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Design and Optimization of One-Way Single-Wire Power Transfer Structure

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Abstract: In this paper, a novel one-way single-wire power transfer structure is proposed. Different from the traditional single-wire power transfer system, power is one-way transmitted from the power source to the load, and no loop is constituted. The structure of one-way single-wire power transfer is studied in detail, and the influences of its length and shapes on the transmission efficiency are determined. Research shows that the length of the receiving structure plays a key role in improving the system's efficiency, while the transmitting structure has a little effect. Based on ensuring transmission efficiency, the space volume optimization method is further applied. The expression of electromagnetic field distribution is derived theoretically, and the proposed structure is verified by simulation and experimental results.

Keywords: single-wire power transfer; coaxial line; transfer structure; volume optimization

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1. Introduction

Most of the existing power transfer methods which use wires to connect power sources and loads have obvious disadvantages in flammable and explosive scenarios, such as mines and oil fields. With the aging and wear of the wire insulation, the wires are prone to spark discharge and short-circuit faults, posing a serious risk to electrical equipment [1]. As a novel method for power transmission, the wireless power transfer (WPT) technology using spatial intangible soft media (e.g., electric fields, magnetic fields, and microwaves) to transmit power has more merits [2–7], and it has attracted attention of researchers worldwide [8–14]. However, the transmission efficiency of WPT will drop sharply with the increase in the transmission distance [15], and the restrictive relationship between transmission distance and transmission efficiency cannot meet the needs of long-distance power transmission for devices such as wireless sensor network. To overcome the restriction on the transmission distance of WPT, the single-wire power transfer technology was proposed accordingly.

As early as the 1890s, the single-wire power transfer technology was proposed by Tesla [16], who believed that by reasonably planning the transmitting and receiving devices, a huge power can be transmitted to any place with the help of the earth [17]. In 2008, researchers reconducted the Tesla experiment, in which the earth was used instead of the single-wire to transmit 801 W power at a transmission distance of 5 m, and the transmission efficiency was 22.27% [18]. In 2009, a single-wire power transfer system was developed, in which water was used to replace the single-wire and a 25 W incandescent lamp was lit 20 m away [19]. In 2016, soil, aluminum foil, and other non-metallic materials were used to replace the single-wire [20,21]. In 2007, the synchronous transmission of power and data was realized using inductive coupling and the single-wire power transfer technology [22]. In 2008, the power communication in a single-wire power transfer system was realized [23]. In the same year, the method of single-wire power transfer using Tesla coils was further studied, and the dynamic equation of the system in its working mode was given by circuit analysis [24]. In 2020, the single-wire power transfer technology was applied to wireless sensor networks, and its directivity and multi-load characteristics were analyzed [25].

Most of the studies mentioned above about single-wire power transfer were based on the traditional Tesla single-wire power transfer structure, which was difficult to achieve long-distance power transmission safely. In addition, since the spatial displacement current and conduction current were used to form a loop to achieve a high efficiency, high voltage was required. In this paper, a novel type of single-wire power transfer structure without forming any loop is proposed, in which power is one-way transmitted from the power supply to the load. The rest of this paper is organized as follows. The principle for the one-way single-wire power transfer system is analyzed in Section 2. The simulation and experimental results in Sections 3 and 4 verify the feasibility of the proposed method, respectively. Finally, the conclusions are drawn in Section 5.

2. Theoretical Analysis

The structure of the traditional single-wire power transfer system is shown in Figure 1, which is evolved from the Tesla WPT system [25]. It consists of a step-up transfer and a step-down transfer at the transmitter and receiver, respectively. When an excitation is applied to the primary coil of the transmitter, the top capacitor ball Q1 will generate a time-varying electromagnetic field. Through the coupling effect between the top capacitor balls Q1 and Q2, power is transferred from the power supply to the load, which is the first path for the system to transmit power. The single-wire is the second path. These two paths form a closed loop. It is important to note that the traditional Tesla single-wire power transfer system is usually too large, and it generates high voltage on the top capacitor ball, which may cause harm to the organisms nearby.

