Research on Serial Radio Energy Transmission System

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Abstract. Wireless Power Transfer (WPT) technology has wide application prospects in electric vehicle charging, medical implantable equipment and other fields owing to its strengths in exceptional productivity and low electromagnetic interference. Based on the principle of magnetic coupling resonance, this paper analyzes the key mathematical models of series WPT systems, including resonant frequency, impedance matching, output current, transmission power and efficiency formula, and verifies the correctness of the theoretical model through MATLAB/Simulink simulation. In this paper, an optimization method based on dynamic impedance matching is proposed, which significantly improves the transmission efficiency of the system. The simulation results show that the transmission efficiency can reach more than 85% when the system works at the resonant frequency and the load is matched. The finding presented herein formulate theoretical principles guiding the enhanced design of series-configured WPT systems, paving the way for more efficient and reliable wireless power solutions in next-generation industrial and consumer applications.

Keywords: Radio Energy Transmission; Matlab Simulation; Output Current; Transmission Power; Efficiency Optimization

1 Introduction

With the rapid development of the Internet of Things, electric vehicles, and portable electronic devices, the limitations of traditional wired charging methods in terms of flexibility and security have become increasingly evident. Radio energy transmission technology enables energy transfer through a non-contact mode, effectively addressing issues such as plug wear and limited environmental adaptability. Depending on the power transmission mechanisms, radio energy transmission technology can be categorized into five types: magnetic field coupling, electric field coupling, microwave, laser, and ultrasonic, each capable of achieving energy transmission over varying distances and powers [1]. The pioneer in the field of radio energy transmission was Nikola Tesla, who successfully illuminated light bulbs using magnetically coupled wireless energy transfer. In 1898, Tesla formally introduced the concept of radio energy transmission [2]. In 1970, with advancements in semiconductor technology, magnetic field-coupled wireless energy transmission gradually gained public attention. Over the subsequent decades, numerous research breakthroughs emerged. In 2007, Marin

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Soljacic from the Massachusetts Institute of Technology incorporated resonant structures into magnetic field-coupled wireless energy transfer systems, successfully illuminating a bulb at a distance of 2 meters with an energy transfer efficiency of 40% [3]. In 2020, Korean researchers applied superconductivity technology to coupling coils, designing a helical superconducting resonant coil that maximizes the efficiency of wireless energy transmission [4]. In 2021, Florida International University in the United States proposed a multi-objective optimization design method for dynamic magnetic field-coupled power transmission systems for electric vehicles [5]. Among these technologies, the series WPT system based on magnetic coupling resonance has emerged as a research focus due to its simple structure and easy tuning.

In this paper, the mathematical model of series WPT is analyzed systematically, and the influence of parameters such as resonant frequency and impedance matching on system performance is verified by MATLAB simulation.

2 The Series-connected WPT System

The series-connected WPT system consists of a transmitter and a receiver, as shown in Figure 1. Figure 2 show sS-S WPT system.

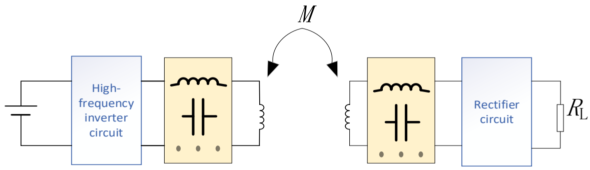

Fig. 1. Universal inductive power transmission frame diagram (Picture credit : Original)

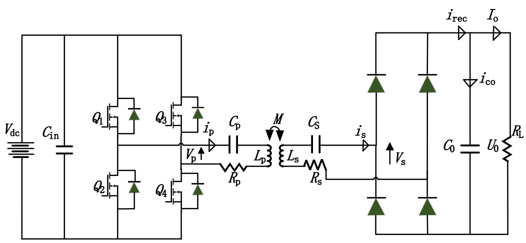

Fig. 2. S-S WPT system(Picture credit : Original)

In 2017, Qi P, Xu J, and Yi F explained the theoretical principle of magnetically coupled resonant radio energy transmission system through mathematical models [6]. According to the circuit coupling theory, the resonant magnetic coupling double coil model of SS (series-series) structure is designed.

