Simulation Analysis of Contactless Energy Transfer System Based on Series Resonant Structure

Ruiming Yang*

School of Engineering, Shanghai Ocean University, Shanghai,20000, China

*Corresponding author: ray13580407450@outlook.com

Abstract. With the rapid development of wireless power transmission technology, wireless charging schemes based on magnetic resonance coupling are gradually becoming one of the mainstream application directions because of their high efficiency and structural flexibility. This paper focuses on the typical basic circuit of wireless charging, constructs a contactless energy transmission system based on a series resonance structure, and completes the modeling and simulation analysis on the Multisim platform. The circuit design includes a high-frequency excitation source, a coupling transformer, a primary and secondary resonant network, a rectifier filter and a load module. It has the characteristics of compact structure and clear parameters. By simulating and measuring the voltage and current waveforms of key nodes in the system, the influence of capacitor matching, inductor setting, and coupling coefficient on output voltage stability and system efficiency is studied quantitatively. The results show that the system can achieve stable wireless power supply performance with small output fluctuation and high transmission efficiency when the parameters are properly configured. This study provides a theoretical basis and technical support for the design optimization of a complex wireless charging system.

Keywords: Wireless power transmission; Magnetic resonance coupling; Series resonance structure.

1. Introduction

In recent years, the rapid popularization of electric vehicles has made charging facilities gradually become a key link restricting their development. Although wired charging has been widely used, it has shortcomings in reliability and environmental adaptability, such as unstable operation under humid conditions [1]. With the proposal and development of wireless power transmission technology, energy exchange between vehicles and charging ports can be completed without direct contact, bringing new possibilities for charging methods [2-4]. Compared with traditional methods, this kind of contactless power supply not only reduces the plugging operation, but also shows certain advantages in safety and flexibility due to the reliance on electromagnetic fields or microwave transmission [5-7]. However, its promotion is still limited by low efficiency and public doubts about the potential impact of electromagnetic radiation. For this reason, domestic scientific research institutions and universities have gradually shifted their research focus to efficient wireless transmission mechanisms and application exploration, with a view to promoting the engineering and industrialization process of this technology [8-11].

Wireless power transmission technology can be roughly divided into inductive coupling, electromagnetic radiation, and magnetic resonance three realization paths. Among them, magnetic resonance coupling has become a hot research topic because of its high transmission efficiency, strong alignment tolerance, and outstanding power supply ability at medium distances. The method realizes efficient contactless power transmission at medium distances through energy exchange between two resonant loops, and is suitable for most embedded electronic and nested packaging scenarios. In order to take full advantage of magnetic resonance, a resonant network, an inductive coupling structure, and a rectifier filter mechanism must be designed reasonably to improve the overall performance of the system.

At present, most of the researches focus on complex system integration, high power transmission and dynamic power regulation, while systematic research on basic circuit structure and parameter optimization process is relatively rare. Based on this, a typical wireless charging basic circuit system is designed and constructed, which adopts a series resonant bilateral structure. The system modeling and performance testing are completed on the Multisim simulation platform, and the influence of main circuit parameters on output characteristics and system efficiency is systematically analyzed.

This paper will comprehensively describe the performance of the wireless charging basic circuit on the simulation platform through circuit modeling, simulation results display, and performance analysis, and strive to establish a connection between basic theory and engineering practice, providing a useful reference for the development and application of wireless energy transmission systems.

