Comparsion and Application of S-S and LCC-S Wireless Energy Transfer Topologies

Hao Wu

School of Automation and Electrical Engineering, Northwestern Polytechnical University, Xi'an, 710072, China
haowu2022302284@mail.nwpu.edu.cn

Abstract. With the in-depth applications of wireless power transmission technology, different application scenarios have different requirements on the output mode, energy efficiency characteristics, and disturbance resistance of the topology. The choice of compensation circuit structure will directly determine the practicality, stability and reliability of power transmission in engineering applications that require stable current or voltage output, adaptation to different load conditions, and ensuring stable system operation. This research systematically compares the output characteristics, power transfer efficiency, and system stability of two wireless energy transmission topologies, S-S type and LCC-S type. The characteristics of two structures are scrutinized through mathematical modeling and simulation experiment analysis. The results show the S-S compensated topology is able to maintain a stable constant-current output state with a maximum efficiency of 96.32% in the 5-10Ωload interval, while the LCC-S topology maintains a constant-voltage output characteristic with a maximum efficiency of 91.55% in the same test range. Research further reveals that the S-S structure has an advantage in terms of power density, but the LCC-S structure exhibits better stability under the mutual inductance change condition. Preferred strategies for both topologies are proposed for a wide range of domains in conjunction with the requirements of specific application scenarios.

Keywords: Wireless Energy Transmission; S-S Structure; LCC -S Structure; ESR System

1 Introduction

In the development process of wireless energy transmission technology, the continuous innovation of topology plays a key role. In the early days, based on the law of electromagnetic induction, S-S topology was proposed and applied, which is based on the principle of efficient transmission of electrical energy through series connected inductors and capacitors at a resonant frequency. It is found that it can realize constant current output under stable working condition, but its output characteristics are greatly affected by mutual inductance changes, which makes it difficult to adapt to the complex and changing application scenarios [1]. With further research, the LCC-S topology was developed, which effectively improves the output characteristics with the help of a

J. Iqbal (ed.), *Proceedings of the 2025 2nd International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2025)*, Advances in Engineering Research 272,
https://doi.org/10.2991/978-94-6463-821-9_121

well-designed LCC compensation network [2]. However, the existing models generally ignore the frequency characteristics of ESR. In this paper, ESR factor will be considered comprehensively, and the performance difference between S-S type and LCC-S type topologies under actual working conditions will be analyzed in depth, so as to provide strong theoretical support for the further development of wireless energy transmission technology and optimization of engineering applications.

2 Methodology

2.1 Mathematical model

2.1.1 Circuit Analysis and Equation Derivation for S-S Type Wireless Energy Transmission System: As shown in Fig. 1., the S-S compensated wireless charging system consists of a transmitter ($\mathbf{T_x}$) and a receiver ($\mathbf{R_x}$). The $\mathbf{T_x}$ side contains inductor $\mathbf{L_P}$, capacitor $\mathbf{C_P}$, and resistor $\mathbf{R_p}$ with input voltage $\mathbf{V_p}$ and primary side current $\mathbf{I_p}$. The $\mathbf{R_x}$ side contains inductor $\mathbf{L_r}$, capacitor $\mathbf{C_r}$, and resistor $\mathbf{R_s}$ with load $\mathbf{R_L}$ and secondary side current $\mathbf{I_r}$. The two coils are coupled by mutual inductance *M*.

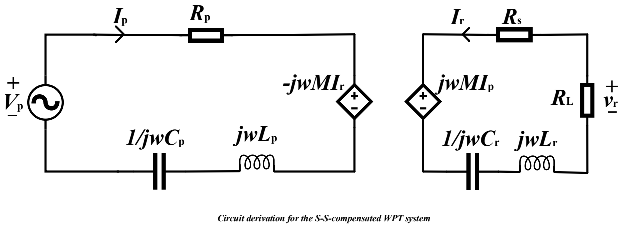

Fig. 1. Equivalent circuit diagram of S-S structure

The system operates at resonant frequency ω, which is satisfied:

$$\omega^2 L_P C_P = 1 \ \omega^2 L_r C_r = 1 \tag{1}$$

According to the Kirchhoff's Voltage Law (KVL), the electric circle equations for the transmitter and receiver can be written as:

