

# Research on Power-Efficiency Synchronization of Wireless Power Transfer



Taiming Chen, Zhongyu Shen, Bo Yu, Xiaoqiang Zhu and Ke Wang

**Abstract** Aiming at the problem that the transmission efficiency and transmission power are difficult to achieve at the same time in the coupled resonant radio energy transmission process, based on the modeling and analysis of the equivalent structure of wireless power transmission S-S structure, this paper gives a method to synchronize transmission power and transmission efficiency under different loads and different distances, and further obtains that the optimal working frequency and the matching load resistance at a certain distance can make the power-efficiency synchronization reach the maximum value. By means of MATLAB simulation software, the experiment platform is set up to analyze the variation rule of system transmission efficiency and transmission power under different loads and different distances. The results demonstrate the correctness of the previous theory and provide a certain reference for improving the transmission efficiency and power of radio energy.

**Keywords** Coupled resonance · Power-efficiency synchronization · Optimal working frequency · Impedance matching

## 1 The Introduction

Traditional charging methods have safety hazards such as electric sparks and inconvenient operations. The emergence of wireless charging not only solves the above-mentioned troubles, but also makes great breakthroughs in some fields such as smart furniture, transportation, and medical care. It is a hot issue and research direction of research in recent years [1–4].

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The focus of current research is on transmission power and transmission efficiency. Literature [5] combined the characteristics of the system's output power, tracked its maximum power output point, and increased power, but did not consider efficiency. Literature [6] used the capacitance matrix method to achieve impedance matching, eliminating the problem of frequency offset, but it would make the structure complex and difficult to control. Literature [7, 12–14] proposed the concept of optimal frequency for transmission efficiency, and analyzed the relationship between maximum transmission efficiency and load or distance. Literature [8, 15, 16] analyzed the relationship between optimal operation frequency of transmission efficiency, optimal operation frequency of transmission power and impedance matching, and gave the idea of system power-efficiency synchronization factor. However, it did not further study the relationship between system power-efficiency synchronization under different distances, and the relationship between efficiency and load under specific distances.

In this paper, power-efficiency synchronization is realized under different loads and different distances, and the optimal working efficiency is obtained under certain distances, so as to realize power-efficiency synchronization.

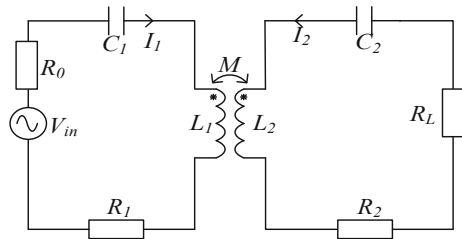
## 2 System Modeling and Theoretical Analysis

This paper focuses on the function of S-S-type radio transmission. It consists of high frequency inverter output voltage  $V_{in}$ , internal resistance of power supply  $R_0$ , equivalent loss resistance  $R_1$  and  $R_2$  of transmit coil and receive coil, compensate capacitor  $C_1$  and  $C_2$  of transmit coil and receive coil, equivalent inductance  $L_1$  and  $L_2$  of transmit and receive coil, the mutual inductance  $M$  between transmitting coil and receiving coil and load impedance constitute  $R_L$ . The circuit is shown in Fig. 1:

The circuit shown in Fig. 1 can be derived from KVL:

$$\begin{cases} V_{in} = (Z_1 + R_0)I_1 + j\omega MI_2 \\ 0 = j\omega MI_1 + (Z_2 + R_L)I_2 \end{cases} \quad (1)$$

Fig. 1 S-S circuit topology



Among them:

$$\begin{cases} Z_1 = R_1 + j\omega L_1 + \frac{1}{j\omega C_1} \\ Z_2 = R_2 + j\omega L_2 + \frac{1}{j\omega C_2} \end{cases} \quad (2)$$

Because of the skin effect, the loss resistance  $R_i$  [9] and radiation resistance  $R_r$  [9] of the coil increase with increasing frequency, which can be approximated as:

$$R_i = \sqrt{\frac{\omega\mu_0}{2\sigma_i}} \cdot \frac{n_i r_i}{\alpha_i} = m_i \sqrt{\omega} \quad i = 1, 2 \quad (3)$$

$$R_r = \sqrt{\frac{\mu_0}{\varepsilon_0}} \left[ \frac{\pi}{12} n^2 \left(\frac{\omega r}{c}\right)^4 + \frac{2}{3\pi^2} \left(\frac{\omega h}{c}\right)^2 \right] \quad (4)$$

