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# Analysis of electric vehicle wireless charging system based on SS topology compensation structure

Qihui Miao, Yaru Liu, Meili Shen*

Qingdao University of Technology, Qingdao, Shandong, 266520, China

## Abstract

**Electric vehicles have effectively alleviated the current environmental problems that are widely concerned, so they have a good application prospect and a broad market in the future, and the wireless charging technology of electric vehicles can effectively solve the inconvenience and leakage caused by traditional wired charging. Insufficient and so on, has been greatly developed and gradually began to be applied. This paper mainly introduces several common circuit compensation topology network structures, and deduces the output power and circuit transmission efficiency formulas of the SS type topology compensation structure. Using MATLAB to draw the output power and circuit transmission efficiency diagram, and draw the conclusion that the SS type can be When the electric vehicle is wirelessly charged, it maintains a high output power, can achieve a transmission efficiency greater than or equal to 80%, and the SS-type structure can withstand large frequency fluctuations. Finally, the SS-type compensation structure for wireless charging of electric vehicles is summarized.**

## Keywords

**Electric vehicle, wireless charging, electromagnetic coupling; compensation topology, transmission efficiency.**

## 1. Introduction

In recent years, environmental pollution has become a major focus of social attention. Reducing the use of natural resources such as oil and coal and finding clean and renewable resources has become one of the main tasks of many scientists. In this context, the electric vehicle industry is growing rapidly, and electric vehicles have two most significant shortcomings. First, the battery life is not strong enough, but charging is more troublesome. In addition, the cost of building a charging pile is high and takes up a lot of space. Therefore, higher requirements are placed on the diversification and convenience of charging methods for electric vehicles. Wireless charging electric vehicles have become an emerging industry [1]. The advantages of wireless charging for electric vehicles and the disadvantages of traditional wired charging are compared in Table 1.

Table 1 Comparison of wireless charging and wired charging

| Wireless charging | Wireless power charging |
|---|---|
| No exposed connector | Electrical connection via exposed connectors |
| No danger of electric spark or shock | Electrical spark and shock hazard |
| No wear problem | Mechanical wear |
| Not subject to weather and environment restrictions | Not suitable for use in bad weather |

| | |
|---|---|
| Distributed charging reduces grid impact | Large-scale charging causes shock to the grid |
| Intelligent automatic control charging | Manual charge |

As an emerging technology, wireless charging technology is currently mainly used in low-power devices such as mobile phones and earphones. It is a new exploration in the field of electric vehicles, which can realize non-direct contact power transmission for electric vehicles within a certain distance.

However, the wireless charging technology of automobiles is not perfect, and the transmission efficiency is not high enough, which is the problem faced by all wireless charging. This project proposes the problem of improving the efficiency of wireless charging of automobiles based on electromagnetic coupling, and solves the problem of low energy transmission efficiency in the process of wireless charging of automobiles and electric energy [2]-[3]. For the problem of large loss, this paper mainly aims at the problem of low efficiency of wireless charging of automobiles, compares SS type and SP type compensation topology networks, optimizes the coupling coil, and analyzes the main characteristics and application scope of these two compensation topologies. We have solved the problem of low energy transmission efficiency during wireless charging, which will make wireless charging technology more mature.

Many institutions at home and abroad have carried out research on electromagnetic coupling mechanism, circuit parameter optimization, compensation topology, control scheme, etc., in order to improve the anti-offset characteristics of wireless charging system. Korea Gao et al. Institute of Science and Technology (KAIST) proposed an "I" type electromagnetic coupling mechanism with narrow guide rail and wide pick-up coil. When the coil gap is 20cm and the horizontal offset is 24cm, the maximum transmission power of 35kW can be achieved. Chongqing University proposed a short-coil cascaded power supply rail coil structure suitable for dynamic wireless power supply of electric vehicles[5]-[6]. By controlling the switch switching of the segmented rail coil, the fluctuation of the system output voltage and power during the coil switching process is avoided. Southeast University studied the effect of the coil size of the transceiver on the offset characteristics. By adopting a method based on frequency control, a magnetic coupling resonant wireless charging device with a charging power of 3kW, a transmission distance of 30cm and a transmission efficiency of 90% was developed. However, due to the influence of factors such as coil offset and vehicle speed, the parameters of the dynamic wireless charging system change all the time. Therefore, it is necessary to continue to study the changing characteristics of the output power and efficiency of the wireless charging system.

