Research on the efficiency of single-wire power transmission

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Abstract. With the development of related theoretical research on Single Wire Power Transfer (SWPT), the SWPT system has demonstrated its advantages in a variety of special environments. In this paper, the influence of capacitance and inductance on transmission efficiency is studied in order to improve the transmission efficiency of the SWPT system. This article simplifies and analyzes the circuit model of the SWPT system. It can be found that the system is a second-order circuit, and its response distribution trend conforms to the Gaussian function distribution. There should be an optimal ratio between the capacitor and the inductance to maximize the circuit response. Through the influence of different capacitance, inductance, and transmission distance on transmission efficiency, multiple sets of experiments and simulations are carried out. The experiment found that the capacitance, inductance, and transmission efficiency are in accordance with the Gaussian non-normal distribution, and the acquired data is fitted by the Gaussian function. The average relative error of the fitting is less than 1% under different transmission distances, which can better reflect the relationship between the three. The study of single-wire power transmission system will provide a key reference for wireless power transmission.

1. Introduction

Wireless power transmission (WPT) is one of the current hot research directions in the field of electrical engineering. The United States, Japan, Germany, France and other countries in this area started early and they occupy an important position in the fields of smart electronics and electric vehicles. China Association for Science and Technology also listed it as ten science and technology leading the future [1-2], this technology has shown advantages in smart grid, aerospace, military and other fields.

In daily life, WPT system has also been widely used, literature [3-6] describes the application of WPT system in the context of electric vehicles, drones, mobile phones, human implantable medical devices, and household appliances. The power supply mode of the WPT system allows people to get rid of the space constraints caused by the wired power supply network.

In the current power network system, the power transmission method is still based on multiple wires [7]. However, in addition to the dangers and shortcomings of such a power network, it is also greatly restricted in space, if the WPT system can be applied to the power network system, it can get rid of many restrictions caused by wired power transmission.

But the WPT system is limited in the transmission distance and transmission power [8]. In order to break through the barriers of wireless technology, people have turned their attention to single-
conductor power transmission technology (SWPT). If a single wire can be replaced by natural conductors such as the earth, wireless power transmission in a broad sense can be realized \[9\].

Compared with the WPT system, the SWPT system uses a wire, so the SWPT system can achieve greater transmission power and longer transmission distance and the SWPT system has advantages that the WPT system does not have in some special environments, for example, the power supply problem of isolated islands or the power supply problem of wireless sensor network sensors \[10\], SWPT system has proposed solutions for these problems with its advantages of low cost and easy laying.

Literature \[11\] briefly described the impact of capacitance on transmission efficiency, but did not carry out a detailed description and systematic research on it; Literature \[12\] conducted related experiments and analysis on the equivalent method of the capacitance between the two Tesla coils in the SWPT system, and further analyzed the circuit model of the system, but there was still no systematic discussion on the relationship of transmission efficiency; In \[13\], a wireless power supply platform based on the SWPT system was constructed by using the capacitance to ground generated by the spiral coil, and the transmission effect of capacitance and electric energy was theoretically analyzed and experimentally verified.

Aiming at the problem of the transmission efficiency of the SWPT system, in this article, we study the influence of capacitance and inductance on the transmission efficiency, which will provide a new way to improve the transmission efficiency of the SWPT system. This article is based on the previous research. Through theoretical derivation, experiment and simulation, the relationship between the two and the transmission efficiency was briefly studied.

2. The influence of capacitance and inductance on transmission efficiency

2.1 Theoretical Derivation of Single-Wire Power Transmission System

In order to realize the high-power electric energy transmission of the SWPT system, not only need for two Tesla coils to be coupled at the same frequency, but also closely related to the inductance and capacitance at the resonance frequency. Therefore, there should be a certain relationship between inductance, capacitance and transmission efficiency, so that the transmission efficiency of inductance and capacitance can reach the maximum value only at a specific value.

To verify the above relationship, first analyze the circuit model of the SWPT system. Literature \[11\] proposed a circuit model of the SWPT system, as shown in Figure 1.

