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Spatial Azimuthal Misalignment Characteristics of High-Temperature Superconducting Wireless Power Transmission Systems

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Abstract: Magnetically coupled resonant wireless power transmission technology (WPT) based on high-temperature superconducting (HTS) coils has gained wide popularity due to its low impedance and high-quality factor Q value characteristics. This technology has greatly improved the energy transfer performance of wireless power transmission (WPT) systems. However, practical applications of conventional WPT, such as wireless charging of autonomous underwater vehicles at mooring points, often encounter spatial misalignment issues due to the complex ocean environment and ocean currents. Nonetheless, few studies have investigated the spatial misalignment of HTS WPT systems, particularly the angular misalignment. This paper presents a solution to address this problem by constructing magnetically coupled resonant wireless energy transmission systems based on HTS coils and copper coils. The study analyzes the relationship between the transmission efficiency of the WPT system and the received power of the load with respect to the spatial orientation of the coil. The performance of the superconducting coil and copper coil WPT systems is compared. The experimental results demonstrate that, under the same spatially misaligned conditions, the WPT system using HTS coils can significantly improve the transmission efficiency and load power compared to the conventional copper WPT system. Moreover, simultaneous adjustment of the lateral misalignment distance and different orientation deflection angles can improve the transmission efficiency and smooth load output power of the high-temperature superconducting WPT system.

Keywords: wireless power transfer; misalignment of angles; high-temperature superconducting; system transmission efficiency; the load output power

1. Introduction

Wireless power transmission is a promising technology with great potential for the future due to its advantages of convenient charging and high safety performance, and it is currently widely used in various fields [1–3], including electronics (such as smartphones and smart homes), medical applications (such as miniaturized pacemakers and implantable health monitoring devices), and industry (such as electric vehicles and drones). In 2007, a team led by Professor Marin Soljačić at the Massachusetts Institute of Technology proposed wireless power transfer (WPT) technology based on magnetic-coupling resonance (MCR) [4]. In the MCR WPT system, the transmitting and receiving coils are designed to resonate at the operating frequency, establishing a stable and efficient energy transfer channel for power transmission. The limitations of copper coils in traditional WPT systems are mainly due to their limited current-carrying capacity and low-quality factor (Q). In recent years, research has been conducted to establish magnetic resonance radio energy transmission systems using high-quality factor superconducting coils as resonant coils, which improves the energy transmission performance of the systems. The
research on high-temperature superconducting WPT systems has mainly focused on coil structure design and transmission efficiency [5–10]. Ref. [5] presents the wireless power transfer via strongly coupled magnetic resonances utilizing a high-temperature superconducting (HTS) coil and a copper coil as intermediate resonators. Simulation and experimental results demonstrate that the use of HTS and copper repeating coils can significantly enhance the space magnetic induction intensity, resulting in improved transmission efficiency and extended transmission distance. In Ref. [6], the analysis indicates that wireless power transfer (WPT) systems using high-temperature superconducting (HTS) coils exhibit higher efficiency and longer operational times in the low frequency range of kHz compared to WPT systems using copper coils. In Ref. [7], the investigation of the effect of various HTS coil configurations on the transmission performance of WPT systems revealed that flat coil and spiral coil designs can be effectively applied to relatively low-frequency WPT systems. On the other hand, the solenoid coil design can achieve the lowest total loss in WPT system applications operating at higher frequencies. In Ref. [8], a model system was fabricated using high-temperature superconducting (HTS) double-pancake coils composed of REBCO tape, and the transmission efficiency characteristics were investigated to evaluate the possibility of using HTS coils for high-efficiency wireless power transmission systems operating in the low-frequency region of kilohertz. The results indicate that HTS coils can achieve high-efficiency wireless power transmission in the low-frequency region of kilohertz. In Ref. [9], an experimental investigation was conducted to analyze the effect of coil offset on the transmission efficiency and load-received power (LRP) in a HTS magnetically coupled resonant wireless power transfer system. The results demonstrated a monotonic decrease in transmission efficiency as the offset distance increased. Additionally, an optimal offset distance was identified, which maximized the LRP. In Ref. [10], a high-temperature superconducting (HTS) WPT system is proposed, and its transmission performance is experimentally tested over a range of operating frequencies (33 kHz to 342 kHz), enabling high-efficiency energy transmission at low operating frequencies.