Aiming at the influence of coil offset on power transmission characteristics in the process of wireless charging, this paper studies the change characteristics of the output power and efficiency of the system during the coil offset process based on the wireless charging system of the bilateral series compensation network to determine the appropriate transmitter coil. Switch position and effective coupling area of the transceiver coil.

## 2. Brief introduction of electromagnetic coupling wireless charging system

Wireless charging technologies include electromagnetic induction, electromagnetic radiation and magnetic coupling resonance. Most of low-power electrical appliances such as smart phones and Bluetooth headsets use electromagnetic induction, while high-power electrical appliances such as electric vehicles often use magnetically coupled resonant charging. This is because the magnetically coupled resonant wireless charging technology has higher transmission power and is more suitable for Medium and long-distance transmission is more

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suitable for the requirements of wireless charging of electric vehicles. In the wireless charging power system of electric vehicles, the alternating current provided by the grid should first be rectified and filtered, converted into direct current, and then changed into high-frequency alternating current through high-frequency changes; then through the compensation network and the transmitting coil The formed primary side resonant unit provides power for the secondary side resonant unit (composed of the secondary side compensation network and receiving coil); finally, through subsequent operations such as rectification and filtering, the high-frequency alternating current received by the secondary side is converted into electric power. Car battery powered direct current. The structure diagram of the wireless charging system for electric vehicles is shown in Fig. 1.

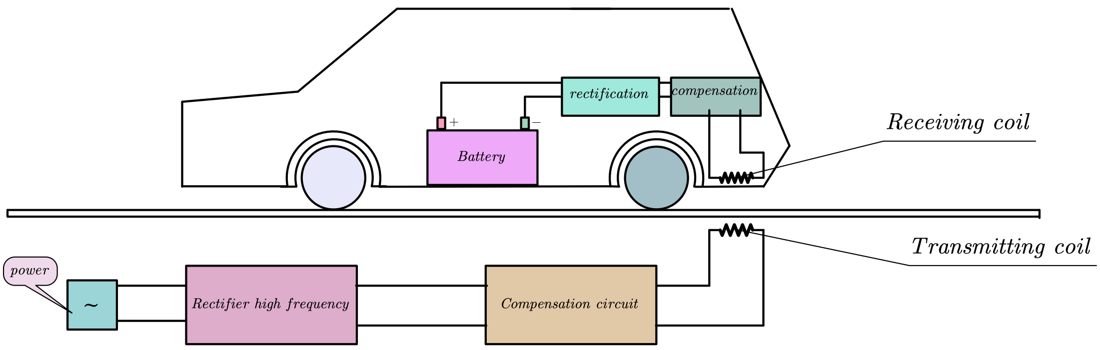


Figure 1 Structure diagram of wireless charging electric vehicle power system

## 3. SS-type topology compensation structure analysis

Magnetic coupling is a phenomenon in which the magnetic flux of one coil is linked to another coil, that is, a physical phenomenon in which the current-carrying coils are connected to each other through each other's magnetic fields. The magnetic coupling wireless charging power system is equivalent to a loose coupling transformer, and there will be a large amount of leakage inductance. The purpose of adding compensation capacitors and inductances in the system is to compensate for the leakage inductance. Compensation capacitors and inductance coils have two forms: series and parallel. There are two sets of inductance coils on the primary side and the secondary side in the charging system, so four basic compensation circuits can be formed, namely series-series (SS) type, series-parallel type (SP) type, parallel-series (PS) type and parallel-parallel (PP) type. The four structures are shown in Fig. 2 to Fig.5.