In the above formula,  $\mu_0$  represents permittivity of vacuum;  $h$  is coil width;  $\varepsilon_0$  represents the dielectric constant;  $c$  is the speed of light;  $\sigma_i$  indicates the conductivity of the receiving or transmitting coil;  $n_i$  indicates the number of turns of the receiving or transmitting coil;  $r_i$  represents the coil radius;  $\alpha_i$  represents the wire diameter;  $m_i$  is a simplified expression. This paper studies the transmission of radio energy in the middle distance. At this time, the radiation resistance is much smaller than the loss resistance, so that the radiation resistance can be omitted in the following calculation.

From this it can be concluded that the input power and output power are:

$$P_{in} = I_1^2 \cdot Z_{in} = \frac{V_{in}^2 \left[ R_1 R_2 + R_1 R_L + (\omega M)^2 \right] (R_2 + R_L)}{\left[ R_1 R_2 + R_1 R_L + R_2 R_0 + R_L R_0 + (\omega M)^2 \right]^2} \quad (5)$$

$$P_{out} = I_2^2 \cdot R_L = \frac{V_{in}^2 (\omega M)^2}{\left[ R_1 R_2 + R_1 R_L + R_2 R_0 + R_L R_0 + (\omega M)^2 \right]^2} \quad (6)$$

From the Eqs. (5) and (6), it can be concluded that the transmission efficiency of the system is:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{(\omega M)^2 R_L}{(R_2 + R_L) \left[ R_1 R_2 + R_1 R_L + (\omega M)^2 \right]} \quad (7)$$

The main parameters of MATLAB simulation are shown in Table 1:

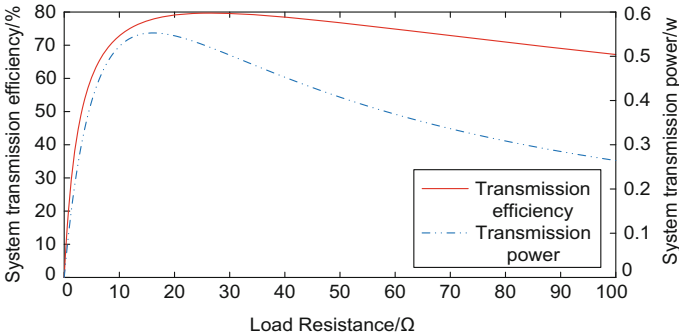
**Table 1** Main parameters of simulation

Coil parameters	Transmit coil	Receive coil	Coil parameters	Parameter values
Radius $r/\text{mm}$	100	100	Voltage $V_{in}/\text{V}$	12
Wire diameter $\alpha_i/\text{mm}$	2	2	Internal resistance $R_0/\Omega$	50
Number of turns $n_i$	15	15	Conductivity $\delta_i/\text{S/m}$	$5.77 \times 10^{-7}$
Loss resistance $R_f/\Omega$	0.3	0.1	Load resistance $R_L/\Omega$	20
Mutual inductance $M/\text{mH}$	3.147		Resonant frequency $f/\text{kHz}$	51

We can see that the size of the load and the size of the mutual inductance affect the transmission efficiency and transmission power of the system. The efficiency and power of different loads and mutual inductances are also different.

It can be seen from Fig. 2 that with the change of the load resistance, the transmission power of the system reaches a maximum when the load resistance is 10–20  $\Omega$ , however the maximum transmission efficiency of the system is when the load value is about 25  $\Omega$ . From this we can see that the power and efficiency have reached the maximum under different load resistances, but there is no function to achieve power-efficiency synchronization.

It can be seen from Fig. 3 that as the distance between the two coils changes, the transmission power of the system reaches a maximum when the distance between the two coils is about 20 cm, but the transmission efficiency of the system reaches a maximum when the distance between the two coils is 10–15 cm. There is also no function to achieve power-efficiency synchronization. What is needed is to maximize the power and efficiency at the same time under the same load and the same distance to achieve the power-efficiency synchronization state, reduce system loss and improve the overall efficiency.