![Figure 1. SWPT system equivalent circuit diagram](image)

Literature \[11\] pointed out that the resistance \(R_2\) will increase due to the transmission distance and skin effect, which can be equivalent to infinity; at this time, the capacitors \(C_2\) and \(C_3\) are connected in series and then connected in parallel with \(C_1\), which is recorded as \(C_{12}\). After \(C_5\) and \(C_6\) are connected in series, they are connected in parallel with \(C_7\) and recorded as \(C_{57}\). Since the wire is close to the ground, the capacitors connected in parallel on both sides are respectively: \(C_{12} \approx C_1 + C_2\) and \(C_{57} \approx C_5 + C_7\). As the transmission distance increases, the capacitance \(C_4\) will decrease rapidly. When \(C_4\) is small enough, it can be equivalent to a wire. At this time, the equivalent capacitance of \(C_{12}\) and \(C_{57}\) in parallel is recorded as \(C_8\), and the Tesla coil is regarded as a transformer. Its decoupling is equivalent
to an inductance, and the two inductances are connected in parallel, denoted as $L_1$, and the circuit is simplified to get the circuit diagram shown in Figure 2.

![Figure 2. Simplified equivalent circuit diagram of SWPT system](image)

By obtaining the current response $i_L$ flowing through the inductor in the above figure 2, the KCL law can be obtained:

$$LC \frac{d^2i_L}{dt^2} + \frac{L}{R} \frac{di_L}{dt} + i_L = i_s$$  \hspace{1cm} (1)

It can be seen from formula (1) that the model is a second-order LC resonant circuit, so the characteristic equation of formula (1) is shown in formula (2):

$$\lambda^2 + \frac{1}{RC} \lambda + \frac{1}{LC} = 0$$  \hspace{1cm} (2)

After substituting the corresponding parameters into equation (2), it can be seen that the characteristic equation has two different solutions, then the general solution of the corresponding homogeneous equation is shown in equation (3):

$$i_L = C_1 e^{\lambda_1 x} + C_2 e^{\lambda_2 x}$$  \hspace{1cm} (3)

Therefore, the transformation trend of the voltage across the load with the capacitance and inductance should conform to the distribution trend of the Gaussian function, then when the capacitance and inductance are at a certain value, the voltage across the load will reach a peak value.

2.2 Single-wire power transmission system experiment

2.2.1 Experimental conditions and test equipment

Experimental conditions: 0.4mm enameled wire, PVC pipe with an outer diameter of 25mm, a ball with a diameter of 35mm, aluminum foil, wire, universal board, and several resistors.

Experimental instruments: signal generator, Tektronix oscilloscope, inductance tester. Among them, the maximum output voltage of the signal generator is 10V, and the maximum operating frequency is 60MHz.

2.2.2 Single-wire power transmission experiment

In order to verify the assumption that there is a certain relationship between inductance, capacitance and transmission efficiency, a SWPT system as shown in Figure 3 \cite{14} is built.

![Figure 3. The single-wire power transmission structure used in this article](image)
With 10V alternating current as the input voltage of the system, the working frequency of the signal generator is constantly adjusted, and the coil is gradually increased from 30 turns to 180 turns, and the experiment is carried out in steps of 10 turns. The distance between the receiving end and the transmitting end is fixed at 3m, 10m, and 40m respectively. With a 50Ω resistor as the load, the peak-to-peak voltage at both ends of the load is detected by an oscilloscope. When the peak-to-peak voltage reaches the maximum, the system is considered to have reached the resonance frequency. After the resonant frequency is obtained, the capacitance to ground of each coil is obtained by formula (4), and the peak-to-peak voltage on both sides of the load at the receiving end under different turns is recorded.

\[ f = \frac{1}{2\pi\sqrt{LC}} \]  

(4)

Adjust the output voltage of the signal generator to 10V and the operating frequency to 17MHz, and gradually reduce it. Calculate the capacitance of the coil to ground. The values are shown in Table 1.

| Turns | Inductance (µH) | Capacitance (pF) | Resonance Frequency (MHz) |
|-------|----------------|------------------|--------------------------|
| 30    | 36             | 2.5376           | 16.66                    |
| 40    | 48             | 2.544            | 14.45                    |
| 50    | 61             | 2.6472           | 12.85                    |
| 60    | 74             | 2.7545           | 11.57                    |
| 70    | 84.5           | 2.8617           | 10.24                    |
| 80    | 94.5           | 2.9355           | 9.398                    |
| 90    | 105.5          | 3.0092           | 8.937                    |
| 100   | 123            | 2.9881           | 8.306                    |
| 110   | 129.5          | 3.1081           | 7.937                    |
| 120   | 143            | 3.1448           | 7.576                    |
| 130   | 154            | 3.1814           | 7.194                    |
| 140   | 166.5          | 3.2131           | 6.978                    |
| 150   | 176            | 3.2447           | 6.8                      |
| 160   | 188.5          | 3.3067           | 6.378                    |
| 170   | 201            | 3.3269           | 6.203                    |
| 180   | 212            | 3.3471           | 6.039                    |

Considering that the SWPT system realizes the transmission of electric energy through the resonance of the Tesla coils at both ends, the resonance frequency determines the transmission efficiency to a large extent. It can be seen from equation (4) that when the inductance and capacitance reach the appropriate When matching, the transmission efficiency is the largest, so the relationship between the three is explored by taking the product of inductance and capacitance.