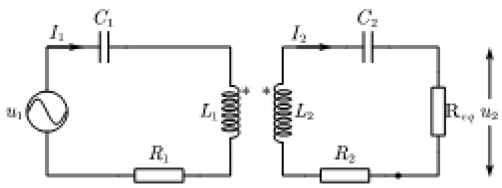


Figure 2 SS type structure diagram

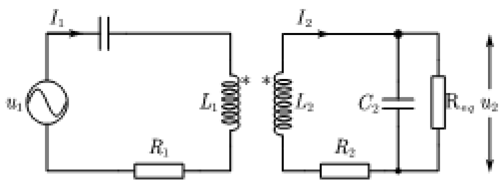


Figure 3 SP type structure diagram

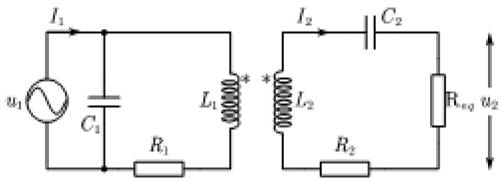

Figure 4 PS type structure diagram

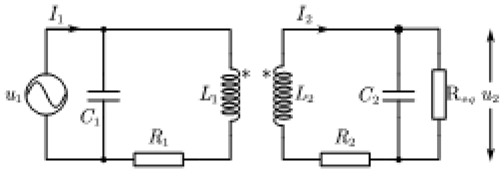

Figure 5 PP type structure diagram

This article will analyze the input, output power and transmission efficiency of the SS-type compensation circuit in detail.

According to the information, the equivalent resistance of the battery of the electric vehicle is 3~20Ω, and the mutual inductance is 10~30$\mu H$[1]. Under these constraints, the output power and circuit output efficiency of the SS-type compensation topology are analyzed.

The equivalent structure diagram of the SS type compensation topology is shown in Fig.6.

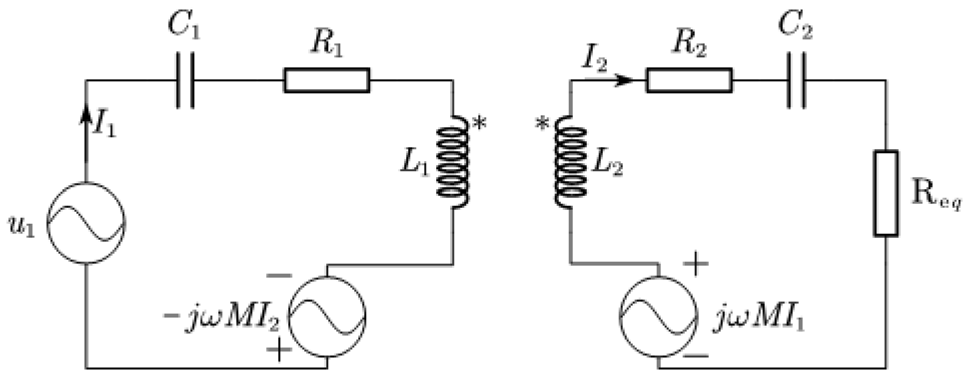


Figure 6 SS type compensation topology

Among them, $R_1$ and $R_2$ are the coil internal resistance, $R_{eq}$ is the load resistance, M is the coil mutual inductance, $j\omega MI_1$ is the primary side mutual inductance voltage source, -$j\omega MI_2$ is the secondary side mutual inductance voltage source.

The Kirchhoff loop equation (KVL) of the primary and secondary sides of the coupled coil is:

$$\begin{cases} \dot{U} = \dot{I}_1\left(\dfrac{1}{j\omega C_1} + R_1 + j\omega L_1\right) - j\omega M\,\dot{I}_2 \\ 0 = \dot{I}_2\left(\dfrac{1}{j\omega C_2} + R_2 + R_{eq} + j\omega L_2\right) - j\omega M\,\dot{I}_1 \end{cases} \tag{1}$$