**Fig. 2** Power-efficiency curve of load

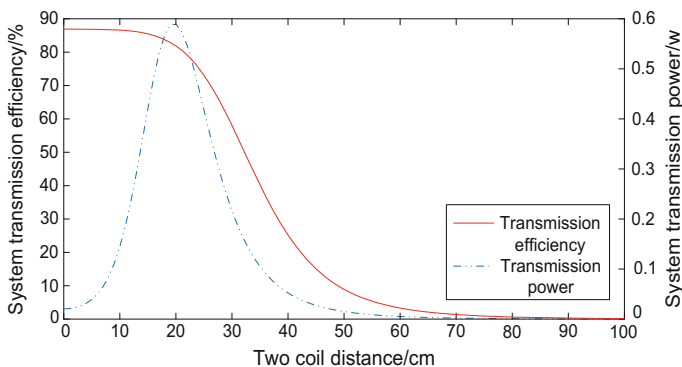


Fig. 3 Power-efficiency curve of distance

### 3 Power-Efficiency Synchronization Matching Parameters

#### 3.1 Power-Efficacy Synchronization Analysis

Substituting the above formula (3) into (5), deriving the parameter  $\omega$  can be obtained [9]:

$$2R_L R_0 + m(R_L + R_0)\sqrt{\omega} - 2(\omega M)^2 = 0 \quad (m_1 = m_2 = m) \quad (8)$$

Thereby, the optimal transmission power angular frequency and the optimal transmission efficiency angular frequency can be solved [11] as follows:

$$\omega_p = \frac{\sqrt{R_L R_0}}{M} \quad (9)$$

$$\omega_\eta = \frac{\sqrt{3R_L}}{M} \quad (10)$$

Under the same frequency condition, the optimal transmission power and the best transmission efficiency of the system can not be obtained at the same time. In order to get the best operating state, the power synchronization factor  $\xi$  [11] is defined to represent the ratio of the two optimal angular frequencies. Expressed as:

$$\xi = \frac{\omega_\eta}{\omega_p} = \sqrt{\frac{3R_L}{R_0}} \quad (11)$$

### 3.2 Impedance Matching Analysis

According to the maximum power transmission theorem, when the total system impedance is equal to the complex conjugate of the internal resistance of the power supply, the system power reaches the maximum. When impedance mismatch occurs, there must be energy loss to reduce transmission efficiency.

According to Fig. 1, the total impedance of the system is:

$$Z_{in} = R_1 + \frac{(\omega M)^2}{R_2 + R_L} \approx \frac{(\omega M)^2}{R_L} \quad (12)$$

When the system is in the state of power-efficiency synchronization,  $(\omega M)^2/R_L = R_0$  can be obtained by substituting the system's best angular frequency  $\omega$  and the power synchronization factor  $\xi = 1$  into Eq. (12). Therefore, when the system works at the optimal operating frequency, not only the load power and transmission efficiency reach the maximum value at the same point, but also meet the condition of impedance matching. It can be seen that the impedance matching can realize the synchronization of the power of the wireless energy transmission system and realize the optimal utilization of energy.

In order to realize the function of power-efficiency synchronization, the above methods can be used to realize the optimal parameters of power and efficiency when selecting various parameters of the system, and simulation is performed in MATLAB.

## 4 Matlab Simulation Verification

When the system is operating at its optimal state, i.e.:  $\omega_\eta = \omega_p = \omega_0$ . Simulation of the above theory by MATLAB can be obtained:

It can be seen from the Fig. 4 that when the load is about 30  $\Omega$ , the transmission efficiency is 86%, the transmission power is 0.66 W, and the transmission efficiency and transmission power of the system reach the maximum at the same time, both the system realizes the power-efficiency synchronization. Compared with Figs. 3 and 5 can clearly see that the power and efficiency decrease as the distance increases, and the power-efficiency synchronization function is realized.