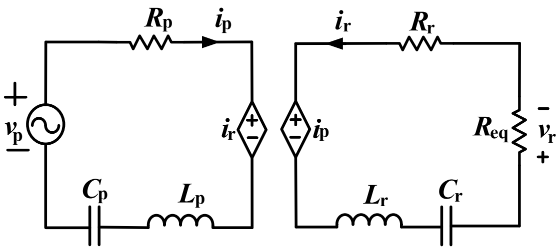

Fig. 3. Equivalent circuit model(Picture credit : Original)

In the mutual inductance model shown in Figure 3, Lp is the transmitting coil, Ls is the receiving coil, Rp and Rr are the internal resistance of the corresponding coil respectively, Cp is the primary side compensation capacitor, Cr is the secondary side compensation capacitor, M is the mutual inductance between the coils, Vp is the equivalent AC power supply set on the transmitting coil, and Req is the equivalent load impedance.

Assume that Vp is the ideal sinusoidal AC voltage and the corresponding frequency is ω

Loop equation

$i_p R_p + i_p j\omega L_p + \frac{j_p}{j\omega C_p} - j\omega M i_r = V_p(1)$

$\mathrm{i_r j\omega l_r + i_r R_r + \frac{i_r}{j\omega C_r} + i_r R_{eq} = j\omega M i_p(2)}$

Type 1 and type 2 are simultaneous

$$\omega = \omega_0 = \frac{1}{\sqrt{C_r L_r}} = \frac{1}{\sqrt{C_p L_p}}$$

$$i_p = \frac{(R_r + R_{eq})V_p}{((R_r + R_{eq})R_p + \omega^2 M^2)}$$

$$i_s = j\omega M V_p \frac{1}{((R_r + R_{eq})R_p + \omega^2 M^2)}$$

Defined reaction impedance$Z_S = -\frac{j\omega M i_r}{i_p} = R_r + jX_r$ the equivalent impedance of the secondary side circuit corresponding to the primary side circuit，when $\omega = \omega_0$，$R_s = \omega^2 M^2 \frac{1}{(R_s + R_p)}$

The energy transfer efficiency of a system is defined as the ratio of the power on the secondary side load to the power provided by the primary side power supply

$$\eta = \frac{R_r}{(R_s + R_p)} \times \frac{R_{eq}}{(R_{eq} + R_r)} = \frac{\omega_0{}^2 M^2 R_{eq}}{R_p(R_r + R_{eq})^2 + \omega_0{}^2 M^2 (R_r + R_{eq})}$$

Since $\omega_0 = (2\pi f_0)^2$, the energy transfer efficiency η of the system is related to f_0, R_p, R_r, R_{eq}, and the mutual inductance coefficient M between the two coils.

3 Code Programming

3.1 Simulation output current

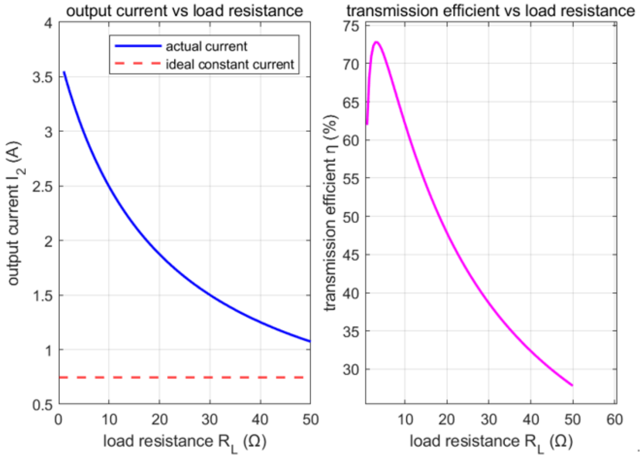

Fig. 4. Relationship between load impedance and output current and transmission efficiency(R=0.5Ω)(Picture credit : Original)

The image shown in Figure 4 is R1=0.5, which is the relationship between the corresponding output current and transmission efficiency. The actual current decreases with the increase of load impedance. When the load impedance approaches to 0 indefinitely, its maximum value is about 3.5A. The peak magnitude of the transmission efficiency curve is about 72.5%.

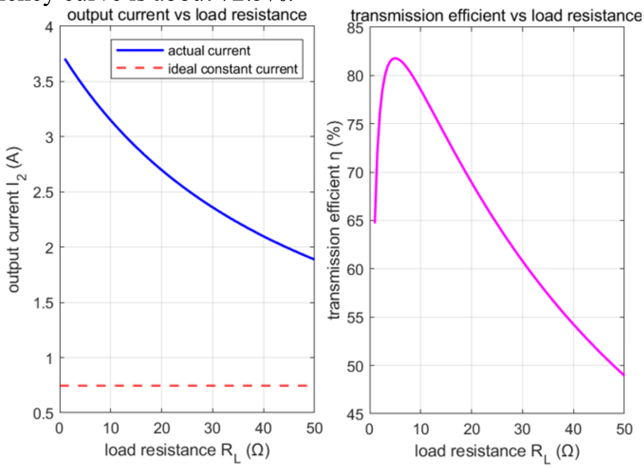

Fig. 5. Relationship between load impedance and output current and transmission efficiency(R=0.2Ω）(Picture credit : Original)

As can be seen from Figure 5, when R1=0.2Ω, the maximum value of the output current at this time becomes larger, its curve tends to be flat, and the transmission efficiency increases to about 82%.