2. Theory

2.1. Basic Principle Analysis Of Series Resonance

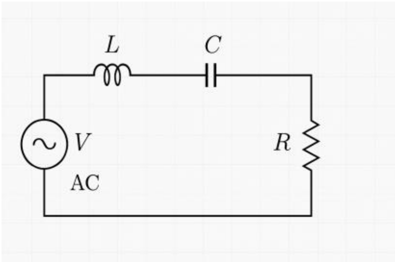

Fig. 1 Basic Series Resonant Circuit

As shown in Figure 1, the series resonant circuit consists of AC voltage source V_{AC}, inductance L, capacitance C and resistance R in series, which is one of the most basic and typical resonant circuits. Under AC excitation, the inductance and capacitance in the circuit will show frequency characteristics of inductive reactance (increasing with frequency) and capacitive reactance (decreasing with frequency), respectively. As the operating frequency of the circuit increases, the inductive reactance ωL of the inductor and the capacitive reactance $1/\omega C$ of the capacitor will be exactly equal at a certain frequency, thus canceling each other in the complex frequency domain. This frequency is the resonant frequency at which the inductive and capacitive elements no longer shift the phase of the current and the impedance of the entire circuit is determined only by the resistance R. At this point, the total impedance of the circuit reaches a minimum value $Z = R$ and the current amplitude reaches a maximum. When the current is maximum, the energy transfer efficiency of the system reaches the peak value, so the resonant working state is often used in wireless charging, RF circuits, filters, signal amplifiers and other occasions, especially in efficient energy transfer and frequency selectivity. It is worth noting that if the frequency deviates from the resonance point, the inductive reactance and capacitive reactance no longer cancel each other, the total impedance increases, the current decreases, and the circuit performance decreases significantly. Therefore, precise control and tuning of resonant states is critical to engineering design.

Formula Description

1. Voltage equation (Kirchhoff voltage law KVL):

$$V_{AC} = I\left(R + j\omega L - \frac{j}{\omega C}\right) \tag{1}$$

2. Total impedance expression:

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{2}$$

3. Resonance conditions: At the resonance point, inductive reactance and capacitive reactance are equal, i.e.:

$$\omega L = \frac{1}{\omega C} \tag{3}$$

Solve for resonant angular frequency:

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{4}$$

The corresponding resonant frequency is:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{5}$$

4. Quality factor (Q value): used to evaluate the system energy concentration and resonance sharpness, defined as follows:

$$Q = \frac{\omega_0 L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{6}$$

3. Experimental Method

3.1. Simulation Circuit

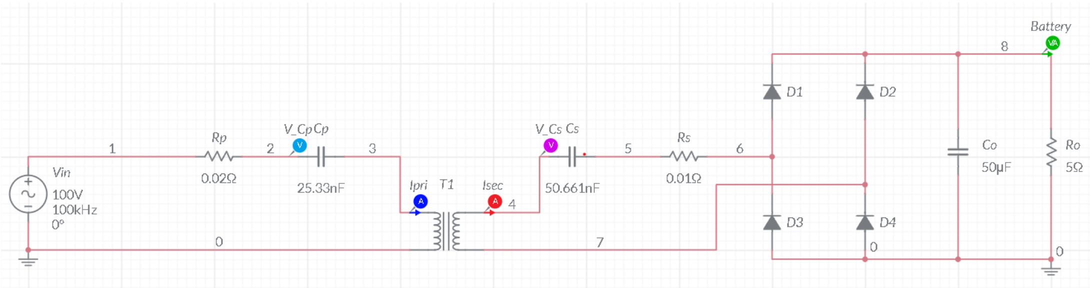

Fig. 2 Wireless charging basic circuit

As shown in Figure 2, this study revolves around a typical wireless power transmission basic circuit, using resonant coupling technology to achieve contactless energy transmission, system modeling based on series resonance topology structure, detailed modeling and simulation analysis on Multisim simulation platform, combined with output waveform characteristics for performance evaluation, and discusses the influence of circuit parameters on system efficiency and output stability, providing practical basis for the basic design and optimization of wireless charging technology.

The wireless charging circuit mainly comprises excitation and primary resonance networks, coupling transformers, secondary resonance and rectification modules, and filter and load modules. A sinusoidal voltage source Vin provides a high-frequency AC signal of 100V and 100kHz, which drives the primary coupling coil through a series resistor Rp and a capacitor Cp. Rp simulates the loss resistance of the wire and MOS tube, Cp and the coil form a series resonant circuit to increase the primary current amplitude to enhance the magnetic field energy coupling efficiency. The primary coil of transformer T1 is connected to the resonant network, and its secondary coil induces an alternating voltage. The coupling efficiency is determined by its self-inductance, mutual inductance and coupling coefficient k. A new series resonant network is formed by connecting the capacitor Cs and the induced voltage at the secondary side. By adjusting Cs to resonate with the induced inductance, the voltage amplitude is further enhanced to achieve high efficiency transmission.