Firstly, the self-impedance of the transmitting coil is

$$Z_1 = \frac{1}{j\omega C_1} + R_1 + j\omega L_1 \tag{2}$$

The self-impedance of the receiving coil is

$$Z_2 = \frac{1}{j\omega C_2} + R_2 + \mathrm{R}_{eq} + j\omega L_2 \tag{3}$$

Putting (2) and (3) into (1) to get

$$\dot{I}_1 = \frac{\dot{U}_1 Z_2}{Z_1 Z_2 + (\omega M)^2} \tag{4}$$

$$\dot{I}_2 = \frac{\dot{U}_1 \, j\omega M}{Z_1 Z_2 + (\omega M)^2} \tag{5}$$

The internal resistance of the coupling coil is much smaller than the primary and secondary side reactance, so its internal resistance $R_1$ and $R_2$ can be ignored.When resonance occurs, there is $\mathrm{jwL} = \frac{1}{jwC}$. At this time, $Z_1 * Z_2 = 0$. It can be seen from this that the output current of the SS type compensation topology is only related to the input voltage, angular frequency and mutual inductance system under the condition of complete resonance, and has nothing to do with the load. It can be regarded as a current source affected by the primary voltage source and constant current output. Therefore, the input power when the circuit is fully resonant can be obtained as:

$$P_{\mathrm{in}} = \dot{U}_1 \dot{I}_1 = \frac{\dot{U}_1^{\,2} \left(\mathrm{R}_{eq} + R_2\right)}{(\omega M)^2 + R_1\left(\mathrm{R}_{eq} + R_2\right)} \tag{6}$$

The output power is

$$P_{out} = \dot{I}_2^{\,2} \mathrm{R}_{eq} = \frac{\left(\omega M \dot{U}_1\right)^2 \mathrm{R}_{eq}}{\left[(\omega M)^2 + R_1\left(\mathrm{R}_{eq} + R_2\right)\right]^2} \tag{7}$$

The transmission efficiency of the circuit is

$$\eta_S = \frac{P_{out}}{P_{in}} = \frac{(\omega M)^2 \mathrm{R}_{eq}}{R_1\left(\mathrm{R}_{eq} + R_2\right)\left[(\omega M)^2 + R_1\left(\mathrm{R}_{eq} + R_2\right)\right]} \tag{8}$$

In engineering, the coupling coefficient k is used to define the tightness of the two coupling coils. If the two coils are very closely attached, the coupling factor is very likely to be close to 1. This situation is an ideal state, which is called full coupling. If the coils are far away or the axes are perpendicular to each other, the value of k is very small and may even be close to 0.

The formula for calculating the coupling coefficient is

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{9}$$

Putting formula (9) into (7) and (8) respectively, we get[3]

$$P_{out} = \frac{U_1^2 k^2 L_1 L_2 \omega^2 R_{eq}}{\left(R_{eq} R_1 + k^2 L_1 L_2 \omega^2\right)^2} \tag{10}$$

$$\eta_S = \frac{k^2 L_1 L_2 \omega^2}{k^2 L_1 L_2 \omega^2 + R_1 R_{eq}} \tag{11}$$

The mutual inductance value is in the range of $10\sim30\mu H$, and it can be taken as $20\mu H$. Assuming that the internal resistance of the primary and secondary coils is $R_1 = R_2 = 1\Omega$, the resonant frequency $f_0 = 80 \times 10^{-3} Hz$, and the resonant angular frequency $\omega \approx 500 \times 10^3 rad/s$.

## 3.1. Load characteristic analysis

Taking the load resistance $R_{eq}$ as the independent variable, and taking the output power $P_{out}$ and the charging efficiency ηas the dependent variables, with the help of MATLAB [7], the variation curve of the output power of the SS-type topology compensation network with the load resistance $R_{eq}$is shown in Fig.7, and the variation curve of the charging efficiency with the resistance $R_{eq}$ is shown in Fig. 8.