## 5 The Matching of Load and Distance

Different distances and different load corresponding synchronization of power and efficacy parameters are inconsistent. From the Eqs. (9) and (10), it can be concluded that [10]:

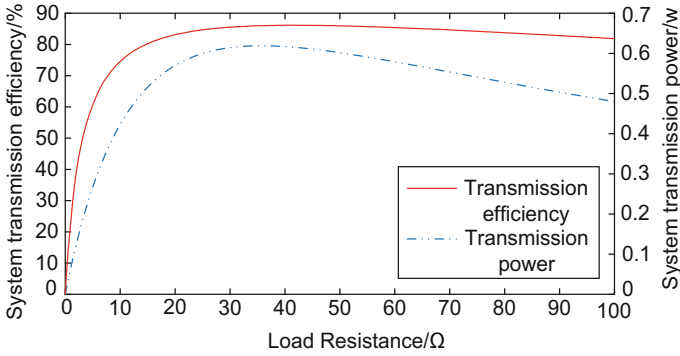


Fig. 4 Load synchronization curve

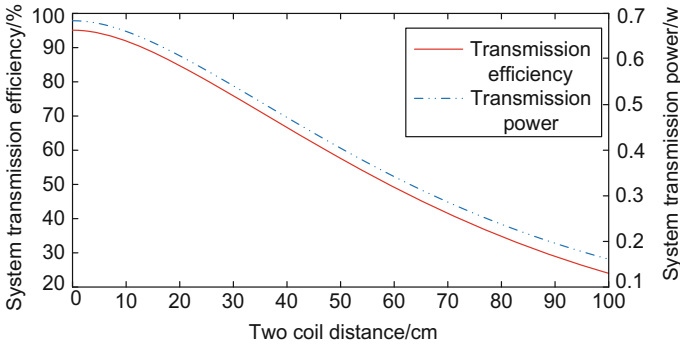


Fig. 5 Distance synchronization curve

$$f_p = \frac{\sqrt{R_L R_0}}{2\pi M} = \frac{\sqrt{R_L R_0} (D^2 + r_1^2)^{1.5}}{\pi^2 \mu_0 n_1 n_2 r_1^2 r_2^2} \tag{13}$$

$$f_\eta = \frac{\sqrt{3} R_L}{2\pi M} = \frac{\sqrt{3} R_L (D^2 + r_1^2)^{1.5}}{\pi^2 \mu_0 n_1 n_2 r_1^2 r_2^2} \tag{14}$$

In the above formula, D denotes the distance between the two coils;  $r_1$  and  $r_2$  denote the radius of the two coils;  $n_1$  and  $n_2$  represent the number of turns of the two coils. MATLAB simulation shows that:

From the Fig. 6, when the distance is 10 cm, the load is 17.3  $\Omega$ , and the frequency is 0.3037 MHz, the system can realize the power-efficiency synchronization.

When the power-efficiency synchronization factor is not equal to 1 ( $\xi < 1$  or  $\xi > 1$ ), that is to say, the situation of distance D = 10 cm, the optimum frequency is not equal to 0.3037 MHz as shown in Fig. 7 [12]:

