Influence of transmission distance on magnetically coupled resonant radio energy transmission system

TONG JUN, Yang Xingchen, LI Facheng and Li Xiang

College of Electrical and Control Engineering, Xi'an University of Science And Technology, xi'an 710054, China

E-mail: 1148212063@qq.com

Abstract. Transmission distance is a key factor in designing a wireless energy transmission system. The change in coil spacing will have a huge impact on the output characteristics of the system. Therefore, this paper theoretically analyzes the mutual inductance model of two coils from the perspective of circuit theory. Studies have shown that coil spacing, impedance, self-inductance, operating frequency, load resistance and many other factors can affect the output characteristics of the system. So, this thesis uses the control variable method to study the relationship between transmission distance and output characteristics, and proposes the optimal output power point. Finally, an experimental prototype was made to verify the feasibility of the method.

1. Introduction

The traditional transmission mode can no longer meet the demand for power supply of today's high-tech products. Getting rid of the constraints of transmission lines has become the only way for many electronic products to go further. As early as 1889, the famous American scientist Tesla began to study radio energy transmission technology. However, limited by the theoretical level, experimental conditions and research funding at the time, Tesla did not make significant scientific research results in the study of radio energy transmission theory. Furthermore, the research on the theory of radio energy transmission has entered a trough. Although many scholars have carried out many projects, the contradiction between transmission distance and transmission efficiency has always been like a mountain that hinders the development of this technology[1-3].

Until 2007, the research team of the Massachusetts Institute of Technology proposed a new theory of radio energy transfer, the theory of magnetically coupled resonant radio energy transmission, and made the research of radio energy transmission theory a hot topic of the era technology[4]. The theory of magnetically coupled resonant radio energy transmission is to use a set of energy transmission devices with the same resonant frequency to realize the transmission of electrical energy over long distances with medium and high frequency magnetic fields as the medium. The magnetic coupling resonance type uses strong coupling technology to improve the output power and transmission efficiency of the system, and has good penetrability. The non-radiation technology adopted by the system also effectively ensures personal safety[5-8].

In this thesis, the system modeling and analysis are carried out by using circuit theory, and the relationship between transmission distance, transmission efficiency and output power is studied. Focusing on a new thinking mode, the specific algorithm of maximum output power point is proposed, and the influence of various factors on transmission efficiency and output power is analyzed. Finally,
an improved method is proposed. This provides a useful reference for optimizing the design of magnetically coupled resonant radio energy transmission.

2. Transmission model selection and theoretical analysis

The magnetic coupling resonant radio energy transmission system is mainly composed of three parts: high frequency power system, energy transmission system and load. The energy transmission system is the key research part of the radio energy transmission system, and its model is shown in Fig. 1.

![Figure 1. Transmitter and receiver model of wireless power transfer](image)

The energy transmission system is composed of a transmitting module and a receiving module, and the energy is transmitted from the transmitting coil to the receiving coil through the magnetic magnetic field by means of magnetic coupling resonance, thereby realizing wireless transmission of electric energy.

System transmission model selection

The transmission structure of the two coils is different according to the connection mode of the inductor and the capacitor, and can be divided into four types: string type, string type, parallel type, and parallel type. When the system is fully resonant, the resonant capacitor value can be obtained according to the topology of the circuit. It can be seen from the analysis that the resonant capacitance of the SS-type transmission structure is only related to the system frequency and the self-inductance of the coil, and has nothing to do with the parasitic resistance and the mutual inductance of the coil, which is convenient for system design and analysis, and has high transmission efficiency. Therefore, the SS-type transmission structure is selected as the research model of this paper.

Circuit Analysis

As shown in Figure 2, it is an SS type transmission model. Among them, R1 and R2 are the equivalent resistance of the coil, C1 and C2 are compensation capacitors, L1 and L2 are coil self-inductance, M is coil mutual inductance, US is high frequency power supply, and RL is load.