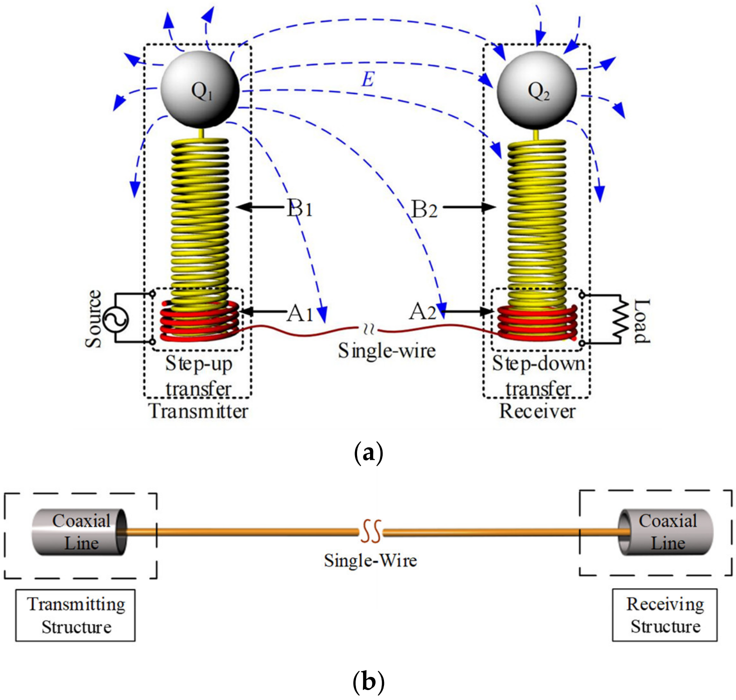


Figure 1. Single-wire power transfer systems: (**a**) traditional single-wire power transfer system; (**b**) one-way single-wire power transfer system.

The structure for implementing the one-way single-wire power transfer method is shown in part b of Figure 1, where the coils and capacitor balls are replaced by coaxial lines. The transfer structure consists of a transmitting structure at the left end of the system and a receiving structure at the right end of the system.

In order to describe the working process of the one-way single-wire power transfer system, the electric field distribution in the coaxial line is analyzed. The distribution of electric field lines in the transmitter at different moments is shown in Figure 2, in which the blue line indicates the electric field, and the dark gray and light gray parts indicate the inner and outer conductors, respectively.

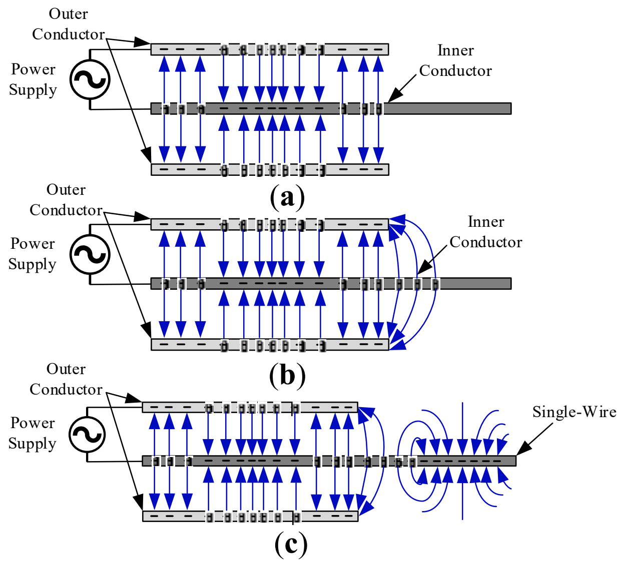


Figure 2. Electric field line coupling process of the system: (**a**) distribution of electric field line on coaxial line; (**b**) the electric field lines begin to bend; (**c**) electric field lines are coupled on the single-wire.

The distribution of electric field lines in the coaxial line at one certain moment is shown in part a of Figure 2. Note that the electric field lines always point from a high electric potential to a low electric potential, and the power supply mode is alternating current (AC). As the direction of the AC power supply voltage changes, the direction of electric field lines in the inner and outer conductors of the coaxial line also changes continuously. When the electric field is transmitted to the end of the coaxial line, it can be regarded as an open circuit. At this time, the electric field lines on the single-wire part connected with the inner conductor will bend and point from the single-wire with a high electric potential to the coaxial outer conductor with a low electric potential, as shown in part b of Figure 2. At the next stage, part of the electric field has already got rid of the constraints from the coaxial line, and begin to couple on the single-wire, as shown in part c of Figure 2. It still follows the rule that the electric field lines point from the high-potential part to the low-potential part. Afterwards, the electromagnetic field will be transmitted into the single-wire in the form of traveling waves.