In the rectifier module, a full-bridge rectifier (D1-D4) composed of four diodes is used to rectify the secondary resonant voltage into pulsating DC. Then filter through Co capacitor to eliminate high-frequency ripple and realize a stable DC output. The output series resistance Ro simulates the actual load, such as a cell phone battery. In practical systems, rectifier devices should be selected for high-speed rectifier diodes (such as Schottky diodes or FR diodes) to adapt to efficient rectification at frequencies above 100kHz and reduce reverse recovery losses.

In the Multisim simulation, Vin is set to 100V, 100kHz sinusoidal source, Rp is 0.02Ω, Cp is 25.33nF, Cs is 50.661nF, Rs is 0.01Ω, Co is 50μF, Ro is 5Ω, transformer T1 primary is set to 100μH, secondary is set to 50μH, and coupling coefficient k is set to 0.25. By placing virtual oscillographic probes at key nodes of a circuit, the resonance state and transmission performance of the circuit can be evaluated comprehensively by monitoring the voltage across the primary capacitor (V_Cp), the voltage across the secondary capacitor (V_Cs), the primary and secondary coil currents (Ipri and Isec) and the output voltage (Vout).

3.2. Rationality of Simulation Parameter Setting

Although the series resonant wireless charging simulation circuit designed by this research institute is based on the basic model, its core parameter selection and system structure setting fully combine the development status, industrial application trend and engineering implementation environment of current wireless power transmission technology in China, and have strong practical pertinence and engineering reference value. The excitation voltage of 100V set by the system is within the range of the current low-voltage DC power supply standard in China, which meets the safety requirements for the voltage power supply system of consumer equipment and small electric vehicles, including the Code for Design of Electrical Installations and GB/T 38775 Standard Series for Wireless Charging. This voltage level not only has good adaptability in actual products, but also takes into account key factors such as electromagnetic radiation, safety isolation, and electrical insulation. It is the mainstream scheme for adapting to China charging piles, electric bicycles, household appliances and other scenarios.

In addition, the excitation frequency was selected as 100kHz, mainly based on comprehensive consideration of transmission efficiency, electromagnetic compatibility and technical maturity of existing components. Compared with traditional power frequency system, 100kHz has better energy concentration and higher power density output capability; meanwhile, this frequency is far away from wireless communication and industrial RF interference frequency band, meeting increasingly strict regulatory requirements for electromagnetic interference (EMI) and electromagnetic compatibility (EMC) in China industrial and consumer electronics fields, and facilitating type test certification in practical application.

In structural design, the system adopts a bilateral series resonance structure, and sets the coupling coefficient k = 0.25 to simulate the characteristics of coupling gap, offset tolerance and non-ideal layout in practical engineering. This parameter configuration is more in line with the technical reality of China in the medium and short distance wireless energy supply scenario, which is convenient for simulation evaluation of the robustness of the system to influencing factors such as coil distance and angle offset. The design also has the characteristics of clear parameters and a simple structure.