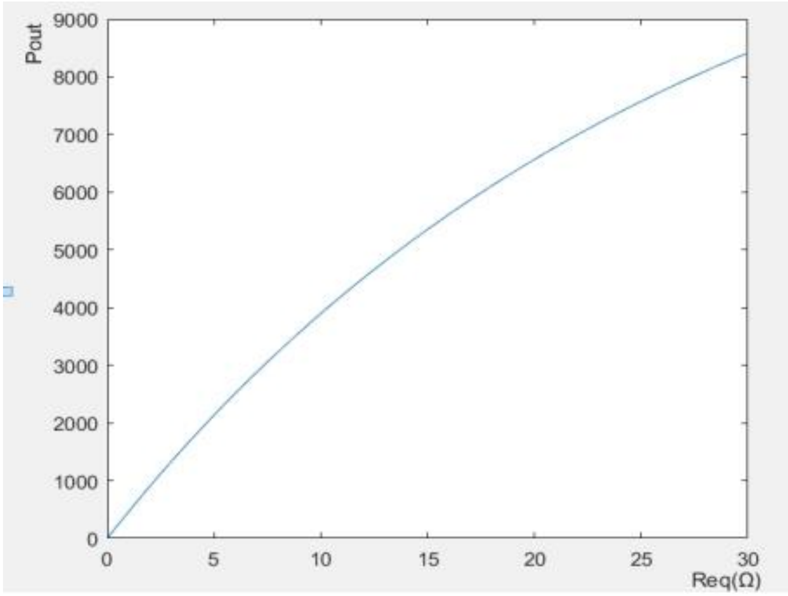


Figure 7 Output power variation curve with load resistance $R_{eq}$

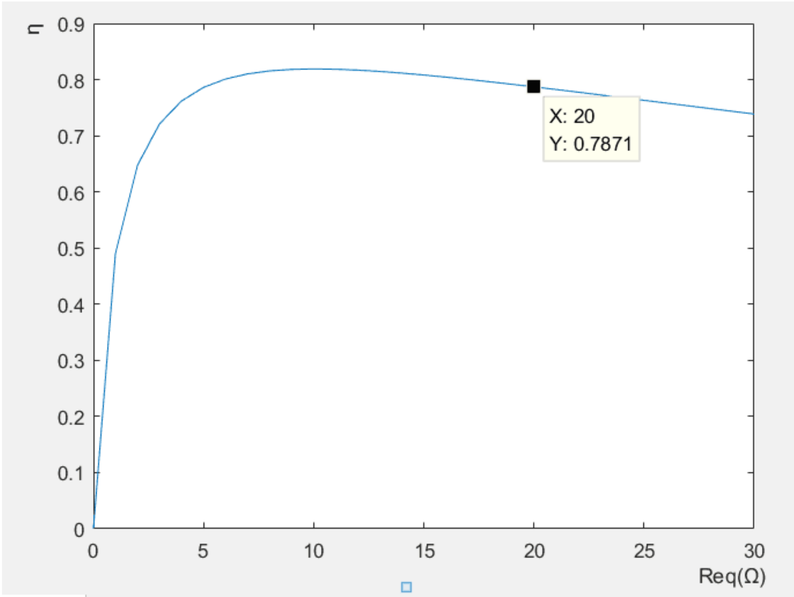


Figure 8 SS type transmission efficiency curve with load resistance $R_{eq}$

From Fig. 7, it can be seen that the output power of the SS-type structure circuit increases approximately linearly with the increase of the load. It can be seen from formula (7) that the output power of the SS-type structure system will change with the change of the input voltage U, but The transmission efficiency of the system is not affected by the input voltage. From Fig. 8, it can be seen that the transmission efficiency of the system increases rapidly, and the transmission efficiency can reach 78% when $\mathrm{R_{eq}} = 20\Omega$, and then the growth rate of transmission efficiency becomes slow. In the process of electric vehicle charging, its battery equivalent resistance is generally 3~20Ω. Therefore, although the SS type topology compensation network structure cannot make the transmission efficiency reach 100%, it can approach 80% transmission efficiency during the wireless charging process of electric vehicles.

## 3.2. Mutual inductance characteristic analysis

The position of the electric vehicle charging and the distance of the vehicle charging equipment from the ground will cause the mutual inductance value to change. Therefore, the value of the mutual inductance value M is in the range of $0 \sim 2 \times 10^{-5} H$ and the load is $R_{eq} = 20\Omega$. With the help of MATLAB [7], the change curve of the SS type output power with the mutual inductance value M is plotted as shown in the Fig. 9, the change curve of the output efficiency with the mutual inductance value M is shown in Fig. 10.