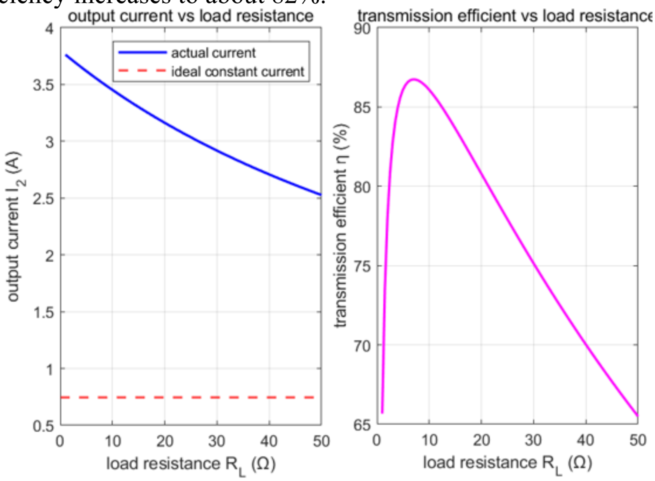

Fig. 6. Relationship between load impedance and output current and transmission efficiency(R=0.1 Ω）(Picture credit : Original)

As can be seen from Figure 6, when R value becomes smaller again, when R1=0.1Ω, the curve of output current and load impedance tends to be flat, and the maximum value increases. Transmission efficiency increased to 87%.

It can be concluded that the smaller the R-value, the smaller the difference between the actual current and the ideal current, and the better the constant current characteristics. The smaller the R-value, the smaller the system loss and the higher the transmission efficiency; In addition, according to the output current formula, its output power will become larger from the reduction of R value.

3.2 Simulation efficiency curve and output power

When the mutual inductance coefficient M = 2e-6H

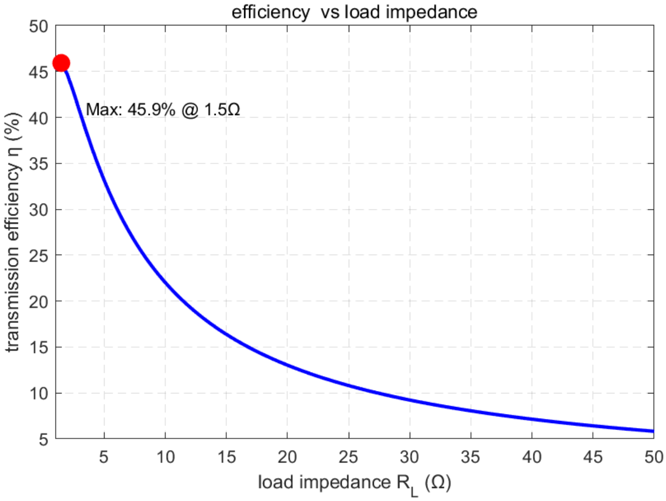

Fig. 7. Efficiency and load resistance (M = 2e-6H)(Picture credit : Original)

Figure 7 shows the transmission efficiency curve of the load resistance under this value. The maximum efficiency is 45.9%, and the corresponding load impedance value is 1.5Ω

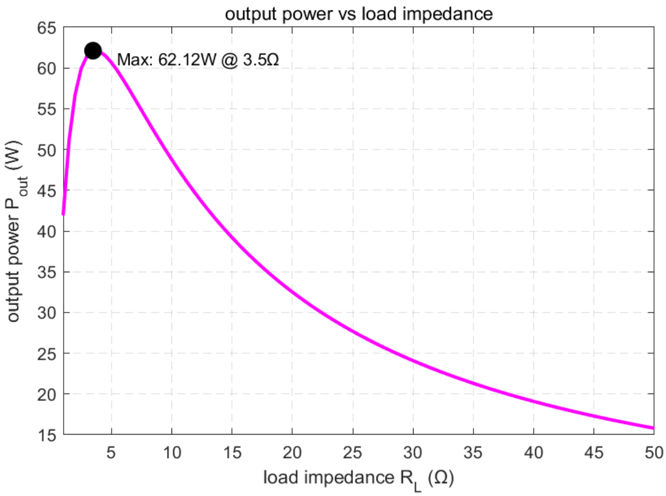

Fig. 8. Output voltage and load resistance(M = 2e-6H)(Picture credit : Original)

Figure 8 shows the output voltage curve of the load resistance under this value. The curve tends to rise first and then decline. The maximum value of the curve is 62.12W and the corresponding resistance value is 3.5Ω.

