have an energy transfer efficiency of around 95%, allowing for a more effective realization of the system's energy transfer from the transmitter to the receiver.

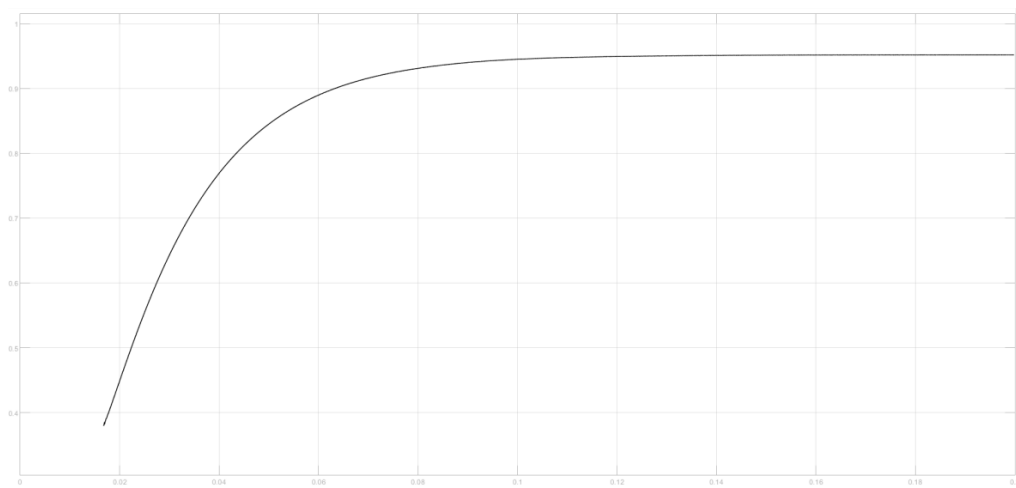


Figure 16. Wireless charging system energy transfer efficiency

Fig 17 and 18 show the primary-side and secondary-side transmitter coil currents, respectively. The current waveforms on both sides are stable sinusoidal curves with basically no fluctuation, which satisfies the control requirements of the system.