Under the transmission distance of 3m, 10m and 40m, the relationship between the product of the inductance L and the capacitance C and the received voltage is shown in Figure 4, where the abscissa is the product of the inductance and the capacitance, and the ordinate is the voltage across the load.

![Figure 4. Waveforms of the voltage at the receiving terminal and the capacitance and inductance under different line lengths](image)
2.3 Experimental simulation of single-wire power transmission

In order to further verify the influence of capacitance and inductance on transmission efficiency, the experiment process was simulated through Simulink. Set up the simulation model shown in Figure 2 in Simulink, the signal input amplitude is a sine wave of 10V, the inductance and capacitance are respectively expanded by 1000 times on the basis of Table 1, and the frequency is correspondingly reduced by 1000 times (because Simulink will have an error when calculating the reciprocal of the too small number or matrix or matrix), use a 50KΩ resistor as the load to detect the peak-to-peak voltage across the load, and then use the product of the inductance L and the capacitance C as the abscissa, and the peak-to-peak voltage across the load as the On the ordinate, plot the experimental and simulated waveforms, as shown in Figure 5.

![Waveform diagram of the peak-to-peak voltage of the load at different transmission distances as a function of the product of capacitance and inductance](image)

Observe Figure 5, it can be seen that the overall change trend is relatively similar, but the overall amplitude of Figure 5 has a certain degree of decline compared to Figure 4. Comprehensive considerations, it is believed that the following reasons are mainly caused: (1) Due to the circuit The model is a lumped parameter model, while the experiment is a distributed parameter, which causes a certain change in the waveform; (2) The load during simulation is larger than the load in the experiment.

3. Analysis of results

It can be seen from Figure 4 and Figure 5 that the increase in line length leads to a rapid drop in the voltage across the load, which is consistent with the conclusion drawn in the literature [11]. Secondly, it can be found that although the transmission efficiency is significantly reduced, the change trend of the voltage at both ends of the load with the capacitance and inductance under different line lengths is still roughly the same, and the maximum value of the transmission voltage is obtained at 40 turns to 50 turns, and then As the inductance and capacitance increase to decrease rapidly, this is consistent with
the previous description, so there is a certain specific relationship between capacitance, inductance and receiving voltage.

In the second section of this article analyzed the circuit model and determined that the circuit model is a second-order circuit. Its waveform should be consistent with the Gaussian function distribution trend. From Figure 4 and Figure 5, we can see the trend of that the voltage across the load varies with inductance and capacitance, which changed waveform is similar to the Gaussian function. This is consistent with the conclusion that in the second section of this article when after obtaining the response of the circuit model. Therefore, use the data of 3m, 10m and 40m are respectively fitted by the Gaussian function through MATLAB to obtain the formula (5):

$$V_L = \alpha_1 \cdot e^{-\left(\frac{LC - \beta_1}{\gamma_1}\right)^2} + \alpha_2 \cdot e^{-\left(\frac{LC - \beta_2}{\gamma_2}\right)^2} + \alpha_3 \cdot e^{-\left(\frac{LC - \beta_3}{\gamma_3}\right)^2}$$  \hspace{1cm} (5)

Among them, V represents the voltage across the load at the receiving end, in V, L represents the coil inductance, in μH, and C represents the coil capacitance, in pF. Among them, the parameter values are shown in Table 2.

| L      | 3m    | 10m   | 40m   |
|--------|-------|-------|-------|
| $\alpha_1$ | 2.469 | 0.994 | 1.525 |
| $\beta_1$ | 175.2 | 114   | 115.9 |
| $\gamma_1$ | 30.42 | 39.03 | 83.05 |
| $\alpha_2$ | 1.005 | 0.6787| 1.253 |
| $\beta_2$ | 268.6 | 284.4 | 263.8 |
| $\gamma_2$ | 88.12 | 63.4  | 111.1 |
| $\alpha_3$ | 4.242 | 3.649 | 1.8   |
| $\beta_3$ | 365. | 104.5 | 524.7 |
| $\gamma_3$ | 558.7 | 795.5 | 440.7 |

Based on the above-fitted model and the measured data, the comparison is shown in Table 3.