When the mutual inductance coefficient M = 5e-6H

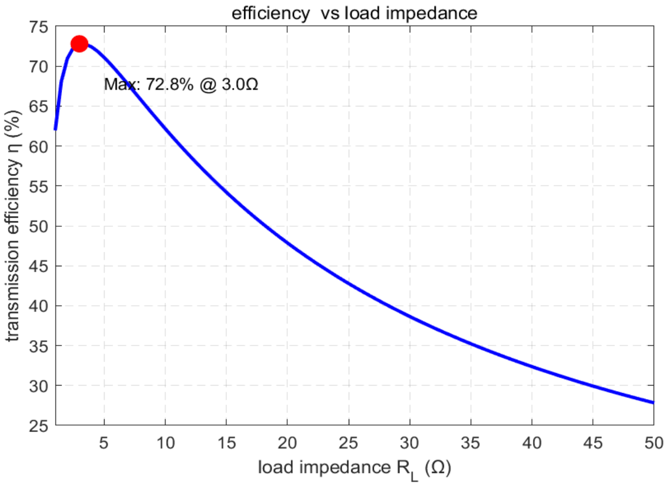

Fig. 9. Efficiency and load resistance(M = 5e-6H)(Picture credit : Original)

Keep the frequency, inductance, capacitance and other values unchanged, and increase the value of mutual inductance coefficient M to 5e-6H. At this time, as shown in Figure 9, the efficiency curve rises first and then decreases, with a maximum value of 72.8% and the corresponding impedance resistance value of 3.0Ω.

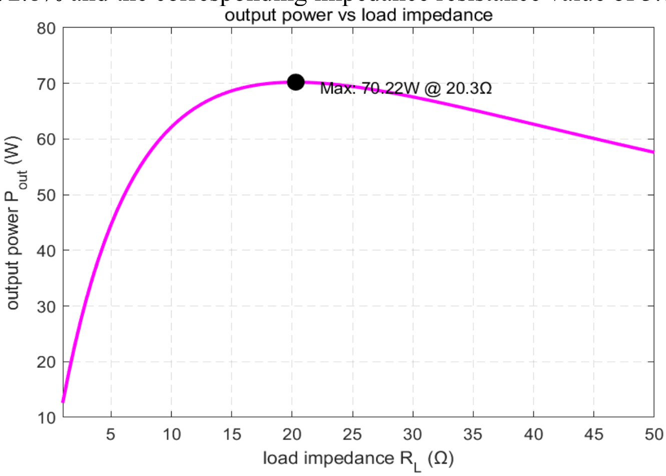

Fig. 10. Output voltage and load resistance(M = 5e-6H)(Picture credit : Original)

The relationship between the output voltage and the load impedance is shown in Figure 10. The curve rises first and then gently decreases. The maximum value is 70.22W and the corresponding load impedance resistance is 20.3Ω.

When the mutual inductance coefficient M = 8e-6H (k is about0.4)

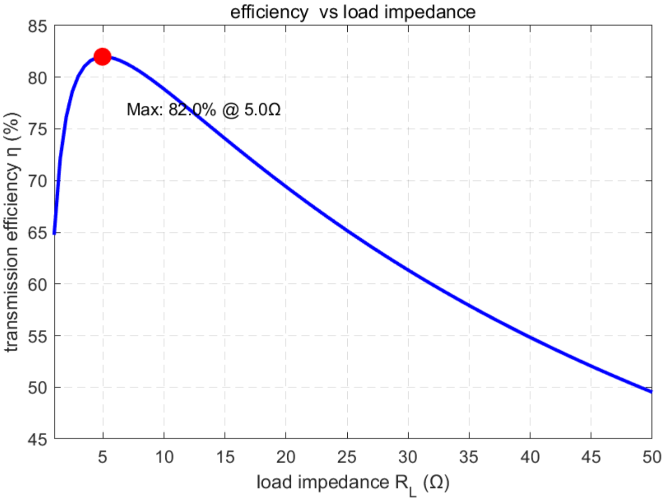

Fig. 11. Efficiency and load resistance (M=8e-6H)(Picture credit : Original)

When the mutual inductance coefficient M is increased again to 8e-6H, as shown in Figure 11, the transmission efficiency is increased again, the maximum value is 82.0%, and the corresponding impedance value is 5.0Ω.