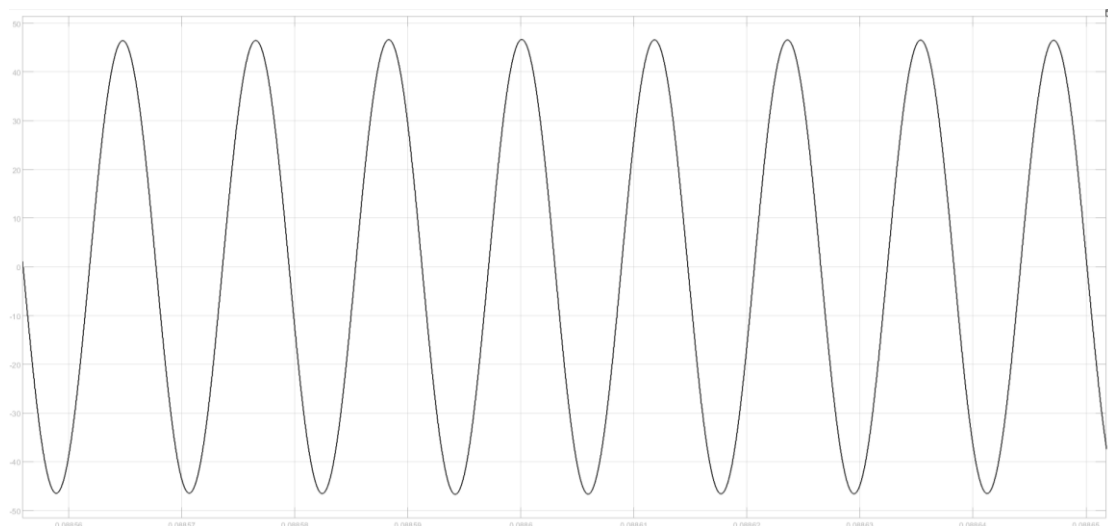


Figure 17. Primary side transmitting coil current

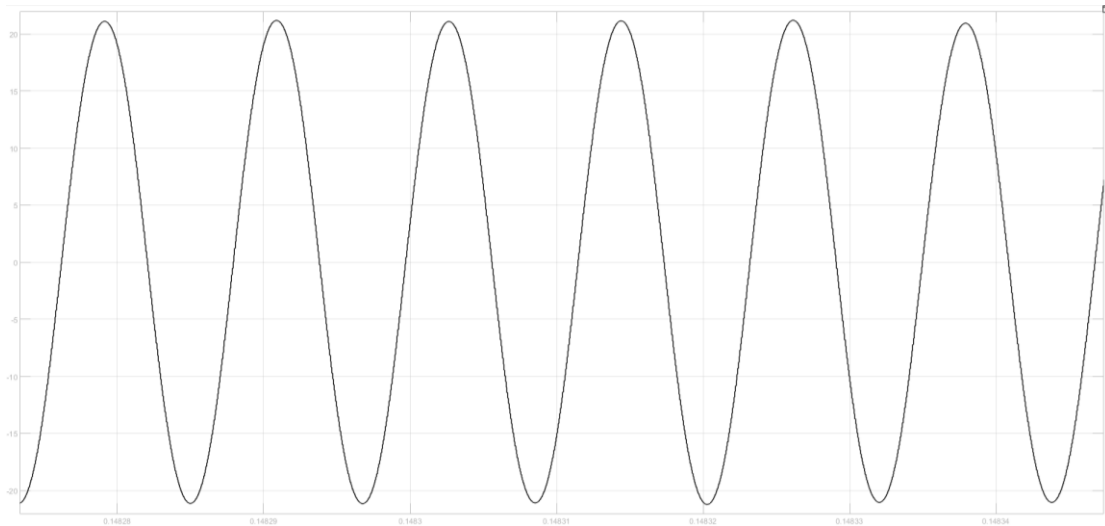


Figure 18. Secondary side transmitting coil current

The capacitance values of C_1 , C_2 , C_p and C_s are obtained by changing the values of L_1 and L_2 several times and according to the resonance conditions of the LCCL structured circuit, the comparative analysis can be obtained in the following table:

Table 6. Effect of different wireless charging system parameters on energy transfer efficiency

Parameter	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Frequency /Hz	85000	85000	85000	85000
V_{DC} / V	540	540	540	540
$L_1 / \mu H$	27	40	70	100
$L_2 / \mu H$	72	60	40	20
$C_1 / \mu F$	0.130	0.0877	0.050	0.035
$C_2 / \mu F$	0.0487	0.0175	0.0206	0.025
$C_p / \mu F$	0.0165	0.0584	0.0876	0.175
$C_s / \mu F$	0.0449	0.0390	0.0319	0.0270
Energy Transfer Efficiency	95%	96%	96.4%	92.3%

The energy transfer efficiency of the four groups of wireless charging systems set according to the bilateral capacitance and inductance parameters in Table 6 is above 90%. It can be concluded that the parameters that meet the resonance conditions can keep the system with high energy transfer efficiency.

Table 7 shows the comparative analysis of the energy transfer efficiency of the wireless charging system designed in this paper and other references. L_p is the coil self-inductance of the primary measurement, L_R is the coil self-inductance of the secondary side, and R_L is the load resistance. Evidently, the built wireless charging system can maintain a high energy transfer efficiency at 85 kHz of high frequency AC under satisfying the LCCL resonance conditions proposed in this paper.

Table 7. Comparison of the parameters with other literature wireless charging systems [11] [12]

Parameter	Values used in this paper	Values used in the literature [11]	Values used in the literature [12]
Frequency/Hz	85000	200000	85000
$L_1 / \mu\text{H}$	27	48.26	16
$C_1 / \mu\text{F}$	0.130	0.01347	0.226
$C_p / \mu\text{F}$	0.0165	0.03954	0.061
$C_s / \mu\text{F}$	0.0449	0.00988	0.015
$L_p / \mu\text{H}$	240	65.67	56.40
$L_R / \mu\text{H}$	150	65.32	52.31
R_L / Ω	40	50	2
Energy Transfer Efficiency	95%	94.127%	83%

It is clear from the analysis and simulation images above that the calculated resonance conditions have been confirmed, and the theoretical foundation put forward in this work is sound. According to the simulation results, not only can the system's output efficiency reach 95% when the primary and secondary transmitting coils' current waveforms are designed to meet resonance conditions, but they also produce stable sinusoidal images in their current waveforms. The findings indicate that tweaking the inductance and capacitance values can enhance the resonant wireless charging system's charging efficiency. This validates the design method's effectiveness. Additionally, it also provides a theoretical reference for practical applications.