The above analysis focuses on the excitation process of the system. Since the working processes of the transmitting and receiving structures are the same, the working process of the receiving structure will not be repeated here.

When the single-wire transmits electromagnetic waves, the alternating electromagnetic field will generate a high-frequency induced current on the single-wire. In fact, the single-wire is composed of good conductor. Under high-frequency conditions, the penetration of electromagnetic fields into good conductor is negligible. Therefore, it can be considered that the induced current inside the single-wire exists in the form of surface current. The current distribution on the single-wire is shown in Figure 3, where the blue and red arrows indicate the displacement current line and conduction current line, respectively. Note that current is distributed periodically on the single-wire.

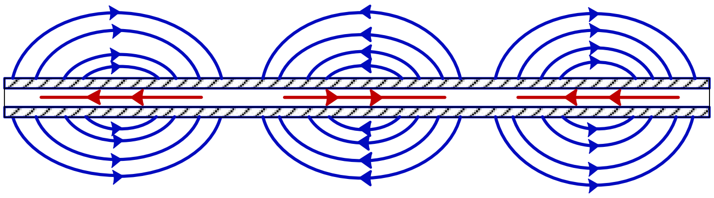


Figure 3. Current distribution on single-wire.

In order to facilitate the theoretical analysis, the cylindrical coordinate system is adopted to study the field distribution in the coaxial line, as shown in Figure 4.

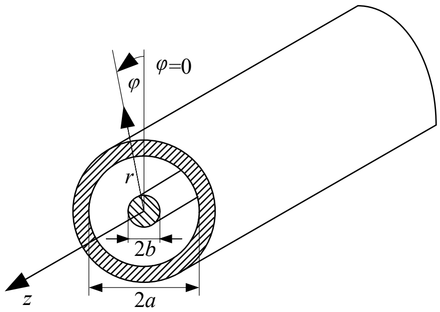


Figure 4. Coaxial line under the cylindrical coordinate system.

The electromagnetic field propagating along the positive z-axis satisfies the following equation:

$$\nabla_{\mathrm{t}}^2 E(r,\varphi) + k_c^2 E(r,\varphi) = 0 \tag{1}$$

$$\nabla_{\mathrm{t}}^2 H(r,\varphi) + k_c^2 H(r,\varphi) = 0 \tag{2}$$

where ∇ is the Laplacian operator, and k_c is the cut-off wave number. The working mode of the coaxial line is TEM wave, and its cut-off frequency f_c, longitudinal electric field E_z and longitudinal magnetic field H_z are all equal to 0. Under the same boundary conditions, the static field in the time-varying TEM mode is consistent with the field structure of the transverse component in the coaxial line. According to the electromagnetic field theory, the electric field in the coaxial line only has component E_r, and the magnetic field only has component H_φ. Since neither H_φ nor E_r changes with φ, the Equations (1) and (2) can be simplified as:

$$\frac{\partial^2 E_r}{\partial_r{}^2} + \frac{1}{r}\frac{\partial E_r}{\partial_r} - \frac{E_r}{r^2} = 0 \tag{3}$$

$$\frac{\partial^2 H_\varphi}{\partial_r{}^2} + \frac{1}{r}\frac{\partial H_\varphi}{\partial_r} - \frac{H_\varphi}{r^2} = 0 \tag{4}$$

Assuming that an excitation is applied at $z = 0$ and $r = a$, then $E_r = E_0$. When the wave attenuation coefficient is β and the wave propagates in the positive direction of the z-axis, the electric field in the coaxial line only has component E_r and the magnetic field only has component H_φ, so the electromagnetic field distribution is:

$$E_r = \frac{E_0 a}{r} e^{-j\beta z} \tag{5}$$

$$H_\varphi = \frac{E_0 a}{\eta r} e^{-j\beta z} \tag{6}$$

According to the derived expressions of electric field strength and magnetic field strength, the complex Poynting vector is calculated as:

$$\langle \mathrm{S} \rangle = \mathrm{Re}(\frac{1}{2}E \times H^*) = \frac{|E_0|^2}{2\eta}\frac{z}{r^2} \tag{7}$$

The real part of the complex Poynting vector along the cross-sectional area is divided to obtain its transmission power:

$$P = \int_0^{2\pi} \mathrm{d}\varphi \int_b^a \langle \mathrm{S} \rangle \cdot zr\mathrm{d}r = \frac{\pi}{\eta}|E_0|^2 \ln\frac{a}{b} \tag{8}$$

