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Design of Anti-deflection Wireless Charging System for Unmanned Surface Vehicles

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Abstract: Compared with the traditional wired charging method, the wireless power transmission technology of unmanned surface vehicles has the characteristics of flexibility, convenience and safety. Aiming at the decline in transmission efficiency and output power fluctuation caused by coil deflection in Marine environment, an anti-deflection wireless charging system with arc three-coil structure is proposed. Firstly, the topology model of wireless charging of unmanned surface vehicles is established under resonant condition, and the influence of attitude change of unmanned surface vehicles on wireless charging transmission performance is analyzed. Then, according to the law that the magnetic field intensity of wireless charging coil varies with the deflection angle, the arc three-coil magnetic coupling mechanism of unmanned surface vehicles is designed, and the remarkable performance of the mechanism in stabilizing the mutual inductance intensity is analyzed theoretically. Finally, finite element software is used to carry out comprehensive simulation verification. The results show that the designed arc three-coil magnetic coupling anti-deflection mechanism can make the power fluctuation not more than 9% in the deflection range of $-20 \sim 20°$. It can provide theoretical reference for optimizing the wireless power transmission technology of unmanned surface vehicles.

1. Introduction

Unmanned surface vehicle is a key component of marine unmanned system, which integrates autonomous perception, intelligent control, autonomous decision-making and other technologies into one, and plays an increasingly important role in the development of marine resources[1,2]. However, unmanned surface vehicles often use iron phosphate or lithium batteries to supply energy, and there are problems such as inconvenient charging on the water, easy to be corroded by seawater, and cable contact failure. As a new type of power transmission method, Wireless Power Transmission (WPT) technology has the advantages of the convenient operation, no contact, safety and flexibility, which provides a novel solution to the problem of power supply for unmanned surface vehicles.

Wireless power transmission methods are mainly divided into magnetically coupled resonant transmission, electric-field coupled transmission, microwave and laser power transmission[3].

Microwave and laser power transmission distance is longer, but the efficiency of transmission is low[4,5]. Electric-field coupled transmission has greater power, but the transmission distance is shorter[6]. Magnetic coupled resonant transmission efficiency is higher than microwave and laser power transmission, and the transmission distance is slightly higher than electric-field coupled transmission[7], which is a wireless charging method suitable for most fields, and is widely used in the fields of electric vehicles, smart homes and medical devices.

Magnetically coupled resonant wireless power transmisson utilizes the coupling of the coil at the transmitter end and the coil at the receiver end to form a magnetic resonance system, which converts a portion of the energy carried by the magnetic field into electrical power. Typically, aligning the two coupling coils results in an optimal coupling coefficient with maximum magnetic flux. In the whole process, the larger the magnetic flux received by the receiving coil, the better the coupling of the two coils. However, in the practical application, the wireless charging coils are often affected by factors such as environmental interference, mechanical deformation, and initial position placement, which interferes with the coupling between the primary and secondary coils. Therefore, how to reduce the alignment requirements of the primary and secondary coils during the charging process and improve the stability of the output power has become a key problem to be solved by this system at present.

In order to solve such problems, scholars have successively carried out research on control strategies, additional coupling channels, coil structures, and the use of composite resonant circuits. In terms of control strategy, Galib et al[8] proposed a two-sided control technique based on hybrid model predictive control and perturbation observation in combination with a series compensation mechanism, which is used to obtain the best system efficiency and better dynamic response. In addition, there also exist methods to adjust the output power and efficiency through buck circuits, phase shift control or PID control algorithms[9,10]. In terms of additional coupled channels, Moon et al[11] established a three-transmitter-single-receiver form of magnetically coupled resonant wireless power transmisson based on a single inverter-single rectifier circuit with two additional relay concentric coils based on a circular coil magnetic coupling mechanism.Chen[12] placed multiple transmitting coils in the same plane, and selectively connected the transmitting coils based on the parking position of the electric vehicle to extend the electric vehicle's charging range in the charging range in the horizontal plane. Tang ZQ[13], on the other hand, realized omnidirectional charging by using two orthogonal plane helical coils. By increasing the coupling pathways, the location requirement during wireless charging can be effectively reduced, but it also increases the complexity and cost of the system. In addition, as the number of coils increases, the difficulty of the control strategy also increases. In terms of coil structure, problems such as output power fluctuation in WPT systems can be addressed by characterizing the coil structure and optimizing its spatial location.Yang[14] designed a "Taiji" coil, and verified its effectiveness by comparing the misalignment tolerance with that of a double-D coil and a circular coil. Zeng[15] used a genetic algorithm to optimize the structural parameters such as the size and the number of winding turns of the DDP (Double-D Quadrature) coil, to optimize the offset range of the coupling mechanism, and to improve its coupling capability. There is also more literature on the anti-offset design of WPT systems by means of composite connection of resonant elements. Zhang Yiming[16] performed WPT system design based on the hybrid compensation topologies of Inductance Capacitance Capacitance-Series (LCC-S) and Series-Series (S-S) to enhance the charging of electric vehicles within the X and Y horizontal directions. Performance. Kung Zhaowei[17] realized a constant current output independent of load by means of a hybrid LCC-LC compensation circuit, which ensures the stability of the output current within 50% of the lateral coil offset. The above compound resonant compensation circuit can improve the offset resistance of the WPT system, but its core resonant element will be subjected to higher operating voltage and current when the offset is large.