4. Results and Discussion

4.1. Simulation Results and Analysis

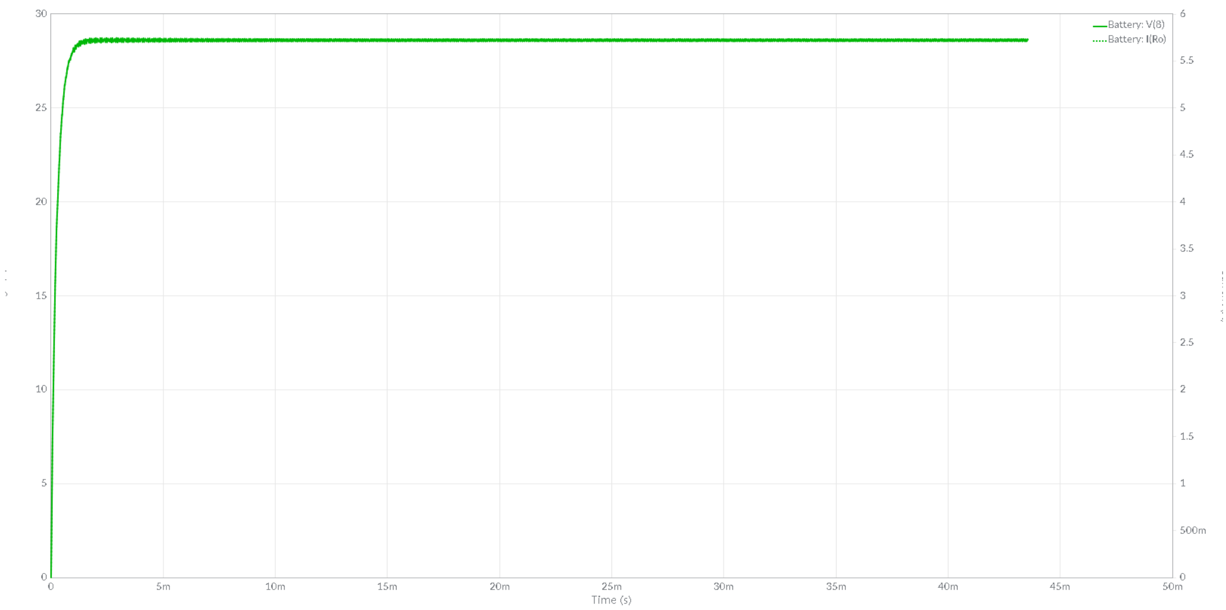

Fig. 3 Output Vout Waveform

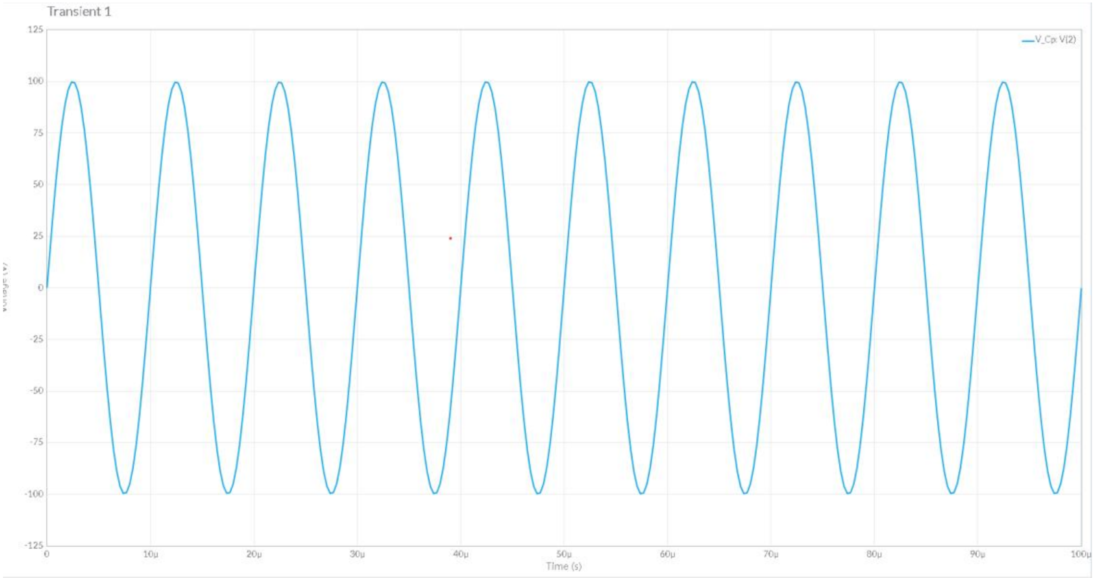

Fig. 4 V_Cp Waveform

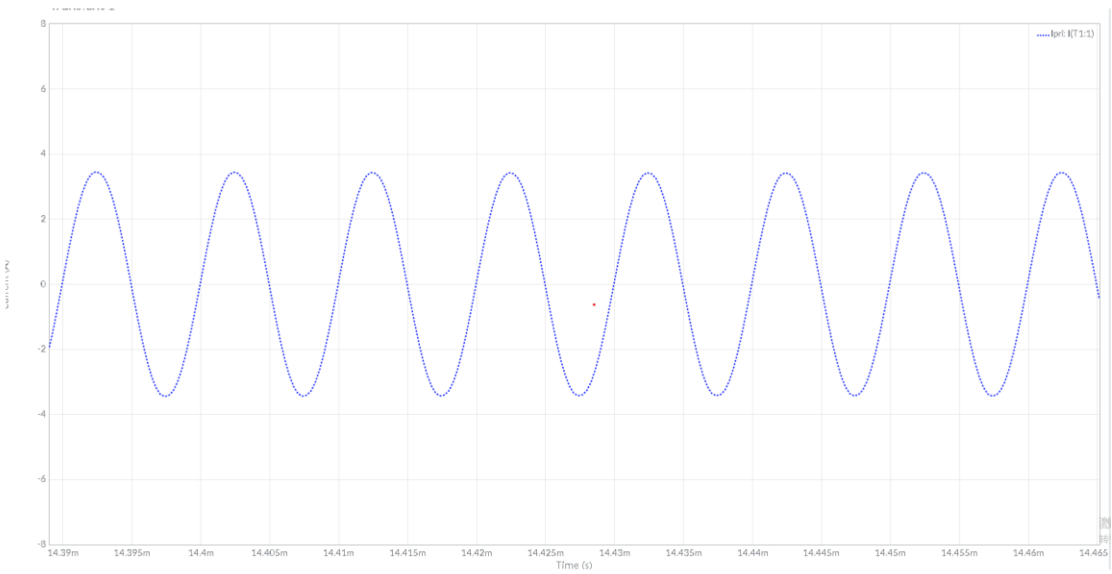

Fig. 5 Ipri Waveform

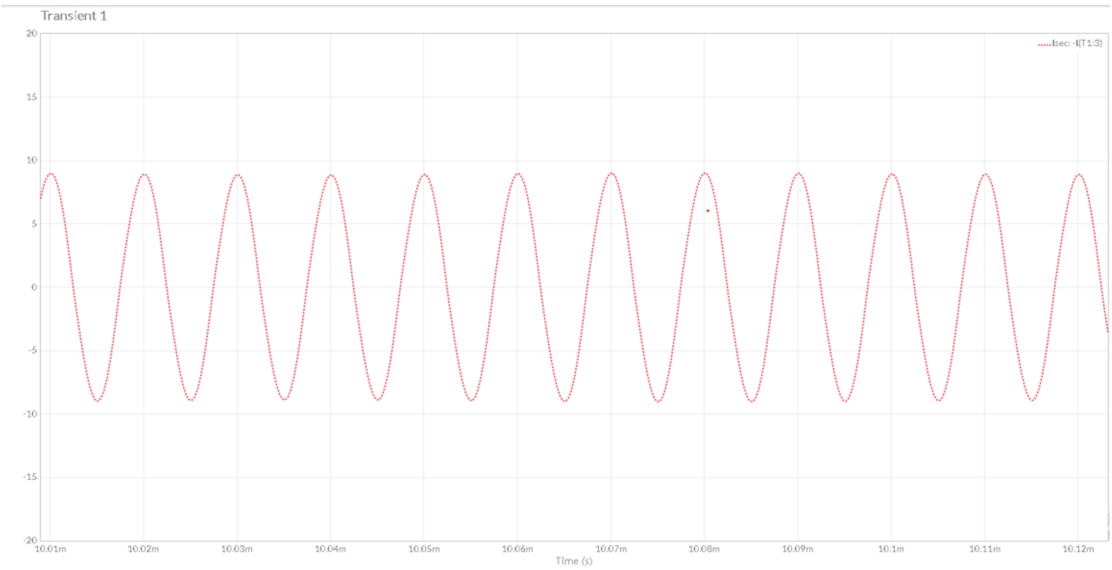

Fig. 6 Isec waveform

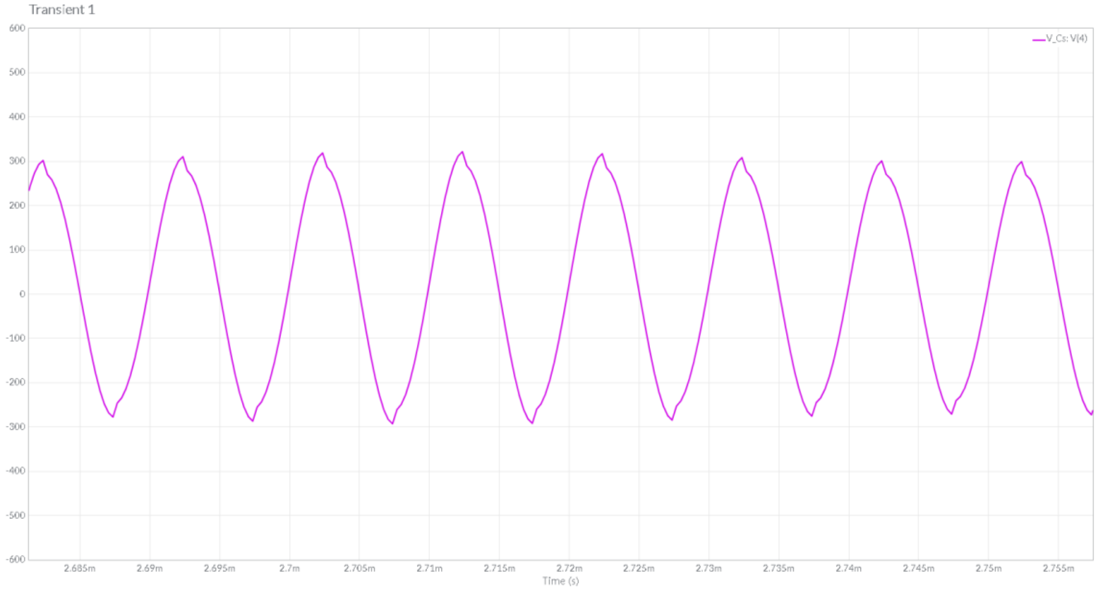

Fig. 7 V_Cs waveform

The simulation results show that V_Cp presents an approximate sinusoidal waveform with a stable frequency of 100kHz and an amplitude of about 90~100V under the condition that Cp forms a resonant match with the primary inductance parameters, as shown in Figure 4. The Ipri waveform is also sinusoidal, and its phase slightly lags behind the voltage waveform, indicating that there is partial resistive damping in the system, but it does not affect the resonance effect. The amplitude of the primary current is large, which indicates that the resonant network effectively amplifies the current and provides a stable magnetic field for wireless energy transmission.