$$V_p = I_p R_p - j\omega M I_r \tag{2}$$

$$0 = I_r(R_s + R_L) - j\omega M I_p \tag{3}$$

Solution:

$$I_p = \frac{(R_S+R_L)V_P}{R_p(R_S+R_L)+\omega^2 M^2} \tag{4}$$

$$I_r = \frac{\omega M I_p}{R_S+R_L} = \frac{\omega M V_p}{R_p(R_S+R_L)+\omega^2 M^2} \tag{5}$$

$$P_{in} = \frac{|V_p|^2}{R_p+\frac{\omega^2 M^2}{R_S+R_L}} \tag{6}$$

$$P_{out} = \frac{\omega^2 M^2 |V_p|^2 R_L}{(R_S+R_L)^2\left(R_p+\frac{\omega^2 M^2}{R_S+R_L}\right)^2} \tag{7}$$

$$\eta_{S-S} = \frac{\omega^2 M^2 R_L}{(R_S+R_L)[R_p(R_S+R_L)+\omega^2 M^2]} \tag{8}$$

2.1.2 Circuit Analysis and Equation Formulation for LCC-S Type Wireless Energy Transfer System: As shown in Fig. 2., the LCC-S compensated wireless charging system consists of an LCC compensation network at the transmitter side (T_x) and a series compensation structure at the receiver side (R_x). The T_x side contains inductors L_f,capacitors C_f, C_t, internal parasitic resistance R_s of the inductor L_f and internal resistance R_p of the coil, with an input voltage of V_p; the R_x contains inductors L_r, capacitors C_r, and internal resistance R_r of the coil, with an internal resistance, and a load is R_L. The two coils are coupled by mutual inductance M.

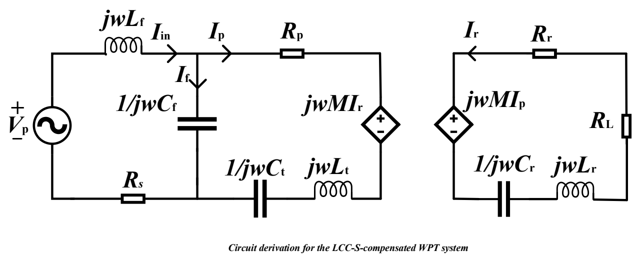

Fig. 2. Equivalent circuit diagram of LCC-S structure

The system operates at resonant frequency ω_0, which is satisfied:

$$\omega_0 = \frac{1}{\sqrt{L_f C_f}} = \frac{1}{\sqrt{L_r C_r}} = \frac{1}{\sqrt{(L_t - L_f)C_t}} \tag{9}$$

At this point the imaginary impedances of the inductor and capacitor cancel each other out, leaving only the real resistance of the ESR.

According to Kirchhoff's voltage law (KVL), the circuit equations for the transmitter and receiver can be written:

$$V_p = I_p(R_p + R_s) - j\omega_0 M I_r \tag{10}$$

$$0 = I_r(R_t + R_L) - j\omega_0 M I_p \tag{11}$$

Solution：

$$I_r = \frac{j\omega_0 M I_p}{R_r + R_L} \tag{12}$$

$$I_p = \frac{V_p}{R_p + R_s + \frac{\omega_0^2 M^2}{R_r + R_L}} \tag{13}$$

$$P_{in} = \frac{|V_p|^2}{R_p + R_s + \frac{\omega_0^2 M^2}{R_r + R_L}} \tag{14}$$

$$P_{out} = \frac{\omega_0^2 M^2 |V_p|^2 R_L}{(R_r + R_L)^2 \left(R_p + R_s + \frac{\omega_0^2 M^2}{R_r + R_L}\right)^2} \tag{15}$$

$$\eta = \frac{\omega_0^2 M^2 R_L}{(R_r + R_L)\left((R_p + R_s)(R_r + R_L) + \omega_0^2 M^2\right)} \tag{16}$$

3 Results

3.1 Constant current output characteristics of S-S type wireless power transmission system

From e.g. (5), it can be seen that the equivalent internal resistance of the coil, R_p and R_s, are constant values, and the current at the receiving end is only related to the system input voltage, V_p, the mutual inductance, M, and the magnitude of the load equivalent resistance R_L. Since R_p and R_s are small, e.g. (5) can be approximated as:

$$I_r = \frac{\omega M V_p}{R_p(R_s+R_L)+\omega^2 M^2} \approx \frac{V_p}{\omega M} \tag{17}$$

From this formula, it can be seen that: During stable system operation, the system operating frequencies, coil inductances and voltage inputs do not change, and the receiving end current is not affected by the size of the load and is a permanent current output.