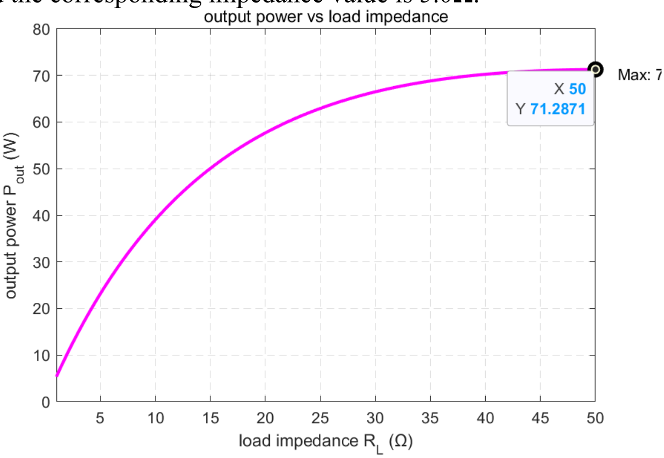

Fig. 12. Output voltage and load resistance(M=8e-6H)(Picture credit : Original)

The maximum value of the output voltage curve corresponding to this M value is about 71.28W, and there is a trend of continuous increase in figure 12.It can be concluded that with the gradual increase of mutual inductance coefficient M, the transmission efficiency will gradually increase, and the maximum transmission power will also gradually increase. Therefore, for an energy transmission system, if you want to try to improve its transmission efficiency and maximum transmission power, then you can improve the mutual inductance coefficient M of the two coils.

For further research on how to improve transmission efficiency and output voltage, the mutual inductance coefficient M is controlled at this time, and the values of R1 and R2 are changed.

When control M=5e-6H, change the values of R1 and R2 for verification,in figure 13

When R1=R2=0.2Ω

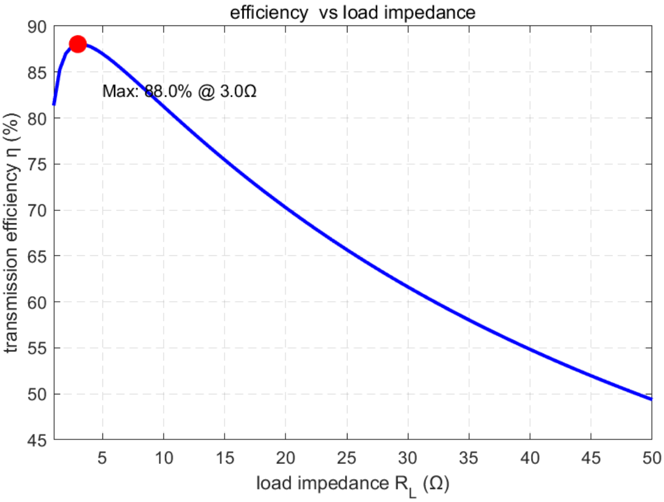

Fig. 13. Efficiency and load resistance(R1=R2=0.2Ω) (Picture credit : Original)

Compared with Fig. 9, the maximum efficiency of R1 and R2 reduced from 0.5Ω to 0.2Ω was increased by about 15% when other conditions remained unchanged.

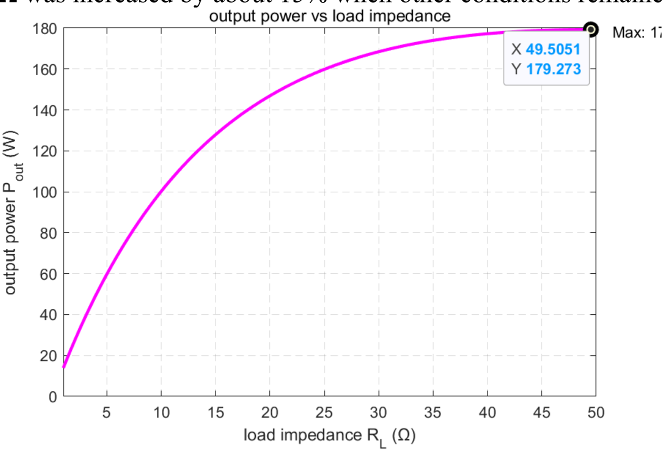

Fig. 14. Output voltage and load resistance(R1=R2=0.2Ω) (Picture credit : Original)

As shown in Figure 14, the output voltage is greatly increased.