However, in certain practical applications, such as when an underwater autonomous vehicle (AUV) is docked at a subsea base station for wireless charging [11], perfect alignment between the transmitter and receiver coils is rarely achieved. Typically, the transmitting and receiving coils are not only laterally misaligned but also have azimuthal deviations, as depicted in Figure 1, which depicts a schematic diagram of wireless charging by an AUV when the angle is not aligned. In such a complex environment, any variation in the azimuthal deviation can alter the mutual inductance of the system, thereby significantly impacting the output power and transmission efficiency of the MCR-WPT system. Hence, exploring the transmission characteristics of HTS-WPT systems with transmission coils under spatial azimuthal misalignment conditions is essential for optimizing superconducting wireless energy transmission systems and understanding the laws governing their practical application scenarios.
This paper focuses on examining the impact of coil orientation variation on the transmission performance of high-temperature superconducting MCR-WPT systems. The experiments investigate the transmission efficiency and load output power of the wireless transmission system under various lateral misalignment conditions of the system with different azimuth angle misalignment and provide a comparative analysis of the transmission performance of the superconducting system and the copper system. The findings presented in this paper offer valuable insights for the application of wireless power transmission systems with superconducting coils under complex spatial conditions.

2. Circuit Topology and Analysis of MCR-WPT System

In Figure 2, the equivalent circuit structure of the MCR-WPT system is presented. The resonant inductances of the transmit and receive coils are denoted by $L_s$ and $L_w$, respectively. The compensated resonant capacitances (including parasitic and compensating capacitances) of the coil system are represented by $C_s$ and $C_w$. The mutual inductance coefficient between the transmit and receive coils is indicated by $M$. The equivalent load resistance is $R_L$, while the equivalent resistances of the transmit and receive coils are $R_s$ and $R_w$, respectively. $U_s$ stands for the high-frequency AC input power supply, while $I_s$ and $I_w$ denote the currents of the Tx and Rx coils in the circuit, respectively. Additionally, $R_s$ refers to the equivalent internal resistance of the power supply, and $\omega$ represents the driving angular frequency of the alternating power supply.
Based on the equivalent circuit structure diagram depicted in Figure 2 and Kirchhoff’s voltage law, the circuit equation for the MCR-WPT system can be derived, as shown in Equation (1).

$$
\begin{bmatrix}
U_S \\
0
\end{bmatrix} = \begin{bmatrix}
Z_s & j\omega M \\
j\omega M & Z_w
\end{bmatrix} \begin{bmatrix}
i_s \\
i_w
\end{bmatrix}
$$

(1)

$$
Z_s = R_s + j\omega L_s + \frac{1}{j\omega C_s} \quad Z_w = R_L + R_w + j\omega L_w + \frac{1}{j\omega C_w}
$$

(2)

Phase $U_S$ represents the fundamental voltage harmonic of the AC supply that powers the transmitter coil. The harmonic currents of the transmitting and receiving coils are represented by $i_s$ and $i_w$, respectively. $Z_s$ and $Z_w$ represent the equivalent impedances of the transmit resonant circuit and the receive resonant circuit, respectively.

Based on Equations (1) and (2), the AC power input ($P_{in}$) and load output power ($P_{out}$) can be computed as follows:

$$
P_{in} = \frac{U_s^2}{Re(Z_s)} = \frac{U_s^2 \left(R_w + R_L + j\left(\omega L_w - \frac{1}{\omega C_w}\right)\right)}{\left(R_s + j\left(\omega L_s - \frac{1}{\omega C_s}\right)\right)\left(R_w + R_L + j\left(\omega L_w - \frac{1}{\omega C_w}\right)\right) + (\omega M)^2}
$$

(3)

$$
P_{out} = I_w^2 R_L = \frac{\omega^2 M^2 R_L U_s^2}{\left(R_s + j\left(\omega L_s - \frac{1}{\omega C_s}\right)\right)\left(R_w + R_L + j\left(\omega L_w - \frac{1}{\omega C_w}\right)\right) + (\omega M)^2}
$$

(4)