To clearly reflect the constant-current output performance of the S-S type wireless energy transmission system more clearly, Simulink is utilized to simulate the results with $R_p = R_s = 0.5\,\Omega$, $V_p = 20V$, and $M = 10\,\mu H$ changing from $5\,\Omega$ to $10\,\Omega$ with R_L, as shown in Fig 3.

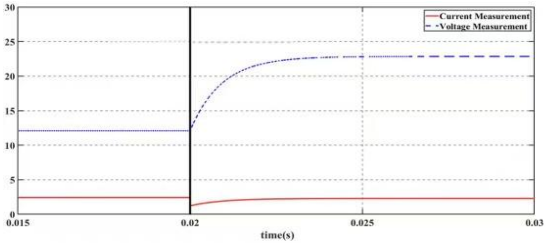

Fig. 3. S-S structure constant current output

From Fig. 3., it can clearly be seen that the output voltage rises when the load resistance changes and the output current returns to the initial state even after a transient change. Therefore, it can confirm that the output characteristic of the S-S wireless energy transmission sys-tem is a permanent current output when the equivalent in-voltage resistances of the coils are small.

3.2 Constant voltage output characteristics and output voltage adjustable section characteristics of LCC-S type wireless power transmission system

As can be seen from Fig. 2., the following expression can be listed, ignoring the internal parasitic resistance R_s of the inductor L_f, the inner resistance R_s of the transmitter and the inter-resistance R_r of the receiver coils:

$$I_p = \frac{V_p}{R_p+R_s+\frac{\omega_0^2 M^2}{R_r+R_L}} \approx j\omega_0 C_f V_p \tag{18}$$

$$I_r \approx \frac{j\omega_0 I_p}{R_L} = \frac{M V_p}{L_f R_L} \tag{19}$$

$$V_{out} = I_r R_L = \frac{MV_p}{L_f} \tag{20}$$

From e.g. (20), it can be seen that the magnitude of the output voltage is only related to the input voltage and the inductance L_f at the transmitting end, and is independent of the load. Therefore, under ideal conditions, the LCC-S type of wireless energy transfer system can realize constant voltage output with constant voltage input. The output voltage of the LCC-S wireless energy transfer system can also be regulated by L_f.

In order to have a clearer reflection of the constant-current output characteristics of the type LCC-S wireless energy transmission system, Simulink is utilized to simulate the results with $R_p = R_s = R_r = 0\,\Omega$, $V_p = 20$V, and $M = 10\,\mu$H changing from 5Ω to 10Ω with R_L, as shown in Fig 4..

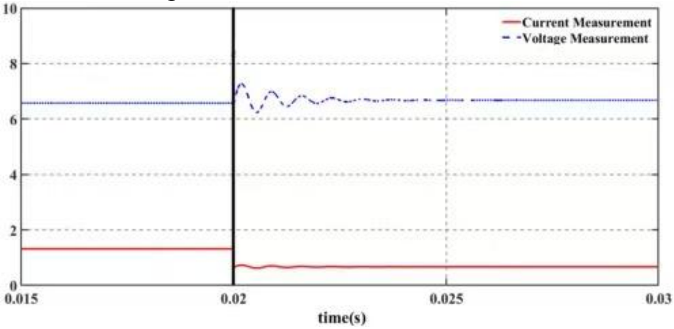

Fig. 4. Constant voltage output of LCC-S structure

From Fig. 4., it can be seen that the output current decreases when the load resistance changes, and the output voltage returns to the initial state even after a brief oscillatory change. Therefore, it can be verified that the output characteristics of the wireless power transmission system type LCC-S are constant voltage outlets under ideal conditions.