4. Conclusion

The resonant wireless system can improve the energy transfer efficiency by optimizing the device materials, coil and core design and circuit parameters. In this paper, the resonant wireless charging system is systematically investigated through theoretical calculation and simulation model verification and construction. Firstly, through theoretical derivation, the mathematical expressions for primary and secondary side currents, system transfer efficiency, and load power are obtained. Next, by establishing the circuit equivalent model of the wireless charging system, the resonance conditions of the LCCL wireless charging system are obtained. Then, using Ansys Maxwell and other simulation software, the differences in self-inductance, mutual inductance, and coupling coefficients before and after the addition of ferrite cores to square coils and round coils are analyzed, and possible explanations are made through theoretical derivation and simulation verification. Finally, simulation software such as Matlab/Simulink is used to construct the LCCL wireless charging system, and the derived bilateral resonance conditions are used to design the inductance and resistance values and perform group testing so that the system maintains a high transmission efficiency (95%).

This project has basically accomplished the initial goal, but there are still imperfections in the model design and construction as well as the control strategy. Even if a set of inductance and capacitance parameters were determined through simulation trials to keep the system's transmission efficiency high, more research is required to determine why the particular values of inductance and capacitance were chosen to get this outcome. Further analysis is required to determine how the coil's form, number of turns, layers, and wire diameter affect the system's transmission efficiency. The simulation does not take into account the impact of these coil parameters on the coils' mutual and self-inductance values. Additional research can be done on the inverter's material and control. All these related works need to be further improved.

References

- [1] Song Y. Research and optimization design of wireless charging system for implantable medical devices. Anhui University, 2018.
- [2] Gao YQ. Characterization research and system design of magnetic resonant wireless energy transmission system. Zhejiang University, 2017.
- [3] Liu T, Ning R, Wong T T Y, et al. Modeling and analysis of SiC MOSFET switching oscillations. *IEEE journal of emerging and selected topics in power electronics*, 2016, 4 (3): 747 - 756.
- [4] Riazmontazer H, Rahnamaee A, Mojab A, et al. Closed-loop control of switching transition of SiC MOSFETs, 2015 IEEE Applied Power Electronics Conference and Exposition (APEC). *IEEE*, 2015: 782 - 788.
- [5] Yue-Cai Fang, Wentao Cui, Lu Shu, Jun-Ming Zhang. A novel SiC MOSFET driving circuit. *Electronic Technology R&D*, 2018: 1 – 5.
- [6] Guo Wangyang. Research and design of resonant wireless charging system. Xi'an University of Technology, 2022.
- [7] G. Liu, Q. Y. Zheng, D. Z. Wang. A wireless charging method based on electromagnetic induction. *Journal of Beijing University of Information Science and Technology (Natural Science Edition)*, 2013, 28 (02): 51 - 54.
- [8] J.P. Zhao. Research and design of high efficiency electric vehicle wireless charging system. Tianjin University of Technology, 2017.
- [9] Guoming Chuai. Research on the efficiency optimization of wireless charging system applying SiC MOSFET. Harbin Institute of Technology, 2020.
- [10] HAN Feng, PAN Sanbo, ZHOU Yang. Output characteristics of LCC-S type magnetically coupled resonant wireless charging system. *Journal of Shanghai Institute of Electrical Engineering*, 2018, 21 (01): 8 - 13.
- [11] T.W. Wu. Research on magnetic coupling full-bridge LCCL resonant wireless energy transmission system. Guangdong University of Technology, 2019. DOI: 10.27029/d.cnki.ggdgu.2019.000481.
- [12] Zhang Guozheng. Research and design of wireless charging system efficiency optimization for UAV. Southwest University of Science and Technology, 2023.