Then, the transmission efficiency ($\eta$) of the system can be evaluated using Equation (5):

$$
\eta = \frac{P_{out}}{P_{in}} = \frac{R_L}{\left(R_w + R_L + j\left(\omega L_w - \frac{1}{\omega C_w}\right)\right) + \left(R_s + j\left(\omega L_s - \frac{1}{\omega C_s}\right)\right)\left(R_w + R_L + j\left(\omega L_w - \frac{1}{\omega C_w}\right)\right) + (\omega M)^2} \times 100\%
$$

(5)

From Equations (4) and (5), it is evident that the reactive power value is zero when the phase angle frequency is zero. In this circumstance, the WPT system reaches a resonant state. It is well known that efficient energy exchange between the transmitting and receiving resonant systems occurs in the magnetically coupled resonant state. The wireless
energy transmission system achieves maximum efficiency when the input frequency is set such that the transmitting and receiving loops reach resonance. This state is defined as:

\[ f_r = f_s = \frac{1}{2\pi \sqrt{L_s C_s}} = \frac{1}{2\pi \sqrt{L_w C_w}} \]  

(6)

As both the transmitting and receiving circuits are tuned to the resonant frequency of the AC power supply, the total equivalent impedance becomes zero. As a result, Equations (4) and (5) can be simplified to determine the maximum output power and transmission efficiency, which can be expressed as:

\[ P_{\text{out}} = I_w^2 R_L = \left( \frac{U_s \omega M}{(\omega M)^2 + (R_w + R_L)(R_s + R_d)} \right)^2 R_L \]  

(7)

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{\omega^2 M^2 R_L}{(R_w + R_L)\omega^2 M^2 + (R_s + R_d)(R_w + R_d)^2} \times 100\% \]  

(8)

Based on Equations (7) and (8), it can be inferred that the wireless energy transmission system’s transmission performance is influenced by critical parameters such as the resistances at the transmitting and receiving loop ends, mutual inductance, and angular frequency. Lowering the equivalent resistance of the transmitting and receiving coils can lead to higher transmission efficiency and output power of the MCR-WPT system, resulting in better transmission performance. High-temperature superconducting materials have the advantages of zero resistance and a high-quality factor, making them an excellent choice for resonant coil materials to achieve high transmission performance in the MCR-WPT system.

### 3. Experimental Design and Procedure

The block diagram of the experimental principle of the MCR-WPT system is shown in Figure 3. The high-frequency AC power supply provides the input voltage, which is converted into DC through the rectifier filter in the circuit. The DC voltage is then converted into high-frequency AC power required by the system through the high-frequency inverter, and then input to the resonant transmitting coil via the primary topology compensation network. This produces a strong electromagnetic coupling with the receiving coil in space, and energy oscillates between the transmitting and receiving loops. The receiving loop generates high-frequency alternating current due to the magnetic resonance effect, which is then transmitted to the receiving load through the secondary compensation network in the receiving loop. The relevant electrical parameters in this system can be obtained by measurement and calculation. Based on the above design of the block diagram, we built an MCR-WPT experimental system using HTS coils and copper coils. An experimental setup was constructed as shown in Figure 4. This is a hybrid HTS-Cu WPT system using HTS Tx coils and copper Rx coils. In addition, a control experiment was also conducted for two copper-coil WPT systems. Based on the frequency characteristics study of the superconducting wireless power transfer (WPT) system in our laboratory and the practical requirements for the topology capacitance value in the resonant experiment circuit [10], we have chosen the operating resonant frequency as 220.5 kHz. The matched load resistor needs to have the following basic characteristics: firstly, since the WPT system operates in a high-frequency state, the selected load resistor must be a high-frequency non-inductive resistor to eliminate the interference of resistance and inductance on the system; secondly, the load resistor dissipates energy in the form of heat, so it needs to have strong thermal stability and heat dissipation capability; finally, when selecting the load resistor, the maximum power that the resistor can withstand should be considered for experimental safety and a certain threshold should be left. Based on the above conditions, a load resistor value of 20 Ω was finally selected. In practical applications of wireless power transmission for electric vehicles or AUVs, the misalignment of orientation is
mostly concentrated within the range of $0^\circ$ to $90^\circ$. Therefore, we have chosen the azimuth angle range of $0^\circ$ to $90^\circ$ as our focus to address this practical application issue.

**Figure 3.** Experiment principle structure block diagram of magnetic resonance wireless power transfer system.

**Figure 4.** Experimental setup for high-temperature superconducting MCR-WPT system.

The coil’s specific parameters and system parameters for the WPT experimental setup are presented in Table 1.