3.3 Power transfer comparative study

3.3.1 Comparative study under different ESR parameters:

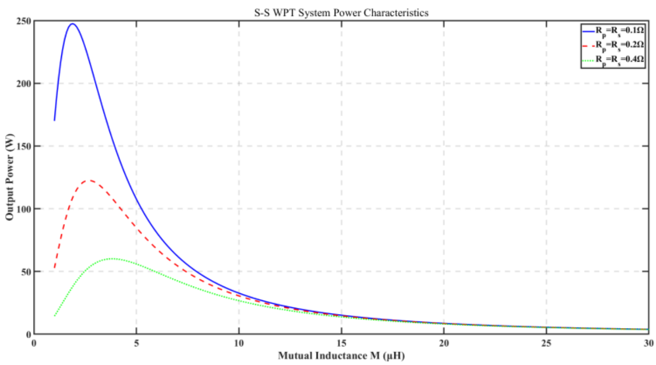

Fig. 5. Output power simulation of S-S structure under different ESR systems

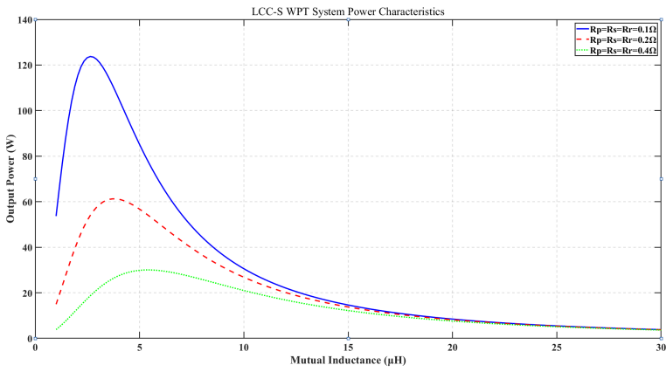

Fig. 6. Output power simulation of LCC-S structure with different ESR systems

From Figs. 5. and Fig. 6., it can be seen that the output power Pout of the S-S-type wireless energy transmission system and the LCC-S wireless energy transfer system shows an increasing and then decreasing trend as the mutual inductance M increases, reach a peak and then decrease significantly. This pattern can be verified by e.g. (7) and (15), when M is small, the denominator of the expression is much smaller than the numerator and the output power is larger. When M is larger, the denominator of the expression is much larger than the numerator and the output power is smaller.

Due to the differences in system topology, their power characteristics show significant differences.

From the perspective of peak power, the peak output power of the S-S style wireless power transfer system is relatively higher than the peak output power of the LCC-S style wireless power transfer system, which has more losses and therefore transmits less power than the S-S type wireless energy transmission system under similar conditions. This means that the S-S type wireless energy transmission system is able to output more power under the same resistive conditions for a given mutual inductance, which may be more attractive for application scenarios that require high power output.

In terms of the shape of the curve and the rate of change, the curve of the S-S type wireless power transmission system rises and falls more steeply, which indicates that the S-S model wireless electrical transmission system's output power is sensitive to variations in mutual inductance, and the small change of mutual inductance value may cause large fluctuation of the output power. In contrast, the curve of the LCC-S wireless power transmission system is relatively flat, which indicates that the output power of the LCC-S wireless power transmission system is relatively gentle with the change of mutual inductance, and has better stability in the face of the change of mutual inductance. This stability may have a unique advantage in applications where power fluctuations are more stringent.

3.3.2 Comparative Study Under Different Loads: From e.g. (4), it is evident that the current at the transmitting end is proportional to the system input voltage, the mutual inductance M, and the magnitude of the load equivalent resistance due to the equivalent internal resistance of the coil, being a constant value of Rs. When the system is unloaded, the load equivalent resistance is infinite and the equivalent inner residence of the coil is extremely small, so the system sending end current becomes very large and may cause damage to the components in the circuit. Therefore, the S-S type wireless energy transmission system should not be operated at no load, or under a very large load.

From e.g. (18), I_p is proportional to C_f, and the C_f of the system is fixed, so the current in the transmitting coil at constant voltage input is constant, independent of the load, which ensures stable transmission of power at the transmitting end, in this way, the LCC-S can work under no-load or oversized loads.

In matlab simulation, set f=85kHz, input voltage V_p=10V and ESR parameter is 0.2Ω to simulate the relationship between output power and mutual inductance under three different loads.