| Turns | 3m line length model | 10m line length model | 40m line length model |
|-------|----------------------|-----------------------|-----------------------|
|       | Measured data | Model calculation | Relative error (%) | Measured data | Model calculation | Relative error (%) | Measured data | Model calculation | Relative error (%) |
| 30    | 3.36     | 3.33                | 0.96                 | 4.36     | 4.36                | 0.02                 | 2.18     | 2.19                | 0.02                 |
| 40    | 3.68     | 3.7                 | 0.55                 | 4.6      | 4.6                 | 0.03                 | 2.53     | 2.58                | 0.19                 |
| 50    | 5.96     | 5.97                | 0.2                  | 3.88     | 3.87                | 0.19                 | 2.54     | 2.49                | 0.71                 |
| 60    | 5.5      | 5.48                | 0.35                 | 3.64     | 3.73                | 2.54                 | 2.54     | 2.55                | 0.39                 |
| 70    | 5.04     | 5.03                | 0.28                 | 4.12     | 3.97                | 3.54                 | 2.53     | 2.83                | 11.86                |
| 80    | 5.1      | 5.1                 | 2.01                 | 4.15     | 3.78                | 3.78                 | 2.04     | 2.11                | 3.43                 |
| 90    | 5.08     | 4.85                | 4.62                 | 4.04     | 3.91                | 3.13                 | 2.52     | 2.44                | 3.17                 |
| 100   | 4.48     | 4.49                | 0.3                  | 3.28     | 3.39                | 3.44                 | 2.04     | 2.11                | 3.43                 |
| 110   | 4.28     | 4.36                | 1.98                 | 3.16     | 3.19                | 1.03                 | 3.16     | 1.93                | 0.52                 |
| 120   | 4.08     | 4.24                | 3.9                  | 3.19     | 3.02                | 5.22                 | 3.19     | 1.82                | 2.67                 |
| 130   | 4.08     | 4.1                 | 6.11                 | 3.22     | 2.89                | 10.38                | 1.98     | 1.81                | 0.55                 |
| 140   | 4.08     | 3.91                | 4.25                 | 2.48     | 2.72                | 9.79                 | 2.48     | 1.8                 | 2.27                 |
| 150   | 3.74     | 3.71                | 0.69                 | 2.46     | 2.59                | 5.16                 | 2.46     | 1.78                | 0.56                 |
| 160   | 3.4      | 3.39                | 0.16                 | 2.26     | 2.38                | 5.52                 | 2.26     | 1.71                | 3.93                 |
| 170   | 2.86     | 3.09                | 7.97                 | 2.06     | 2.21                | 11.11                | 2.06     | 1.62                | 0                   |
| 180   | 2.88     | 2.8                 | 2.81                 | 2.16     | 2.05                | 5.28                 | 2.16     | 1.51                | 6.34                 |
It can be seen from Table 3 that the average relative error of the model with a transmission distance of 3m is 0.8123%, SSE is 0.2259, R-square is 0.9840, Adj R-sq is 0.9679, and RMSE is 0.1680; the model with a transmission distance of 10m The average relative error is 0.664%, SSE is 0.3681, R-square is 0.9687, Adj R-sq is 0.9375, RMSE is 0.2145; the average relative error of the model with a transmission distance of 40m is 0.8771%, SSE is 0.0396, R-square It is 0.9855, Adj R-sq is 0.9710, and RMSE is 0.0704.

From the above indicators, the fitting accuracy of the three models is acceptable, and the average relative error with the measured data is less than 1%, which is relatively accurate. It is confirmed that there is indeed a certain relationship between capacitance, inductance and transmission efficiency. As the transmission distance increases, the transmission efficiency decreases, and the coefficients of the fitted mathematical model also change accordingly, but there is no obvious change in the overall change trend.

Based on the above model, we can consider adjusting the parameters when the capacitance or inductance is known to control the quality factor in a more appropriate range, so that the receiving voltage at the receiving end can achieve the desired receiving effect.

4. Conclusion
In this paper, three sets of SWPT systems with different transmission distances are built through 18 sets of Tesla coils. The hypothesis that capacitance and inductance have nonlinear effects on transmission efficiency is deduced and verified by theory, experiment and simulation, it is confirmed that there is a correlation between the three. When the capacitance and inductance are at the right value, the transmission efficiency can be maximized. After obtaining the experimental data, the Gaussian function is used to fit the relationship between the three, and the error is analyzed. Various error indicators show that the fitting relationship can accurately reflect the relationship of capacitance, inductance and transmission efficiency. It provides new ideas and directions for improving the transmission efficiency of the SWPT system.

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