Suppose that the breakdown field strength of the coaxial line filled medium in the coaxial line is E_c. Obviously, the field strength at $r = b$ is the largest, so the power capacity is:

$$P \leq P_c = \frac{\pi}{\eta}b^2 E_c^2 \ln\frac{a}{b} \tag{9}$$

The voltage between inner and outer conductors is:

$$\mathrm{U} = \int_b^a E\cdot r\mathrm{dr} = E_0 \ln\frac{b}{a} \tag{10}$$

The characteristic impedance Z_0 is:

$$Z_0 = \mathrm{ss}60\sqrt{\frac{\mu_r}{\varepsilon_r}}\ln\frac{a}{b} \tag{11}$$

The attenuation coefficient of the conductor is:

$$\alpha_c = \frac{R_\mathrm{s}}{2\mathrm{a}\eta}\frac{(1+\frac{a}{b})}{\ln\frac{a}{b}} \tag{12}$$

The sizes (*a/b*) of the coaxial line are different, and its power capacity, conductor loss, and characteristic impedance are also different. According to expression of power, the power capacity will be the largest when $a/b \approx 1.65(Z_0 \approx 30)$. According to the expression of the conductor attenuation coefficient, the conductor loss will be the lowest when $a/b \approx 3.59(Z_0 \approx 77)$.

Obviously, the power capacity and conductor loss have different requirements for the characteristic impedance. When both a high-power capacity and a low loss are considered, the characteristic impedance is often fixed to 50 Ω, $a/b \approx 2.3$. In this case, the size of the coaxial line is fixed, and the only amount that can be adjusted in the system with a fixed transmission distance is the lengths of transmitting and receiving structures. Next, the relationship between the length of transfer structures and the system's transmission efficiency will be explored.

3. Simulation Analysis

The finite element simulation software COMOSL Multiphysics is used to construct a one-way single-wire power transfer model, as shown in Figure 5, where the transmitting and receiving structures are on the left and right, respectively. The power excitation and load are added to the inner and outer conductors of the transmitting and receiving structures, respectively, and the single-wire is connected to the inner conductor of the transmitting and receiving structures. Power probes are added to the power supply and load to measure transmitting power, receiving power, and reflected power. A perfectly matched layer is used to simulate infinity in the experimental environment, where the intensity of the electromagnetic field at infinity is completely attenuated.

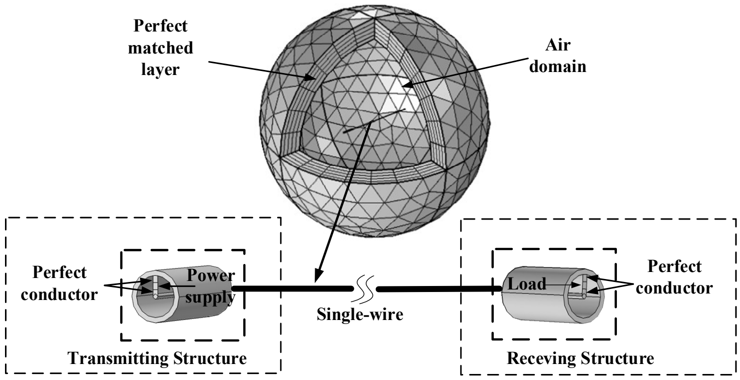


Figure 5. Simulation model of one-way single-wire power transfer system.

In a one-way single-wire power transfer system, the transmitting and receiving structure is the key to the system, which determines the transmission characteristics of the entire system. The parameters of the transmitting and receiving structures mainly include their sizes (*a*/*b*) and lengths. In the previous theoretical analysis, it has been assumed that the size (*a*/*b*) of the transfer structure is fixed, and only the lengths of the transmitting and receiving structures can be adjusted.

3.1. Lengths of Transmitting and Receiving Structures

Since the transmitting structure and the receiving structure are both coaxial lines, the transmitting structure and the receiving structure are collectively referred to as the transfer structure. The transmission efficiency is compared among six groups with different lengths of the transfer structure as shown in Figure 6, where the transmission distance is fixed to 10 m, and the lengths of transmitting and receiving structures are the same, i.e., 0.1, 1, 5, 10, 15, and 20 m, respectively.