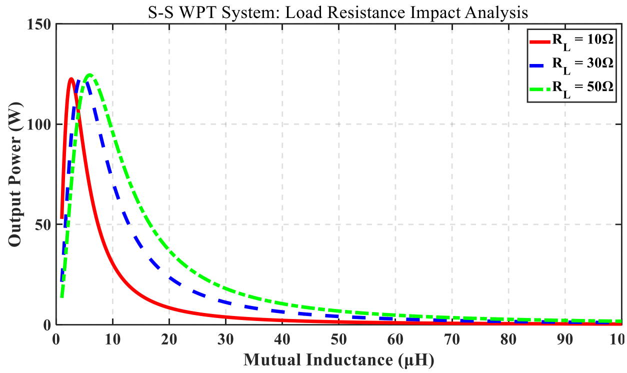

Fig. 7. Output power simulation of S-S structure under different load cases

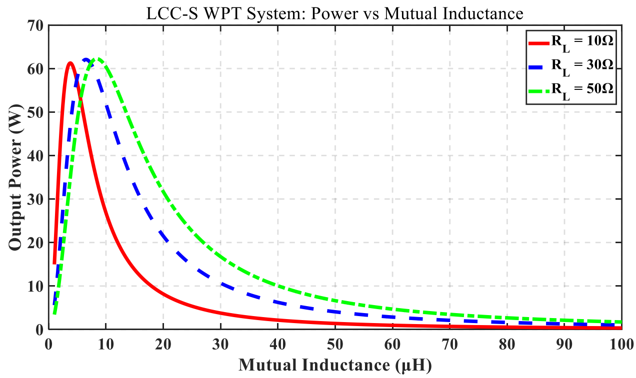

Fig. 8. Output power simulation of LCC-S structure under different load cases

Analyzing Fig. 7. and Fig. 8., it can be seen that the maximum output power of the S-S-type wireless power transmission system and the LCC-S-type wireless power transmission system increases with the load resistance and the mutual inductance required to reach the maximum power also increases. As the load resistance increases, the wider power operating platform of both systems means that the change in output power is relatively small when the mutual inductance is changed. However, there are differences in the output power curves of the two systems due to topology differences. For example, for the same load, the S-S type wireless power transmission system has a larger power peak, requires less mutual inductance to reach the peak value, but is less stable, While there is more mutual stability in LCC-S Wireless Transmission system, but has a smaller power peak and requires more mutual inductance to reach the peak value.

3.4 Comparative study of efficiency transmission

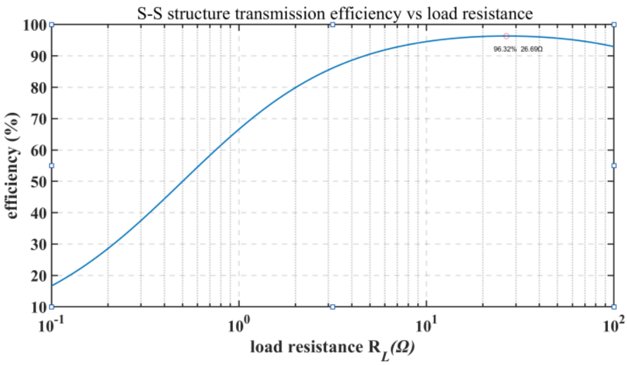

Fig. 9. S-S structure transmission efficiency vs load resistance

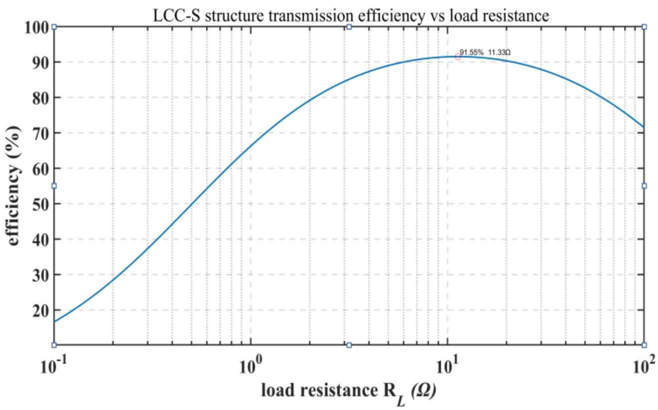

Fig. 10. LCC-S structure transmission efficiency vs load resistance

In matlab simulation, the output power versus mutual inductance is simulated under three different loads by setting f=85kHz, input voltage V_p=10V, M =30μH, and ESR parameter of 0.2Ω.