Unlike the land environment, the ocean has stronger environmental perturbations such as winds, waves and currents, which can cause the unmanned surface vehicles to deviate from its balance position and undergo motions such as large-angle transverse and longitudinal tilts. This type of motion will prevent the wireless charging transmitter and receiver coils from being squarely aligned, resulting in decreased coupling and unstable power output. The fluctuation of output power during wireless charging will reduce the safety and life of the equipment and prevent the system from working properly. In order to improve the anti-deflection performance of the unmanned surface vehicles WPT system further, this paper proposes an anti-deflection wireless charging system for unmanned surface vehicles based on the arc three-coil magnetic coupling mechanism. In the paper, we first analyze the transmission characteristics of the WPT system and explain the influence of mutual inductance strength on the WPT system in different attitudes of the unmanned surface vehicles, then we establish the mutual inductance calculation model of the arc three-coil magnetic coupling mechanism and analyze the anti-deflection characteristics of the magnetic coupling mechanism based on Niehlmann's formula and the topology theory of the coupling coil circuit. Finally, the finite element software Ansys is used to analyze the overall wireless power transfer system and verify its more stable power output in the case of $-20 \sim 20°$ deflection.

2. LCC resonant network transmission characteristics

The WPT system adopts LCC-LCC resonant network, and its equivalent circuit is shown in figure 1. Where, L_s , L_p are the self-inductance of the transmitting and receiving coils, respectively; U_{AB} is the AC voltage after the inverter change; I_1 is the input current; U_o is the output voltage; I_o is the output current; R_o is the load resistance; L_1 , C_1 and C_{f1} constitute the primary resonant network; M is the mutual inductance of the coils; R_p and R_s are the parasitic resistances of the transmitting coil and the receiving coil; L_2 , C_2 and C_{f2} constitute the secondary resonant network; d is the axial phase distance; h is the transverse offset distance; α is the axial deflection angle. The primary and secondary side resonance compensation networks utilize the principle of inductance-capacitance resonance at a specific frequency, eliminating the influence of the coil's own magnetic leakage on the energy transfer, reducing reactive power, and improving efficiency.

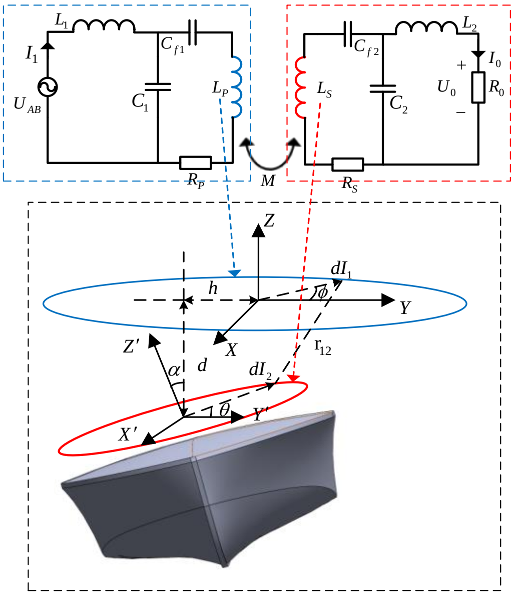


Figure 1: WPT system equivalent circuit.

When the system is in resonance, the following relationship is obtained:

$$\begin{cases} \omega^2 L_1 C_1 = 1 \\ \omega^2 L_2 C_2 = 1 \\ \omega^2 \left(L_p - L_1\right) C_{f1} = 1 \\ \omega^2 \left(L_s - L_2\right) C_{f2} = 1 \end{cases} \tag{1}$$

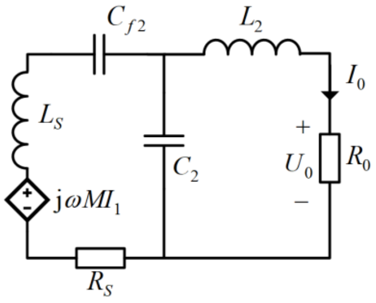


Figure 2: LCC subside compensation structure.