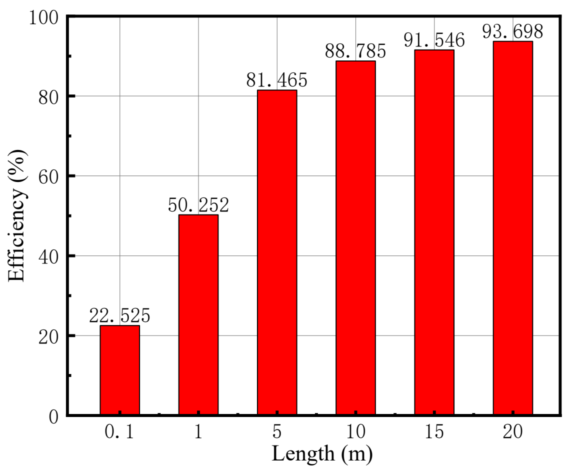


Figure 6. Length of transfer structure versus transmission efficiency.

From Figure 6, the system's transmission efficiency is 22.525%, 50.252%, 81.465%, 88.785%, 91.546%, and 93.698% when the length of transfer structure is 0.1, 1, 5, 10, 15, and 20 m, respectively. Apparently, the transmission efficiency increase rapidly as the length of the transfer structure increases in the range of 0.1–10 m. If the length of the transfer structure continues to increase after it reaches 10 m, the system loss will also increase, so the increase in transmission efficiency is not obvious. When the transfer structure increases from 10 m to 20 m, the transmission efficiency of the system only increases by 4.913%. In other word, after the transfer structure is longer than 10 m, the upward trend of transmission efficiency begins to become particularly slow as the transmission structure increases. Clearly, in the case of symmetrical transmitting and receiving structures, the system's transmission efficiency can only be effectively improved by increasing the length of the transfer structure within a certain range.

Next, the effect of variation in the transmitting or receiving structure length on the system's transmission efficiency will be investigated separately. Two sets of simulations are compared as shown in Figure 7.

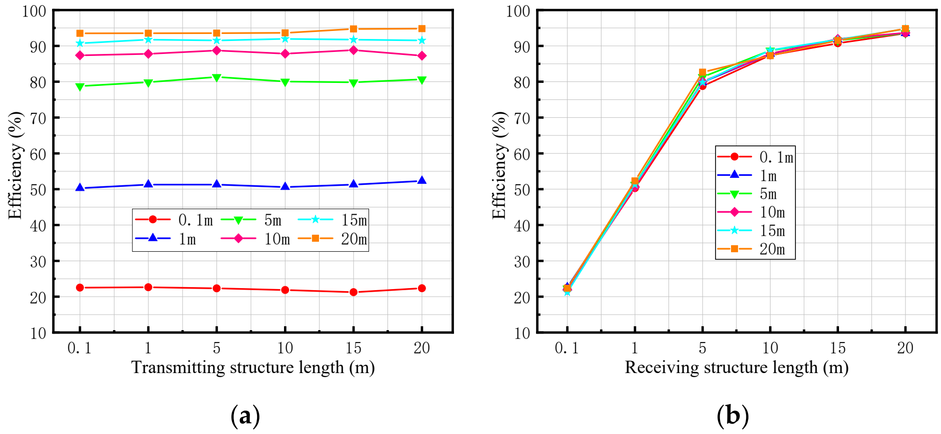


Figure 7. Influences of structure lengths on transmission efficiency under asymmetry: (**a**) length of transmitting structure; (**b**) length of receiving structure.

From part a of Figure 7, it can be clearly seen that increasing the length of the transmitting structure has little impact on the system's transmission efficiency. From part b of Figure 7, the transmission efficiency tends to improve as the length of the receiving structure increases. Especially, the efficiency improves rapidly when the length of the receiving structure is shorter than 10 m.

In summary, the transmission efficiency is mainly influenced by the length of the receiving structure. Therefore, in the design of a one-way single-wire power transfer system structure, a shorter transmitting structure and a longer receiving structure are recommended.

3.2. Volume Optimization

As mentioned above, increasing the length of the receiving structure can effectively improve the system's transmission efficiency, but it will also expand the system's overall length and lead to less convenient applications. Aimed at reducing the space occupation and broadening the application scenarios of this technology, the effect of coaxial line shapes on transmission performance will be studied. Here, both the linear coaxial line and the transmission distance are 10 m, and the coiling line is coiled into three typical shapes, conical, cylindrical, and planar, as shown in Figure 8.