In terms of secondary side response, as shown in Figure 7, the basic shape of the V_Cs waveform is close to a sine wave, its frequency is consistent with V_Cp, and its amplitude is slightly lower but still at a higher level, which proves that secondary resonance adjustment is effective. As shown in Figures 5 and Figure 6, Isec waveforms are highly similar to Ipri, indicating good coupling and successful secondary reception of energy transferred by the primary magnetic field. Due to the unequal self-inductance and low coupling coefficient of the T1 coil, the secondary induced voltage is approximately equal to the primary voltage, which shows the high efficiency of wireless energy transmission over a short distance.

As shown in Figure 3, the rectified and filtered output voltage Vout is maintained between 25V and 30V across the load Ro, and the ripple amplitude does not exceed 0.8V. The output voltage is stable with minimal fluctuations, indicating that the rectification and filter circuits are designed reasonably, and the system can stably supply energy to the load. This performance is particularly important in practical wireless charging applications, especially when charging sensitive loads such as batteries, where excessive ripple can cause charging control errors or aging of electronic components.

4.2. Discussion

Sensitivity simulation of Cp, Cs, inductance L and coupling coefficient k is carried out to further explore the dependence of system performance on key parameters. The results show that when Cp is lowered to 20nF, the primary current decreases significantly and V_Cp exhibits obvious detuning fluctuations; on the contrary, when Cp rises above 30nF, the system will also deviate from the resonance point and the output voltage fluctuations increase. The secondary side is also highly sensitive to Cs value. When Cs setting deviates from the matching value, the V_Cs amplitude decreases and the output power decreases accordingly.

In addition, the coupling coefficient k has a decisive influence on the transmission efficiency of the system. When k decreases from 0.25 to 0.1, Vout decreases by more than 30%, indicating that coupling strength directly affects secondary induction efficiency. In physical implementation, this phenomenon often corresponds to problems such as increased coil spacing, inaccurate alignment, or flux leakage. Therefore, coil arrangement, magnetic conductor, or shielding structure should be optimized as much as possible in engineering design to improve the k value.