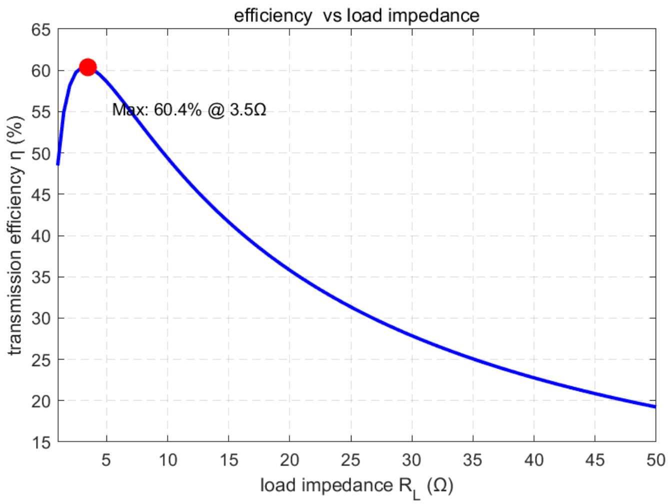

Fig. 15. Efficiency and load resistance(R1=R2=0.8Ω) (Picture credit : Original)

When the values of R1 and R2 are increased from 0.5Ω to 0.8Ω, the transmission efficiency at this time is shown in Figure 15, with a maximum value of 60.4%, which is about 13% lower than that in Figure 9.

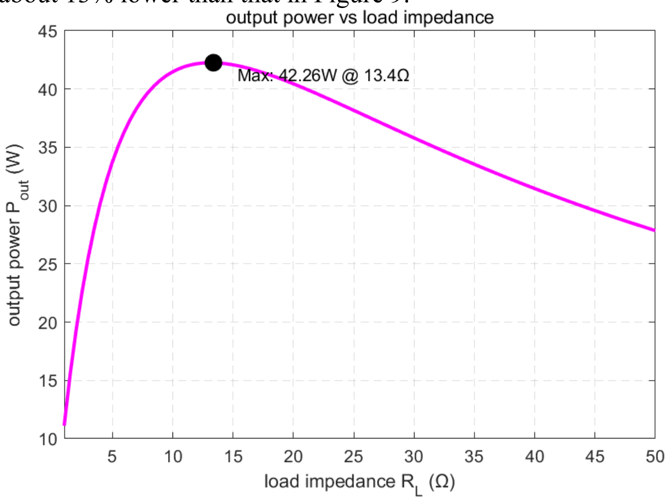

Fig. 16. Output voltage and load resistance(R1=R2=0.8Ω) (Picture credit : Original)

The corresponding maximum output voltage is 42.26W in figure 16, which is about 28W lower than Figure 10. The experiments show that with the increase of R value, the efficiency and output power will decrease. The optimization direction of the above experiments can be increased mutual inductance coefficient M, such as reducing coil spacing and optimizing coil design. Reduce coil internal resistance R1 and R2, reduce wire loss;Enhancing the coil's quality factor (Q) through parasitic resistance minimization constitutes a fundamental strategy for elevating power transfer efficiency in magnetically coupled systems[7]. The impedance regulation method can be used to optimize the transmission performance, and the signal frequency is no longer controlled under the dynamic change of load, and the variable reactor and fixed capacitor are used to dynamically compensate the primary circuit through the power switch tube to control the conduction Angle of the unsaturated reactor and then control its equivalent inductance, so as to ensure the zero phase Angle operation of the system power supply current and voltage. Compared with static compensation, dynamic compensation at a fixed frequency ensures the power transmission performance of the contactless power transmission system while effectively reducing the capacity of the system power supply [8]. An impedance regulating circuit composed of non-energy-consuming components can also be used to improve power efficiency [9]. Zhang Yanqiang proposed a load impedance matching method to solve the problem of reduced efficiency caused by large load changes during wireless battery charging [10]. In Figure 11, a Boost circuit is added on the secondary side to adjust the load equivalent impedance by controlling the duty cycle D of the control signal of MOSFET to ensure the constant output voltage. By controlling the phase shift Angle of the primary full-bridge inverter, changing the input power, detecting the minimum value of the input current, and tracking the maximum efficiency point, the efficiency is always above 80% when the load resistance changes in the range of 5 ~ 500Ω,in figure 17.

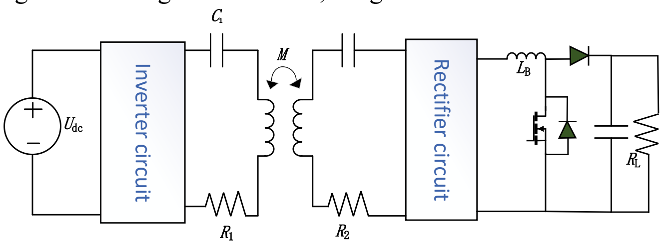

Fig. 17. Radio energy transmission frame diagram(Picture credit : Original)

4 Simulink simulation

4.1 Parallel

Set capacitance 10e-9 inductance 10e-3 resistance 10000Ω

Theoretical resonant frequency：F0=1/2 π √LC≈15.9kHz

Theoretical impedance value：Z=1/R+j（ωC-1/ωL）Figure 18 is parallel circuit diagram.