The simulation results of the distribution of the electric field intensity modulus of the four transfer structures from 0 to 100 V/m are shown in Figure 9. The simulation results show that the maximum electric field modulus of the load side of the linear transmission structure is 92 V/m, while the maximum electric field modulus of the conical, cylindrical, and planar transfer structures are 93 V/m, 94 V/m, and 96 V/m, respectively. From the comparison, it can be seen that electric field modulus of coiled structures is not lower than that of the linear one.

The changes in transmission efficiency of four kinds of transfer structures with frequency is shown in Figure 10. When the transfer distance is 10 m and the transfer structure length is 10 m, the maximum transmission efficiency value of four kinds of structures is 88.793%, 93.993%, 92.689%, and 96.683%, respectively. Simulation results show that compared with the linear structure, the coiled ones do not reduce the electric field modulus or the system's transmission efficiency which also proves the feasibility of coiled structures in power transmission.

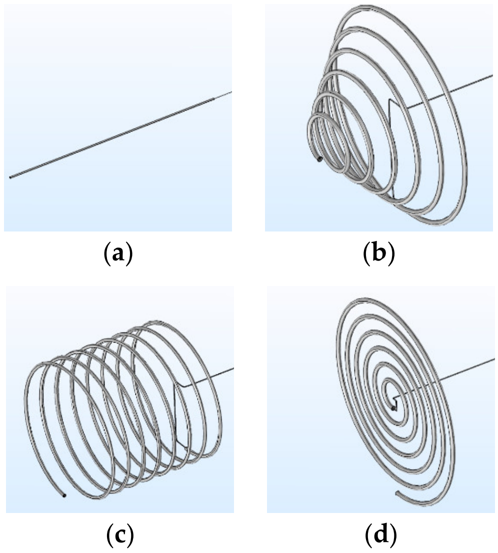


Figure 8. Four different shapes of transfer structures: (**a**) Linear; (**b**) Conical; (**c**) Cylindrical; (**d**) Planar.

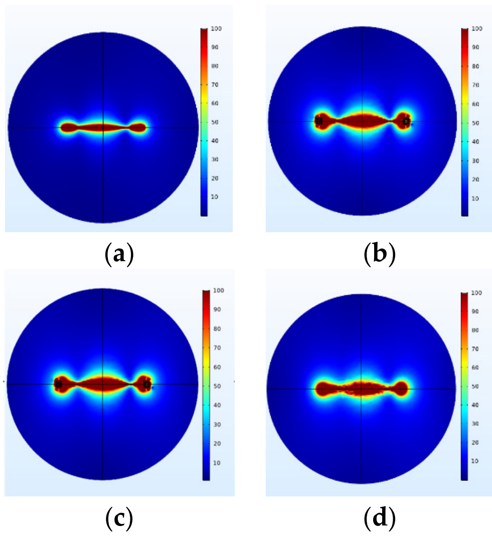


Figure 9. Electric field modulus of four kinds of transfer structures: (**a**) Linear; (**b**) Conical; (**c**) Cylindrical; (**d**) Planar.

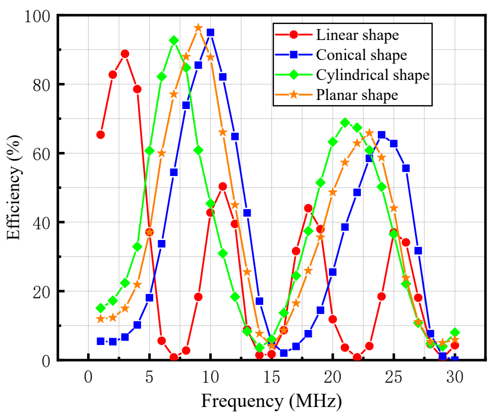


Figure 10. Comparison of transmission efficiency among four kinds of transfer structures.

To further compare the transmission performance among four transfer structures, the developing trends of the maximum transmission efficiency are compared. The length of the transfer structures is fixed to 10 m, and the transmission distance increases from 10 to 20 m, with a step length of 1 m. From Figure 11, it can be seen distinctly that the efficiency decreases significantly as the transmission distance increases. The developing trends of planar and conical structure are similar, and the corresponding transmission declines in efficiency are relatively slow as the transmission distance increases.