**Table 1.** Parameters for WPT experimental system and coils.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire type</td>
<td>YBCO tape</td>
</tr>
<tr>
<td>Circuit topology</td>
<td>S-S (series–series)</td>
</tr>
<tr>
<td>Critical current of the coil $I_c$ (A) 77 K</td>
<td>130</td>
</tr>
<tr>
<td>Load resistor $R_L$ (Ω)</td>
<td>20</td>
</tr>
<tr>
<td>AC Power frequency (kHz)</td>
<td>220.5</td>
</tr>
<tr>
<td>Input voltage (V)</td>
<td>25</td>
</tr>
<tr>
<td>HTS coil</td>
<td></td>
</tr>
<tr>
<td>Number of turns</td>
<td>11</td>
</tr>
<tr>
<td>Size of the bobbin (cm)</td>
<td>16</td>
</tr>
</tbody>
</table>
Table 1. Parameters of the HTS and Cu coils.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HTS coil</th>
<th>Cu coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width × thickness (mm × mm)</td>
<td>4 × 0.1</td>
<td>4 × 0.1</td>
</tr>
<tr>
<td>Coil Self-inductance (μH)</td>
<td>51.9</td>
<td>51.6</td>
</tr>
<tr>
<td>Operating temperature (K)</td>
<td>77</td>
<td>300</td>
</tr>
<tr>
<td>Q-factor</td>
<td>148.3</td>
<td>48.6</td>
</tr>
<tr>
<td>Primary capacitor (μF)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Number of turns</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Size of the bobbin (cm)</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5 shows the schematic diagram of the azimuth misalignment of the MCR-WPT system coils. In the experiment, the HTS transmitting resonant coil was immersed in a cooling container (liquid nitrogen, 77 K), while the copper receiving resonant coil was placed in a room temperature environment (300 K). Figure 5 illustrates the experimental process. Firstly, we investigated the azimuth deviation characteristics of the system under the condition of no misalignment. We fixed the distance between the TX coil and RX coil at 10 cm, and then we rotated the RX coil from 0° to 90° in the XY plane, recording the voltage-current values and relevant parameters of the receiving loop under various azimuth deviation angles. Then, we further explored the azimuth deviation characteristics under the condition of lateral misalignment. We rotated the RX coil from 0° to 90° in the XY plane under the conditions where the RX coil was laterally misaligned at fixed distances of 4 cm and 8 cm, respectively, and recorded the relevant parameters of the system under each experimental condition.

![Figure 5](image.png)

Figure 5. Schematic diagram of the misalignment of the system coil azimuth. (a) Coaxial deflection (b) Lateral misalignment deflection.

4. Results and Discussion

4.1. PTE and LOP of WPT System

The azimuthal deflection characteristics of the WPT system in the coaxial alignment case were investigated, and the power transfer efficiency (PTE) and load output power (LOP) of the HTS-Cu and Cu-Cu WPT systems were presented for the coil deflection range of 0°–90° in the coaxial direction, as shown in Figure 6. The results indicate that as the azimuthal deflection angle of the coil increases, the system PTE gradually decreases. However, there is a flat interval of system PTE and the transmission efficiency remains stable without significant changes in the range of 0°–50°. The decrease in coupling flux between the coils with increasing azimuth angle results in a reduction in the system PTE. As the azimuthal deflection angle increases to 60°, the system PTE exhibits a sharp decrease, and
with further increase in the azimuthal deflection angle, the system PTE continues to decrease until the azimuthal deflection angle reaches 90°, where the system PTE tends to approach 0. The reduction in coupling flux between the coils with an increasing azimuthal angle causes a decline in the system PTE. When the transmitting coil is perpendicular to the receiving coil, the mutual inductance coefficient of the system approaches zero, in accordance with Equation (5). Furthermore, the load output power (LOP) of the WPT system exhibits a similar decreasing trend with increasing azimuthal deflection angle as the power transfer efficiency (PTE), but with a longer period of stability between 0° to 60°, after which the LOP starts to decrease sharply until it reaches zero as the azimuthal deflection angle exceeds 70°. This behavior can be attributed to the gradual decrease in the coupling flux between the coils with increasing azimuthal angle, leading to a decrease in both PTE and LOP.