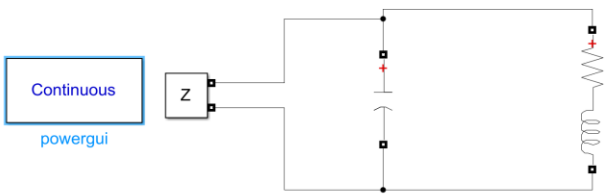

Fig. 18. Parallel circuit diagram (Picture credit : Original)

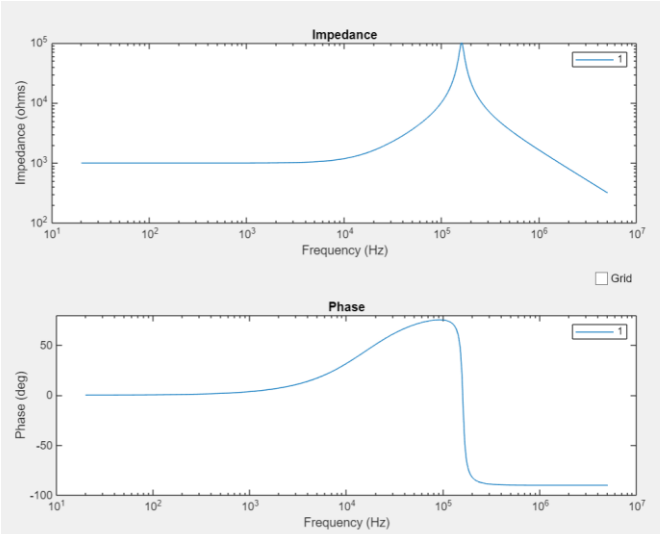

Fig. 19. Parallel circuit diagram corresponding frequency image(Picture credit : Original)

L is 10e-3F, and C is 10e-9, so omega is 10 to the sixth power, which is a million radians per second.The frequency is 15.9 KHZ, and at this resonant frequency, the impedance is about 10 to the fourth power, which is consistent with the theoretical value.Figure 19 is parallel circuit diagram corresponding frequency image

4.2 Serial Mode

Set capacitance to 10e-9 inductance to 10e-3H resistance to 100 ohms Buffer circuit resistance to 1,000,000Ω.Theoretical resonant frequency $F0=1/2\pi\sqrt{LC}\approx 15.9kHz$. Theoretical impedance value $Z=R+j(\omega L-1/\omega C)$ Figure 20 is series circuit diagram

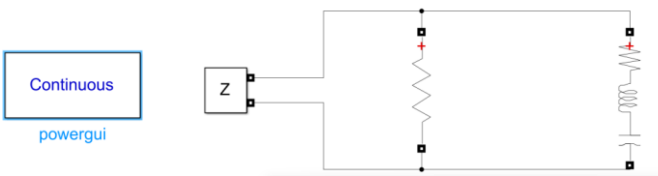

Fig. 20. Series circuit diagram(Picture credit : Original)

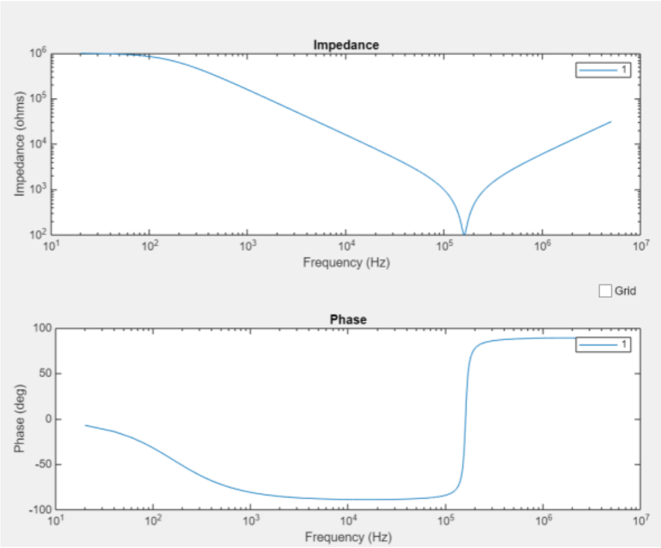

Fig. 21. Serial circuit corresponding frequency(Picture credit : Original)