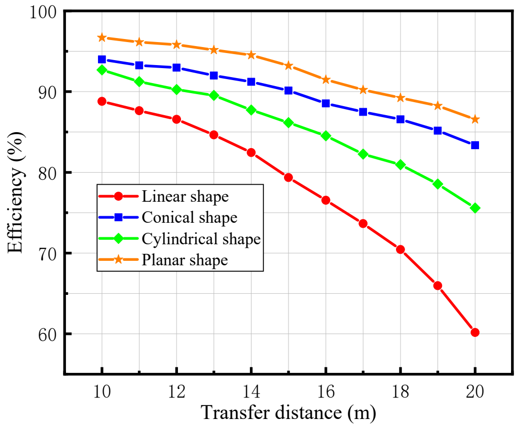


Figure 11. Comparison of transmission efficiency among four transfer structures at different distances.

When the transmission distance is longer than 13 m, the transmission efficiency of the linear structure drops sharply. The transmission efficiency of the planar one is always the highest, and it has a relatively gentle downward trend when the transmission distance increases.

The research results show that coiled structures do not reduce the system's transmission efficiency. In contrary, they are better than the linear one in terms of the transmission performance. Especially, the planar shape transfer structure has the highest transmission performance among the three coiled ones. In practical applications, the transfer structure can be made into a planar one to achieve an efficient power transmission as well as an optimal space volume.

4. Experiment Research

To verify the reliability of theoretical derivation and simulation results, an experimental system was built, as shown in Figure 12. As the excitation source of the system, the signal generator generated the high-frequency signals through a power amplifier. Power was transmitted to load via coaxial lines and a single-wire. A high-precision power meter connected between the power amplifier and the coaxial line is used to measure the transmitting power, while the power meter connected between the load and the coaxial line is used to measure the receiving power and reflected power.

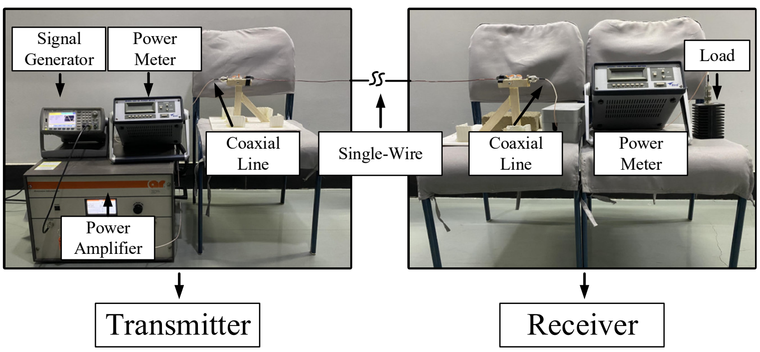


Figure 12. Experimental system of one-way single-wire power transfer.

It can be seen from Figure 13 that the simulation and experimental data are in good agreement. As the length of the transfer structure increases, the system's transmission efficiency continues to rise. In the range of 0.1 to 10 m, the efficiency rises sharply. However, this trend is not so obvious if the length is longer than 10 m.

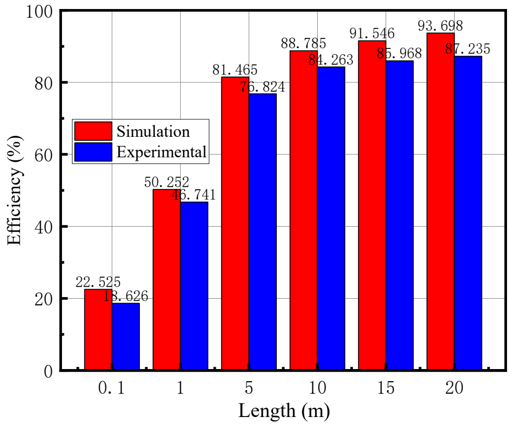
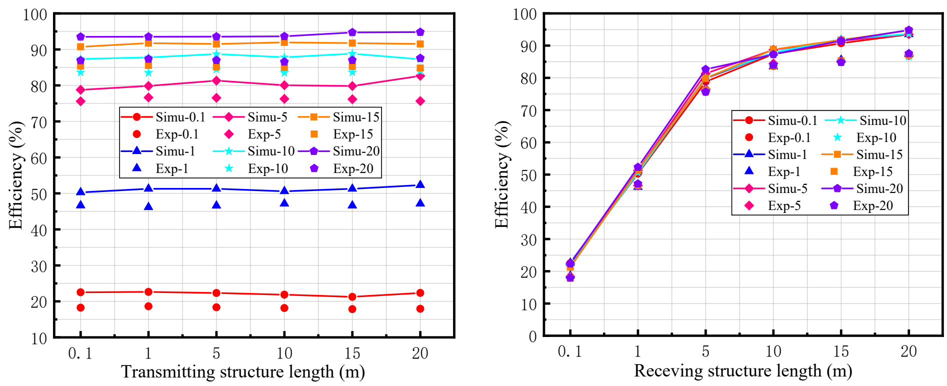