According to the simulation results in Fig. 9. and Fig. 10., it can be seen from the curves in the figure that the transmission efficiency of the S-S structure rises gradually with the increase of load resistance, reaches the maximum value (96.32%, corresponding to a load resistance of 26.69Ω), and then basically stays stable. The transmission efficiency of the LCC-S structure rises with the increase of load resistance, reaches the maximum value (91.55%, corresponding to a load resistance of 11.33 Ω), and then gradually decreases.

In the same case, the S-S structure has higher efficiency and better efficiency stability than the LCC-S structure, but the peak efficiency occurs when the corresponding load resistance is larger.

4 Discussion

4.1 Field of application of S-S type system

The S-S type wireless power transmission structure with fixed-current output characteristics and high transmission efficiency, has significant advantages in scenarios requiring stable transmission of high power with controlled coupling conditions. For example, Y. Ouyang et al. fully demonstrated the constant-current characteristics, high efficiency, and adaptability to coupling conditions of the S-S compensated WPT system through theoretical derivation, control method design, and experimental validation, clearly supporting its advantages in adapting the CC-CV curve of Li-ion batteries and realizing stable transmission of high power in static wireless charging scenarios of electric vehicles [3]. In scenarios such as inspection robots with precise stopping capabilities, S-S structures have significant advantages due to their high transmission efficiency [4]. With respect to wireless charging of devices such as underwater vehicles, the specially designed S-S topology can achieve high efficiency (86%) and maintain constant current output in complex underwater environments [5][6]. In terms of implantable row medical devices, the S-S compensation structure can achieve up to 71% transmission efficiency at low load (20Ω) and accommodate 30mm lateral displacement through geometric optimization, meeting the need for miniaturization and thermal safety of implantable medical devices [7].D. Zhao et al. showed through theoretical modeling and dynamic analysis that the specially designed S-S type WPT system has significant advantages in aerospace (requiring high power, high reliability with dynamic coupling adaptability) by virtue of the efficient energy transfer from the resonant network, the dynamic stability driven by parameter identification, and the controllability of nonlinear inputs [8].

4.2 Field of application of LCC-S type system

LCC-S type systems are widely used in dynamic or wide load range scenarios due to their constant voltage output, low mutual inductance sensitivity and no-load safety. The LCC-S topology is suitable for dynamic wireless charging combined with direct power supply scenarios due to its low sensitivity to mutual inductance coefficient variations, and the experimental data of M. Zavrel et al. show that the system efficiency still maintains more than 72% and the output power fluctuation is less than 5% when k varies in the 0.2-0.3 interval. This topology successfully suppresses the voltage fluctuation within ±7% by group control strategy during Rx movement, which verifies its strong robustness under coupling change condition [9]. In the field of consumer electronics, such as wide load range and dynamic scenarios such as multi-position charging for cell phones and watches, X. Yu et al. verified the applicability of the LCC-S structure in consumer electronics through experimental data (output voltage range, efficiency variations) and parameter design (compensation network, coil optimization) [10]. In dynamic wireless power supply scenarios in the UAV domain where the load range is from no load to full load, the constant voltage characteristics and low mutual inductance sensitivity of the LCC-S topology enable it to adapt to a wide load range [11]. Due to the constant voltage output characteristic of only ±30 V when the voltage fluctuates during load fluctuation, the low mutual inductance sensitivity of decoupling the transmitter current from the inverter, and the no-load safety of controllable voltage overshoot under extreme working conditions, LCC-S wireless transmission topology meets power supply requirements under dynamic operating conditions, such as acceleration and deceleration of vehicles and a wide range of loads from 5.5 kW to 1 MW in rail transportation, and the experimental validation of its maximum efficiency can reach up to 89% [12].

4.3 Limitations and shortcomings

First, the ESR parameters in this study only consider the intrinsic resistance of the circuit components and do not incorporate the influence of the dynamic on-resistance variation of high-frequency switching devices on the efficiency. Simulation results are based on typical parameter settings only, but equipment aging or ambient temperature changes in real-world applications may significantly alter ESR values, resulting in deviations between model predictions and actual conditions.

Second, in the comparative analysis, the study focuses on the efficiency characteristics under single load conditions and does not address the scenarios of dynamic load adjustment or simultaneous charging of multiple devices. Wireless energy transmission systems often face the problem of sudden load changes, and the existing conclusions are difficult to directly generalize to complex working conditions.