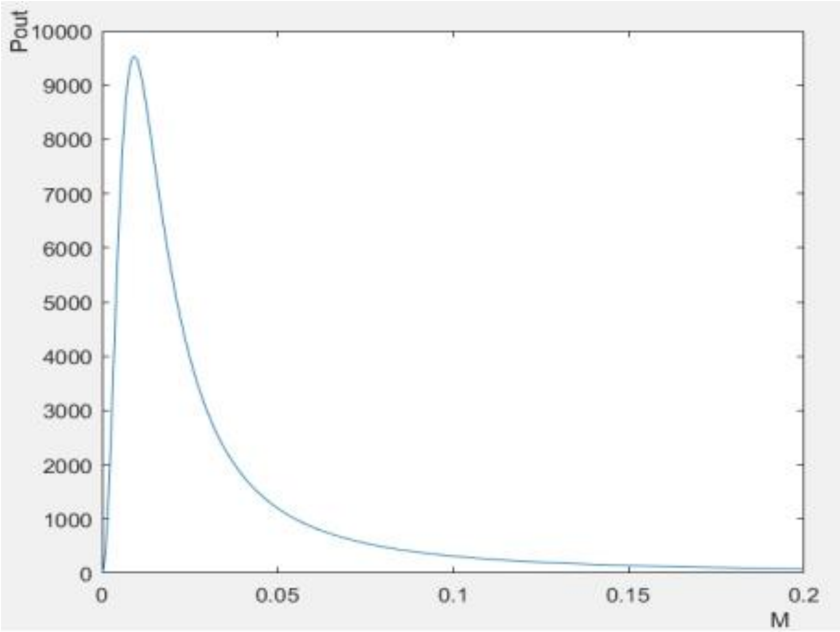


Figure 9 Variation curve of SS type output power with mutual inductance

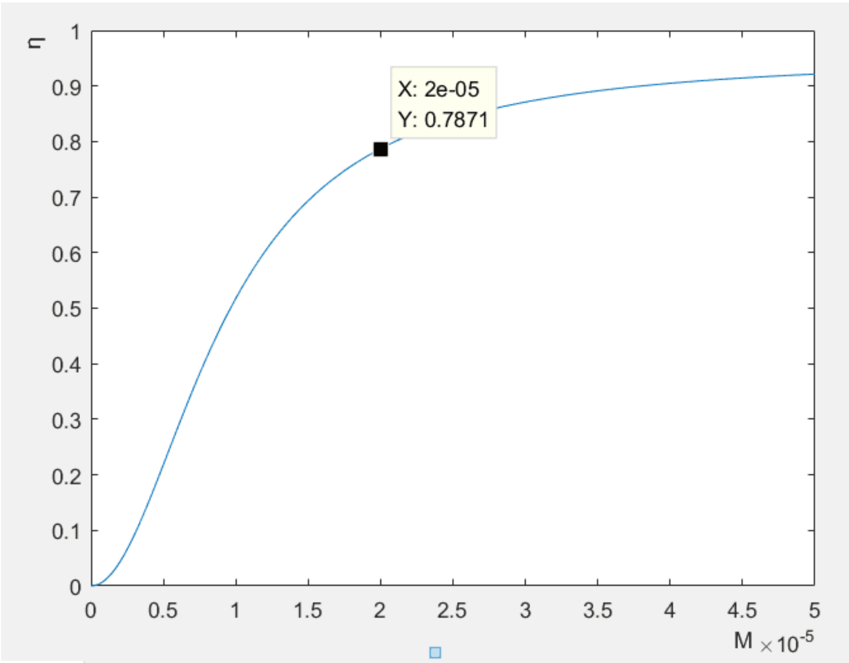


Figure 10 Variation curve of SS type transmission efficiency with mutual inductance

It can be seen from Fig. 9 that in the SS-type topology compensation network structure, with the increase of the mutual inductance value, the output power not only does not increase but decreases, but still maintains a high output power. In Fig. 10, it can be seen that with the increase of the mutual inductance value, the charging efficiency of the wireless charging system is improving. In the range of the inductance value of the car wireless charging, the value of the transmission efficiency is close to 80%, which can be obtained. In conclusion, the SS-type compensation topology can maintain high output power and transmission efficiency within the mutual inductance variation range of the wireless charging system of electric vehicles, which also proves the importance of controlling the coupling degree of the mutual inductance coil.