Figure 13. Comparison of simulation and experimental data under different lengths of transfer structure.

The effect of the lengths of the transmitting and receiving structures on the system's transmission efficiency are shown in Figure 14. The length of the transmitting structure has little effect on the system's transmission efficiency, while that of the length of the receiving structure plays a key role. Within a certain range, increasing the length of the receiving structure can effectively improve the system's transmission efficiency. Therefore, in the construction of a one-way single-wire power transfer system, a shorter transmitting structure and a longer receiving structure are recommended.



(**a**) (**b**)

Figure 14. Comparison of simulation and experimental data of transfer structures under asymmetry: (**a**) length of transmitting structure; (**b**) length of receiving structure.

The comparison of the simulation and experimental data of transmission efficiency among four kinds of transfer structures at different frequencies are shown in Figure 15. It can be visibly seen that the coiled structures are not less effective than the linear one, and the maximum transmission efficiencies of coiled ones are all higher than that of the linear one. The planar structure has the highest transmission efficiency, which is the most suitable for long-distance power transmission.

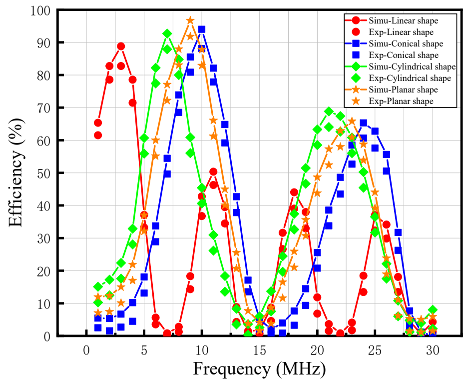


Figure 15. Comparison of simulation and experimental data of transmission efficiency among four transfer structures.

The comparison of simulation and experimental data among different transfer structures at different transmission distances are shown in Figure 16. It is clear that as the transmission distance increases, the transmission efficiency of the linear structure drops sharply. The planar one maintains a high transmission efficiency in both the simulation and experiment. In comparison, the transmission efficiencies of three coiled ones are higher than that of the linear one. Especially, the transmission efficiency of the planar one is always the highest, indicating that it is more suitable for long-distance power transmission.

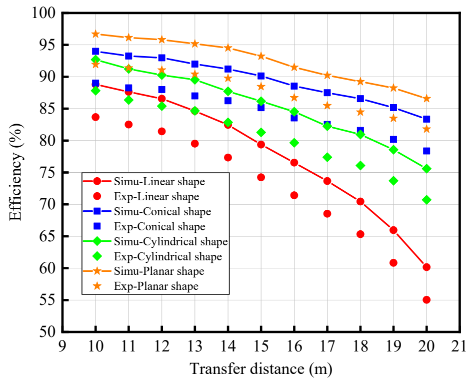


Figure 16. Comparison of simulation and experimental data of transmission efficiency among four transfer structures at different distances.

5. Conclusions

A novel one-way single-wire power transfer structure is proposed in this paper. The relationships between the transfer structure and the system's transmission efficiency under the symmetrical and asymmetrical conditions are analyzed, and the transmission efficiency is compared among four transfer structures. The conclusions are as follows:

(1) Under the symmetrical condition, the system's transmission efficiency increases with the increasing length of the transfer structure.
(2) The length of the receiving structure plays a key role in improving the system's transmission efficiency, while that of the transmitting structure has little effect.
(3) The coiled structures have a better power transmission performance than the linear ones.
(4) Among the three coiled structures, the planar one has the highest transmission efficiency, which is more suitable for long-distance power transmission.

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