4.4 Recommendations for future research

In view of the sensitivity of S-S type wireless energy transmission system to mutual inductance changes, the future can focus on the study of dynamic compensation technology. For example, by detecting the mutual inductance value in real time and automatically adjusting the compensation capacitance, the impedance matching is adjusted in combination with an intelligent optimization algorithm, thus expanding the system's anti-offset range.

On the other hand, the problem of significant efficiency degradation of LCC-S-type systems at light loads needs to be solved. It is suggested to explore light-load optimization strategies, such as designing a switchable compensation circuit structure that automatically switches to high-frequency low-loss mode at low power, or using a digital controller to dynamically adjust the operating parameters to reduce energy waste.

5 Conclusion

The S-S type wireless energy transmission topology has significant advantages in constant current output with high power density scenarios. The LCC-S wireless power transmission topology is characterized by excellent load adaptation and environmental robustness.

In pursuit of the ultimate efficiency and cost control of fixed scenarios preferred S-S structures; while in the field of safety-sensitive, changing working conditions of mobile equipment, the comprehensive performance advantages of LCC-S is more competitive.

With the development of the integration of intelligent control algorithms and new semiconductor materials, the dynamic optimization capability of the topology will usher in a new era of wireless energy transmission technology.

References

1. Zhang, B., Zhang, Z., Yang, B., et al.: 'Anti-offset method of LCC-S compensated inductive energy transmission system based on clamp circuit', J. Electrotechnol., 2024, 39, (8), pp. 2388–2399
2. Cui, J., Zhai, Y., Zhang, Y., et al.: 'Characterization of LCC-S type wireless energy transmission system', Electrotechnology, 2021, (3), pp. 37–44
3. Ouyang, Y., Chen, K., Luo, J., et al.: 'An S-S Compensated WPT System for Electric Vehicle Battery Charging with Capacitor Matrix', Proc. IEEE 9th Int. Conf. Power Electron. Syst. Appl., 2022, pp. 1–5
4. Kou, Z., Kong, Z., Jing, G., et al.: 'Research and Design of Wireless Charging System for Inspection Robot', Proc. IEEE 6th Int. Conf. Inf. Technol. Netw. Electron. Autom. Control, 2023, pp. 824–827
5. Zeng, Y., et al.: 'Misalignment Insensitive Wireless Power Transfer System Using a Hybrid Transmitter for Autonomous Underwater Vehicles', IEEE Trans. Ind. Appl., 2022, 58, (1), pp. 1298–1306
6. Yang, L., et al.: 'Comparison Survey of Effects of Hull on AUVs for Underwater Capacitive Wireless Power Transfer System and Underwater Inductive Wireless Power Transfer System', IEEE Access, 2022, 10, pp. 125401–125410
7. Aubakirov, R.: 'Comparison of the Geometry of the Optimized Coil Pair of Wireless Power Transmission Systems with SS and SP Compensation', Proc. IEEE Conf. Russ. Young Res. Electr. Electron. Eng., 2021, pp. 2783–2786
8. Zhao, D., Xiao, J., Wu, X., et al.: 'Frequency Domain Identification of Series-Series Wireless Power Transfer System', Proc. IEEE 5th Int. Conf. Power Intell. Comput. Syst., 2023, pp. 28–32
9. Zavrel, M., Kindl, V., Tyrpekl, M.: 'Dynamic Wireless Charging Using LCC-S Compensation Topology in Low and Medium Power Applications', Proc. IEEE 32nd Int. Symp. Ind. Electron., 2023, pp. 1–6
10. Yu, X., Feng, J., Zhu, L., et al.: 'Design and Optimization of a Planar Omnidirectional Wireless Power Transfer System for Consumer Electronics', IEEE Open J. Power Electron., 2024, 5, pp. 311–322

11. Duan, S., Lu, X., Wu, H., et al.: 'Unmanned Aerial Vehicle Wireless Power Transfer System for Long-Distance Transmission Line Patrol', Proc. IEEE Int. Power Electron. Appl. Conf. Expo., 2022, pp. 1324–1329
12. Lee, G., Kim, M., Lee, S.-G., et al.: 'Operational Verification of Semidynamic Wireless Power Transfer in Light-Rail Transit Systems', IEEE Trans. Transp. Electrific., 2025, 11, (1), pp. 348–358