Figure 6. Transmission characteristics of the system with a deflection angle of 0° to 90° in the coaxial state.

In the case of coaxial alignment between the transmitting coil and receiving coil in the HTS-WPT system, the system’s transmission performance remains nearly unchanged for azimuthal deflection angles less than 60°, which is often encountered in practical applications. This finding suggests a promising future for high-temperature superconducting WPT. In addition, we conducted further investigation into the transmission characteristics of the WPT system with superimposed azimuthal deflection in the case of lateral misalignment. Figure 7 depicts the PTE and LOP of the HTS-Cu and Cu-Cu WPT systems for the coil azimuthal deflection of 0°−90° at lateral misalignment distances of 4 cm and 8 cm, respectively. It is noteworthy that, in contrast to the transmission characteristics of the system at coaxial azimuthal deflection, for the lateral misalignment distance of 4 cm, the PTE of the system exhibits a changing pattern of increase and then decrease as the coil azimuthal deflection angle varies. At an azimuthal deflection angle of 0°, the power transfer efficiencies (PTEs) of both the HTS-WPT and Cu-WPT systems are at their lowest, with values of 45.2% and 37%, respectively. The PTE of both systems reaches a peak at an
azimuthal deflection angle of approximately 70°, with values of 58.3% and 49%, respectively. It is worth noting that the PTE growth rate is higher for the HTS-WPT system than for the Cu-WPT system from 0° to 25°, indicating stronger coil coupling performance and more dramatic changes in mutual inductance under small-angle misalignment conditions. Consequently, the transmission efficiency of the HTS-WPT system increases more rapidly, suggesting that this advantage can be fully exploited in actual misalignment deflection applications of HTS-WPT.

(a)

(b)
Figure 7. Transmission characteristics of the system under different misalignment states with deflection angles ranging from 0° to 90°: (a) Lateral misalignment of 4 cm; (b) Lateral misalignment of 8 cm.

Compared with PTE, the LOP of the system shows a different variation curve. In the range of the azimuthal deviation angle of 0°−80°, the LOP of the HTS-WPT and Cu-WPT systems remain almost constant, exhibiting a period of power plateau until a sharp drop occurs at 90°. For a lateral misalignment distance of 8 cm, it can be observed that both the PTE and LOP of the HTS-WPT and Cu-WPT systems exhibit a monotonically increasing trend with increasing coil azimuthal deflection angles. At 0° azimuthal deflection angle, the PTE and LOP of the HTS-WPT system are the smallest, with values of 31.3% and 14.5 W, respectively. As the azimuthal deflection angle increases, both the PTE and LOP of the HTS-WPT and Cu-WPT systems show a peak at 90° when there is a lateral misalignment distance of 8 cm. Thus, it can be concluded that in practical misalignment scenarios of the HTS-WPT system, the efficiency can be significantly enhanced by increasing the azimuthal deflection angle of the system when the coil experiences moderate lateral misalignment. The power output of the system remains stable for a wide range of deflection angles less than 80°. For larger lateral misalignment distances, increasing the azimuthal deflection angle of the system can simultaneously improve both the transmission efficiency and load power. These findings suggest that this characteristic of the HTS-WPT system is highly valuable.

4.2. Differences in System Transmission Performance

In this section, we compare the differences in transmission performance between the HTS-Cu and Cu-Cu systems when azimuthal misalignment occurred under coaxial alignment conditions, as well as under different lateral misalignment conditions with azimuthal misalignment.

In order to investigate the performance improvement of WPT systems using HTS coils, and to make a quantitative comparison analysis of their transmission performance, we defined the increase in transmission efficiency (ΔPTE) as follows:

\[ \Delta PTE = PTE_{HTS-Cu} - PTE_{Cu-Cu} \]  

Similarly, following reference [8], the increase ratio of LOP (ξP) can be expressed as:

\[ \xi P = \frac{P_{out:HTS-Cu} - P_{out:Cu-Cu}}{P_{out:Cu-Cu}} \]  