## 3.3. Relationship between Transmission Efficiency and Coupling Coefficient

The angular frequency range of the specified system is between $200 \times 10^3 rad/s \sim 600 \times 10^3 rad/s$, and changes within this angular frequency range may cause the system to appear non-resonant. The load $R_{eq} = 20\Omega$, and other parameter values are as above, let k be 0.15, 0.25, 0.35, 0.45, 0.55 respectively, and take the resonance angular frequency as the independent variable to draw the relationship between the transmission efficiency and the coupling coefficient as shown in Fig. 11.

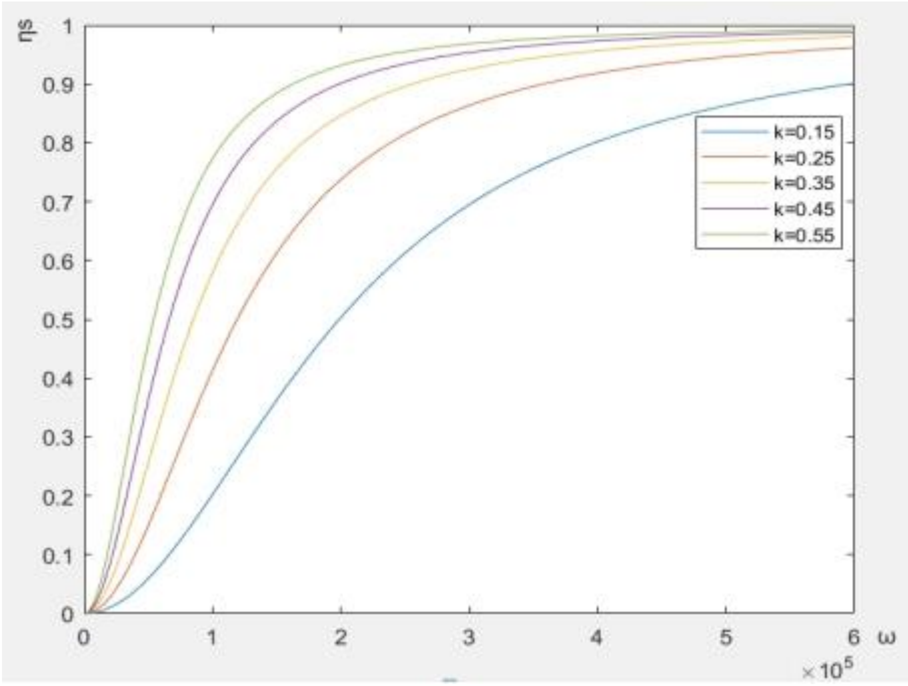


Figure 11 Relationship between transmission efficiency and coupling coefficient

In Fig. 11, it can be seen that when the resonant frequency is constant, the transmission efficiency of the SS type compensation topology increases with the increase of k value, when k is constant, the transmission efficiency of the SS type increases with the increase of the resonant frequency. When the efficiency reaches a certain value, it will not change with the change of the resonant frequency. And it can be found that the SS type can keep the transmission efficiency at a level higher than 80% within the range of the resonant frequency change during the wireless charging of the car.

# 4. Conclusion

One of the explanations of the physical characteristics of a capacitor compensator in series in the transmission line is to reduce the total equivalent series impedance of the transmission line from the transmitting end to the receiving end, which can be regarded as an equivalent "shortening" of the physical distance of the transmission line. Another explanation is that

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adding a series capacitor is equivalent to increasing the total voltage amplitude across the series impedance, so the current of the transmission line will increase, and the transmission power will also increase. The series compensation can be regarded as the compensation connected in series on the transmission line. power source. When the series compensation structure resonates, the capacitive voltage drop and the inductive voltage drop are equal in value and opposite in phase, and can cancel each other out. The LC port is equivalent to a short circuit to the outside, showing the characteristics of a voltage source, also known as "voltage resonance". In series resonance, the voltage on the inductor and the compensation capacitor is generally very high, so the insulation performance of the device is required to be very high. When powered by a constant voltage source, the system mostly adopts a series compensation structure. Through the analysis of this paper, it can be concluded that the SS-type topology compensation network structure is simpler and suitable for practical applications, because it can still maintain a high output efficiency in the case of large frequency fluctuations.

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