![Figure 2. SS type transmission model](image)

According to Kirchhoff's voltage law, the circuit analysis of Figure 2 can be obtained by equation (1)(2)

\[
U_s = (R_1 + \frac{1}{j\omega C_1} + j\omega L_1)I_1 + j\omega MI_2
\]

\[
0 = (R_1 + R_2 + \frac{1}{j\omega C_2} + j\omega L_2)I_2 + j\omega MI_1
\]
When the radio energy transmission system is operating in a resonant state, the loop equation can be reduced to:

\[ U_s = R_1 I_1 + j\omega M I_2 \]  
(3)

\[ 0 = (R_2 + R_L) I_2 + j\omega M I_2 \]  
(4)

The simultaneous equation (3) (4) can be used to find the primary and secondary currents of the system:

\[ I_1 = \frac{(R_2 + R_L) U_s}{R_1 R_2 + R_1 R_L + \omega^2 M^2} \]  
(5)

\[ I_2 = -\frac{j\omega M U_s}{R_1 R_2 + R_1 R_L + \omega^2 M^2} \]  
(6)

When the system resonates, its input impedance is:

\[ Z_{in} = R_1 + \frac{\omega^2 M^2}{R_2 + R_L} \]  
(7)

Then, the input power and output power of the system are:

\[ P_1 = P_{in} = I_1^2 Z_{in} = \frac{U_s^2 (R_2 + R_L) (\omega^2 M^2 + R_1 R_2 + R_1 R_L)^2}{(\omega^2 M^2 + R_1 R_2 + R_1 R_L)^2} \]  
(8)

\[ P_2 = P_{out} = I_2^2 R_L = \frac{\omega^2 M^2 U_s^2 R_L}{(\omega^2 M^2 + R_1 R_2 + R_1 R_L)^2} \]  
(9)

In turn, the transmission efficiency of the system can be solved:

\[ \eta = \frac{P_{out}}{P_{in}} = \frac{\omega^2 M^2 R_L}{(R_1 + R_L) (R_1 R_2 + R_1 R_L + \omega^2 M^2)} \]  
(10)

Deriving the expression of the output power:

\[ \frac{dP_2}{dM} = 0 \]

Got

\[ M_1 = 0 \quad M_2 = -\frac{\sqrt{R_1 (R_1 + R_L)}}{\omega} \quad M_3 = \frac{\sqrt{R_L (R_1 + R_L)}}{\omega} \]

Because M1 and M2 do not meet the actual situation, they are discarded.

According to the derivative relationship of the output power, it can be obtained that when 0<\(M < M_3\), the output power monotonically increases; when \(M_3 < M < 1\), the output power monotonically decreases.

Therefore, when the system output power is at the M3 point, the maximum value is taken. The mutual inductance of the coil is related to the impedance, self-inductance, load resistance and angular frequency of the secondary side coil. By changing one of the parameters, the mutual inductance of the coil of the system can be changed, thereby affecting the output power.

When the secondary side is a spiral coil and the central axis is on the same straight line, the distance and mutual inductance of the magnetically coupled resonant radio energy transmission system are:

\[ M = M_{12} = M_{21} = \frac{\pi \mu_0 (n_1 n_2)^{0.5} (r_1 r_2)^3}{2D^3} \]  
(11)

Where \(\mu_0\) is the vacuum permeability, D is the horizontal distance of the coil center point, and n1, n2, r1, and r2 are the turns and radii of the primary side and the secondary side coil, respectively. When n1=n2=n, r1=r2=r, the above formula can be reduced to:

\[ M = \frac{\pi \mu_0 n^4}{2D^3} \]  
(12)
The mutual inductance of the maximum output power point is:

\[ M_3 = \frac{\sqrt{R_1(R_1 + R_2)}}{\omega} \quad (13) \]

The simultaneous output formula (12) (13) can be used to derive the maximum output power point:

\[ D = 3\sqrt{\frac{\pi \mu_0 n r^4 \omega}{2 \sqrt{R_1(R_1 + R_2)}}} \quad (14) \]

Similarly, for the system transmission efficiency, the derivative function about the mutual inductance \( M \) is obtained:

\[ \frac{d\eta}{dM} = 0 \]

According to the system transmission efficiency derivation relationship, when \( M = 0 \), \( x \) takes the minimum value. When \( 0 < M < 1 \), the transmission efficiency monotonically increases. The mutual inductance \( M \) of the coil is inversely proportional to the transmission distance \( D \). When the transmission distance increases, the mutual inductance of the coil will decrease and the transmission power of the system will also decrease.