At this time, the capacitor has a large impedance, so the branch has a large impedance, and the total impedance is the resistance. The resonance frequency is the same as that of the series, and the phase of Figure 2 tends to 0. The circuit is approximately 100 ohms and 1 million ohms in parallel, with a total resistance of about 100 ohms Phase from -90 to 90. Figure 21 shows serial circuit corresponding frequency

When resonant, the system impedance is minimum and the energy transmission efficiency is highest. The series application scenario can be used for the resonant matching network of the high-frequency power supply and the wireless charging transmitter circuit. The parallel application scenario can be noise filtering of precision instruments and frequency selection load of RF receivers.

The impedance minimization of the resonant system is the physical basis for efficient energy transmission. By precisely controlling the resonant frequency, optimizing the impedance matching and reducing the influence of parasitic parameters, the energy transmission efficiency can be maximized. Future research needs to further explore the wide band adaptive resonance technology to deal with the multi-variable interference in complex environment and promote the practical process of radio energy transmission technology.

4.3 Waveform simulation in Simulink

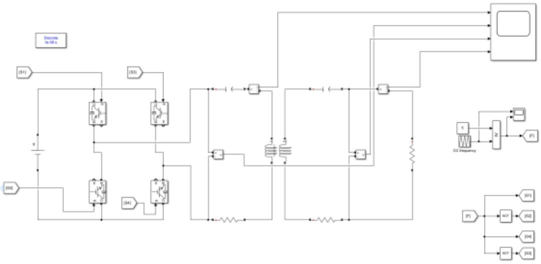

Fig. 22. Simulink simulation circuit diagram (Picture credit : Original)

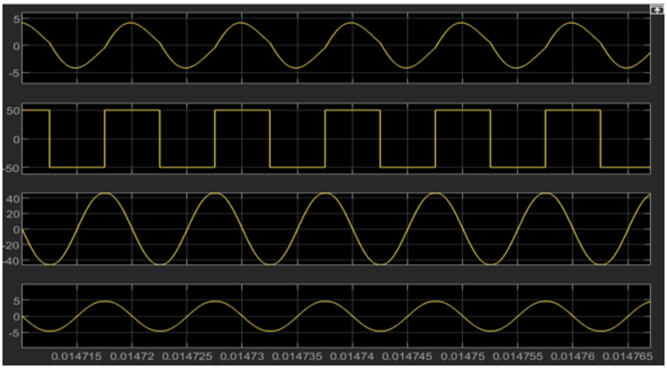

Fig. 23. Simulink simulation circuit diagram corresponds to waveform diagram(Picture credit : Original)

As can be seen from Figure 22, the voltage and current of the primary measurement (transmitting end) are in phase with those of the secondary measurement (receiving end), which means that the system is in a resonant state, and the reactance is partially offset at this time, leaving only the resistance.Figure 23 is simulink simulation circuit diagram corresponds to waveform diagram. In the resonant state, the impedance of the system is minimum and the current is maximum, which optimizes energy conversion efficiency. When the voltage and current of the primary and secondary measurements are in the same phase, the power factor of the system is close to 1, which reduces the loss of reactive power and improves the transmission efficiency of active power. In addition, in the resonant system, the system works at the resonant frequency, at this time the impedance of the inductor and the capacitor cancel each other, to achieve the minimum impedance, phase alignment means that the coupling coefficient and the load impedance match, thus reducing the impact of the reflected impedance, the highest energy forward transmission efficiency, improve the transmission efficiency. The correctness of the theoretical model is verified, which provides a design basis for high-efficiency energy transmission. Firstly, the compensation capacitance and inductance L should be accurately adjusted to ensure that the system works at the theoretical resonant frequency. During the resonance, the reflected impedance of the receiving end should match the internal resistance of the transmitting end, so as to avoid energy reflection.

5 Conclusion

In this paper, the high efficiency constant current output and corresponding output efficiency of series compensation extension in the resonant state are proved. At the same time, it is pointed out that the core of achieving high-efficiency radio energy transmission lies in the precise control of the resonant state and the dynamic optimization of impedance matching. Through simulation and experimental verification, the dynamic matching and low-loss design proposed in this paper can significantly improve the efficiency of the system. In the future, adaptive algorithms and new materials can be combined to further break through the limitations of transmission distance and power density, and research multi-band resonance or broadband impedance matching schemes should be multi-device coexistence scenarios in complex electromagnetic environments, or superimposed in the energy carrier signal, to achieve the integration of power supply and data transmission, so as to promote the wide application of this technology in various fields.

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