Figure 8 illustrates the ΔPTE and ξP of HTS-WPT and Cu-WPT systems under coaxial alignment of the coils. It can be observed that when the azimuthal misalignment angle between the coils is 90°, the minimum value of ΔPTE is 0.13%, indicating that when the transmitting and receiving coils are completely perpendicular to each other, the mutual inductance between the systems tends to be zero, and the improvement of the superconducting WPT system on the transmission efficiency is very limited. When the azimuthal misalignment angle is 70°, the maximum value of ΔPTE is 12.3%, and the ΔPTE of the systems corresponding to other azimuthal misalignment angles can be stabilized at 9.4–12.3%, which indicates that the superconducting coil has a higher quality factor and lower electromagnetic loss. At the same time, it can be observed that the power enhancement of the WPT system with superconducting coils is much more significant than ΔPTE. In the full range of azimuthal misalignment from 0° to 90°, ξP values are between 61.9% and 71.0%, which means that the HTS system is more sensitive to changes in transmission power. Therefore, by introducing high-Q HTS coils, both the output power and efficiency have been significantly improved.
Figure 8. ΔPTE and ξP with coaxial deflection.

Figure 9 shows the ΔPTE and ξP of the HTS-WPT and Cu-WPT systems under lateral misalignment distances of 4 cm and 8 cm. For the case of ▲ = 4 cm, it can be observed that, except for the azimuthal misalignment of 90°, where the minimum value of ΔPTE is 6.11%, the values of ΔPTE are stable and mostly within the range of 8%–9.8% for any other azimuthal misalignment angles. Additionally, the ξP value reaches its minimum of 60.2% at an azimuthal misalignment angle of 50° and its maximum of 66.3% at an azimuthal misalignment angle of 70°. For the case of ▲ = 8 cm, the minimum value of ΔPTE is 7.4% at a deviation angle of 0°, and the maximum value is 11.1% at a deviation angle of 80°. Unlike the completely aligned and laterally displaced by 4 cm cases, at a deviation angle of 90°, ΔPTE can still reach a relatively high value of 10.6%, indicating that the HTS coil can still maintain a strong electromagnetic coupling with the WPT system under this condition due to its larger mutual inductance compared to the previous two cases. For ξP, its range of values is between 64.6% and 84.3%. Overall, the experimental results demonstrate that replacing copper coils with HTS coils can significantly improve the transmission efficiency and transmission power of the WPT system.
Figure 9. ΔPTE and ξ with different deflection angles: (a) lateral misalignment of 4 cm; (b) lateral misalignment of 8 cm.
5. Conclusions

This paper investigates the transmission characteristics of a high-temperature superconducting magnetically coupled resonant wireless energy transmission system under coaxial and lateral misalignment conditions, focusing on the effect of azimuthal misalignment. The experimental results demonstrate that when azimuthal deflection angle increases under coaxial alignment, the transmission efficiency and load output power of the system gradually decrease with a flat slope period, and the turning point of the sharp decrease of the power lags behind the transmission efficiency, which is beneficial for practical applications. Under lateral misalignment at a distance of 4 cm, the PTE of the system initially increases and then decreases, while the load output power is stable. Under transverse misalignment at a distance of 8 cm, both the PTE and load output power of the system increase with the increase in azimuthal deflection. By adjusting the lateral misalignment distance and azimuthal deflection angle simultaneously, the transmission efficiency and load output power of the high-temperature superconducting WPT system can be improved. Moreover, using high-temperature superconducting coils instead of copper coils under different azimuthal misalignments can significantly enhance the PTE and load output power of the MCR-WPT system by 6.1%–12.3% for PTE and 60.2%–84.3% for LOP. These properties predict that magnetically coupled resonant superconducting wireless power transmission systems have good prospects for practical applications in wireless power transmission scenarios for devices such as electric vehicles or AUVs. Since the experimental power selected in this paper is low, we will use Leeds wire to make coils with higher current-carrying capacity to build the prototype in the future. Further study is needed of the transmission characteristics of the superconducting MCR-WPT system at kilowatt-level high-power conditions.

Author Contributions: Conceptualization, Z.Y. and T.Z.; methodology, M.C.; software, D.Z.; validation, M.C., S.Z. and Y.G.; formal analysis, Z.Y.; investigation, M.C.; resources, Y.G.; data curation, M.C.; writing—original draft preparation, Z.Y.; writing—review and editing, Z.Y.; visualization, Y.G.; supervision, Y.G.; project administration, S.Z.; funding acquisition, C.C. All authors have read and agreed to the published version of the manuscript.

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