3. EXPERIMENT

In order to verify the correctness of the theoretical analysis, based on the SS-type transmission model, combined with the circuit theory, an experimental prototype of the radio energy transmission system is designed, as shown in Figure 3.

![Figure 3. Experiment platform](image)

The prototype of this experiment is mainly composed of signal generation controller, DC high-frequency inverter and electromagnetic emission and receiving system. Among them, in order to avoid the influence of the skin effect on the experimental data, the litz wire is used instead of the solid copper wire to wind the high frequency coil. The main experimental parameters of this experiment are shown in Table 1:

| Element | Numerical value |
|---------|----------------|
| \( f \) | 201KHz |
| \( L_1 \) | 28.3uH |
| \( L_2 \) | 28.7uH |
| \( C_1 \) | 0.022uF |
| \( C_2 \) | 0.022uF |
| \( R_1 \) | 0.394 \( \Omega \) |
| \( R_2 \) | 0.408 \( \Omega \) |
The experimental results are shown in Figures 4 and 5:

Figure 4. Influence of transmission distance on the output power

Figure 5. Influence of transmission distance on the system efficiency

It can be seen from Fig. 4 and Fig. 5 that as the distance increases, the transmission efficiency decreases continuously, while the output power shows a trend of increasing first and then decreasing, and the output power of the system reaches the maximum value when the transmission distance is 35 mm, and the formula (14) The calculated values are basically consistent. This shows that the variation law of the output power of the magnetically coupled resonant radio energy transmission system increases first and then decreases, and the maximum value can be reached at a certain point, but the output efficiency will gradually decrease as the transmission distance increases. Further analysis of Figures 4 and 5 shows that when the transmission distance is increased, the transmission efficiency is significantly reduced, but the output power is not significantly improved. Therefore, when designing the wireless energy transmission system, the pursuit of the maximum output power can be appropriately abandoned. The distance between the system transmission efficiency and the output power can be considered.

4. Optimization Analysis

4.1. Improve the working frequency

When the system works under high frequency conditions, the internal resistance of the coil is mainly composed of two parts: ohmic loss resistance and radiation loss resistance. Generally, in the frequency range of 1-50MHz, the radiation loss resistance is negligible, then the internal resistance of the coil is mainly ohmic loss resistance.

\[
R_0 = \sqrt{\frac{\omega \mu_0 \mu}{2\delta}} \frac{l}{4\pi a} = \frac{\pi f \mu_0}{\delta} \frac{l}{4\pi a}
\]  

(15)

Where a is the wire radius, L is the wire length, \(\mu_0\) is the vacuum permeability, \(\delta\) is the conductivity, and f is the system operating frequency.

As can be seen from equation (15), when the system frequency is increased, the internal resistance of the coil increases at the square root speed. Increasing the internal resistance of the coil will reduce the transmission efficiency of the system, but its growth rate is far less than the growth rate of the angular frequency. Therefore, the distance of the maximum output power point can be increased by increasing the operating frequency of the system.

4.2. Reduce the internal resistance of the coil
According to the formula analysis, when the internal resistance of the coil is reduced, the maximum transmission distance point can be effectively increased. Therefore, when designing the coil, a plurality of twisted silver-plated copper thick wires should be selected as much as possible to reduce the skin effect of the coil, increase the conductivity of the wire, and reduce the self-resistance of the coil.

5. Conclusion

In this paper, the distance characteristics of the magnetically coupled resonant radio energy transmission system are analyzed, and the experimental demonstration is carried out based on the derivation results. Finally, an optimization analysis was carried out. The specific conclusions are as follows:

(1) As the transmission distance increases, the output power of the system increases first and then decreases, while the transmission efficiency of the system is always reduced. Also, near the maximum output power point, as the transmission distance continues to increase, the transmission efficiency will be significantly reduced, but the output power is not significantly improved.

(2) When the transmission distance is (14), the output power of the system will reach the maximum value.

(3) Increasing the operating frequency of the system and reducing the coil self-resistance can effectively increase the distance of the maximum output power point.

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