In the rectifier part, the ideal diode model is used by default, and it is recommended to replace it with a Schottky diode to adapt to high-frequency operating conditions. At the same time, the selection of the Co filter capacitance is very important to the output ripple suppression effect. When Co decreases to 10μF, Vout fluctuation increases significantly; when Co increases to 100μF, Vout ripple is basically eliminated, but it will bring problems such as excessive initial charging current, which should be considered comprehensively in combination with the system start-up mechanism.

Overall, the basic circuit successfully verifies the feasibility of wireless energy transmission in resonant coupling mode, and shows the influence of circuit parameters on transmission efficiency and output quality. The simulation results are in good agreement with the theoretical analysis and verify the correctness of the circuit model.

In future work, the system can be further extended to a bilateral parallel resonance structure, introducing a power factor correction circuit, an intelligent load identification mechanism, and combining an MPPT control algorithm to realize intelligent regulation of the charging process, so as to meet more complex and diversified wireless charging application scenarios.

5. Conclusion

To sum up, this paper designs and simulates a compact and well-defined basic circuit model of wireless charging based on the magnetic resonance coupling principle. Through simulation experiments on the Multisim platform, the influence of coupling coefficient, capacitance matching and inductance parameters on output voltage, resonance state and overall efficiency of the system is clarified. Especially under the condition of a low coupling coefficient (k=0.25), the system can still maintain stable output performance, which verifies the practicability of this structure in short-distance transmission scenarios. In addition, the capacitors Cp and Cs are particularly sensitive to resonant states and need to be precisely matched for optimal performance. In the rectifier filter design, Schottky diodes combined with high-capacity filter capacitors significantly suppress output ripple and ensure stable operation of the system under charging loads. This circuit model can be used as a prophase verification scheme in engineering. Future research can be further combined with bilateral resonant structure, frequency tracking control and intelligent load identification strategy to expand its engineering application potential in complex wireless energy transmission systems.

References

[1] Yang Lu, Zhang Yiyuan. The relationship between trip chain mode and charging choice in different scenarios. Highway Traffic Science and Technology, 2024, 41(9): 36-43.

[2] COVIC G A, BOYS J T. Modern trends in inductive power transfer for transportation applications. IEEE Journal of Emerging & Selected Topics in Power Electronics, 2013, 1(1):28-41.

[3] KALWAR K A, AAMIR M, MEKHILEF S. Inductively coupled power transfer (ICPT) for electric vehicle charging: A review. Renewable & Sustainable Energy Reviews, 2015, 47: 462-475.

[4] BOSSHARD R, KOLAR J W. Inductive power transfer for electric vehicle charging: Technical challenges and tradeoffs. IEEE Power Electronics Magazine, 2016, 3(3): 22-30.

[5] NING P Q, MILLER J M, ONAR O C, et al. A compact wireless charging system for electric vehicles 2013 28th Annual IEEE Applied Power Electronics Conference and Exposition (APEC). New York: IEEE, 2013: 3629-3634.

[6] QUÍLEZ M G, ABDEL-MONEM M, EL BAGHDADI M, et al. Modelling, analysis and performance evaluation of power conversion unit in G2V/V2G application: A review. Energies , 2018, 11 (5): 1082.

[7] MAI R K, YANG B, CHEN Y, et al. A misalignment tolerant IPT system with intermediate coils for constant- current output. IEEE Transactions on Power Electronics, 2019, 34 (8): 7151-7155.

[8] Tian Zihan, Cheng Shihao, Li Liangchen, et al. Dual coupling LCC-S topology modular wireless charging system with fault tolerance. Journal of China Electrical Engineering, 2024, 1-9.

[9] Liu Qi, Xue Ming, Zhang Pengcheng, et al. Research and Design of Multi-module Extended Voltage Sharing Technology Based on Wireless Charging System. Journal of Electrotechnology, 2024, 39 (22): 6980-6989.

[10] Zi Jing, Qiu Dongyuan, Xiao Wenxun, et al. Research summary of key technologies of three-phase wireless charging system for electric vehicles. Acta Electrica Sinica, 2022, 20 (6): 24-33.

[11] Tang Zhibo, Qiao Yangyang, Gao Yan. Research on the Control Strategy of Electric Vehicle Driving on and off Based on D2P Platform. Special Purpose Vehicle, 2025 (5): 73-76.