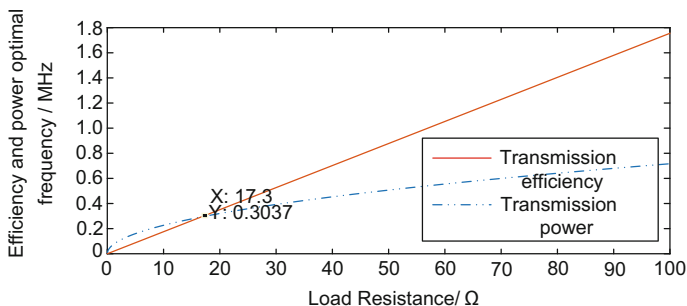


Fig. 6 Optimal working position

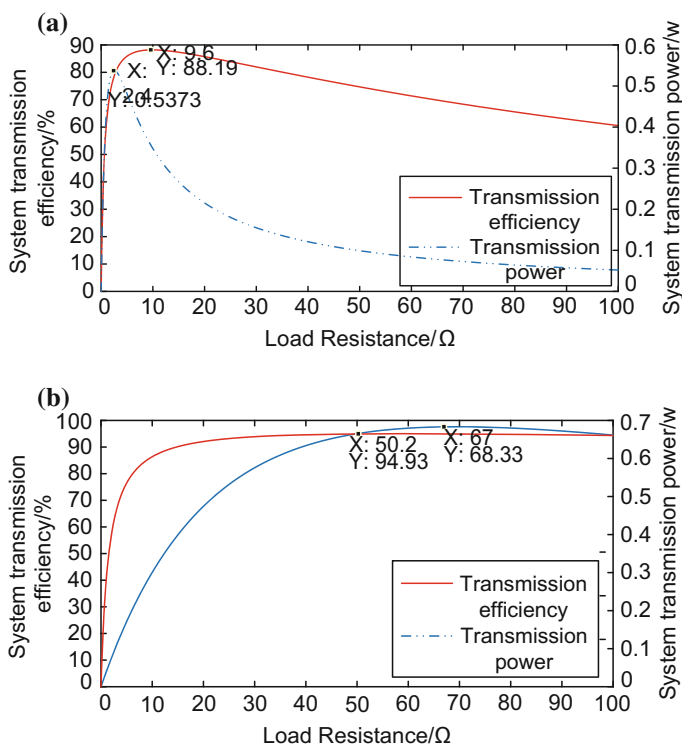
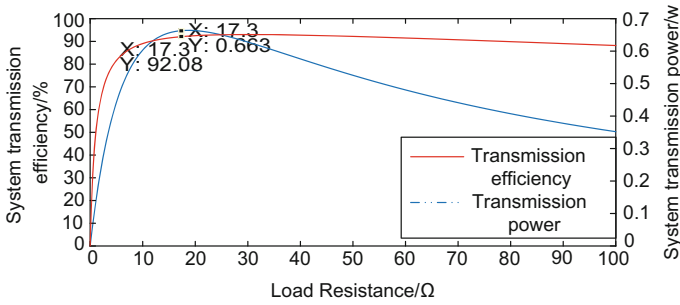


Fig. 7  $D = 10 \text{ cm}$  ( $\xi \neq 1$ )

From Fig. 7a, it can be seen that when  $D = 10 \text{ cm}$ , the system operating frequency is less than the optimal operating frequency. The transmission power increases first and then decreases. When the load resistance reaches  $2.4 \text{ } \Omega$ , the transmission power reaches the maximum value. The transmission efficiency also





**Fig. 8**  $D = 10 \text{ cm}$  ( $\xi = 1$ )

increases first and then decreases. When the load resistance reaches  $9.6 \Omega$ , the transmission efficiency reaches the maximum. But they can't achieve power-efficiency synchronization. From Fig. 7b, it can be seen that when  $D = 10 \text{ cm}$ , the system operating frequency is more than the optimal operating frequency. As with Fig. 7a, power-efficiency synchronization is not achieved.

When the system operating frequency is equal to the optimal operating frequency and the load satisfies the critical load conditions, the efficiency and power simulated by MATLAB are as follows [12].

It can be seen from Fig. 8 that when the distance  $D = 10 \text{ cm}$  and the system operating frequency is equal to the optimum operating frequency, the transmission efficiency and power are maximized at different loads. When the load resistance reaches  $17.3 \Omega$ , the transmission power reaches a maximum of  $92.08\%$  and the transmission efficiency reaches a maximum of  $0.663 \text{ W}$ . In this case, the synchronization of power and efficiency can be achieved.

## 6 Conclusion

In order to synchronize transmission efficiency and transmission power in the coupled resonant wireless power transmission, we mainly study the transmission efficiency and transmission power of S-S structure pure resistive load. When the optimal frequency of the transmission efficiency is equal to the optimal frequency of the transmission power, the synchronization of power and efficacy can be realized. If not, the synchronization of power and efficacy can not be achieved. It can be achieved of synchronization of power and efficacy when the conditions of synchronization of power and efficacy are met under different loads and different distances. At the same time, the required frequencies are different at different distances. The farther the distance is, the higher of the required optimal operating frequency is. Through simulation, the correctness of the research results is obtained, and the optimal transmission of energy can be realized.

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