As shown in figure 2, the induced voltage of the secondary coil is represented by the controlled voltage source, and the total impedance of the secondary coil is:

$$\begin{aligned} Z &= j\omega L_S + \frac{1}{j\omega C_{f2}} + \frac{\left(j\omega L_2 + R\right)\frac{1}{j\omega C_2}}{j\omega L_2 + R + j\omega C_2} + R_S \\ &= \frac{L_2}{C_2 R} + R_S \end{aligned} \tag{2}$$

The current flowing through the resistive load is:

$$I_0 = \frac{MU_{AB}}{\left(\omega L_1 L_2 + \omega L_1 C_2 R_S R\right)} \tag{3}$$

The output power on the load can be obtained as:

$$P = I_0{}^2 R = \left(\frac{MU_{AB}}{\omega L_1 L_2 + \omega C_2 L_1 R_S R}\right)^2 R \tag{4}$$

According to Niemann's equation[18], the mutual inductance between the two single coils is:

$$M = \frac{\mu_0}{4\pi} \oint_{C_1} \oint_{C_2} \frac{dI_1 dI_2}{r_{12}} d\theta d\varphi \tag{5}$$

For wireless charging of unmanned surface vehicles, its shore power system is usually fixed on the shore, and the unmanned surface vehicles will do multi-degree-of-freedom movements such as rolling and pithcing with wind and waves. As shown in figure 1, the docking attitude between the two coils during wireless charging changes with the wind and waves, the h , d and angle of α changes, so that the r_{12} in equation (5) change, which in turn have an effect on the coil mutual inductance[19]. From equation (3) and (4), it can be seen that the wireless charging power transmission is related to the mutual inductance of the coil as well as the system parameters f_0 , L_1 , L_2 , R . When the compensation structure and load are determined, the transmission efficiency and power are proportional to the mutual inductance between the coils. Under the disturbance of wind and waves, the mutual inductance of wireless charging coil of unmanned surface vehicles will change, which will have a greater impact on the output power and efficiency of the system. In order to ensure the transmission energy efficiency of the system and the stability of the power output, further analysis of the change of mutual inductance strength is carried out.

3. Design and analysis of arc three-coil magnetic coupling mechanism

The magnetic coupling mutual inductance curve is an important basis for analyzing the change of mutual inductance in the magnetic coupling mechanism, and it is also the basis for analyzing and designing the relevant device parameters of the WPT system. For further study, the mutual inductance waveform is obtained using electromagnetic simulation software as shown in figure 3, and the mutual inductance value of the wireless charging coil decreases with the change of the deflection angle when the receiving coil is deflected.

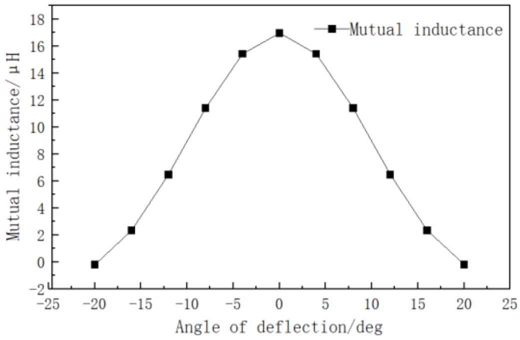
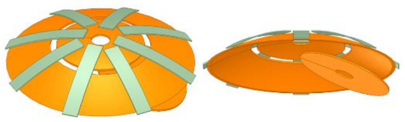


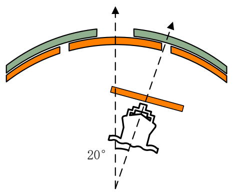
Figure 3: Mutual inductance curve of traditional magnetic coupling mechanism.

At high deflections, the mutual inductance value varies greatly. This can be reduced by adding a reverse series coil and applying a reverse magnetic field to create a more homogeneous magnetic field. In addition, when the dual coils are deflected, the distance r_{12} between the two coils will also increase. From equation (5), the variation of M can also be reduced by decreasing the variation of the distance between the coils.

From the above optimization direction, the magnetic coupling mechanism is designed as shown in figure 4. In order to reduce the magnetic field variation between the transmitting and receiving coils, additional coil is added to the primary side coil as a compensation coil. The compensation coil and the primary side coil are wound by a single wire, and two arc coils are connected in series, with the two arc coils sharing the center of the circle.



(a) Schematic of the model.



(b) Schematic of coil deflection.

Figure 4: Arc three coil structure model.

The spatial location relationship of any two arc-shaped coils is shown in figure 5, where coil 1 is the primary transmitting coil, coil 2 is the coil whose projection is to the plane, and coil 3 is the secondary receiving coil, x is the axial phase distance,x is the lateral offset distance, x is the axial deflection angle, and x , x are the different radiuses of the coils. Coil 1 is shaped as a curved coil, which reduces the geometrical distance between the two coils during deflection, and has stronger misalignment tolerance and higher mutual inductance value compared to planar coils.

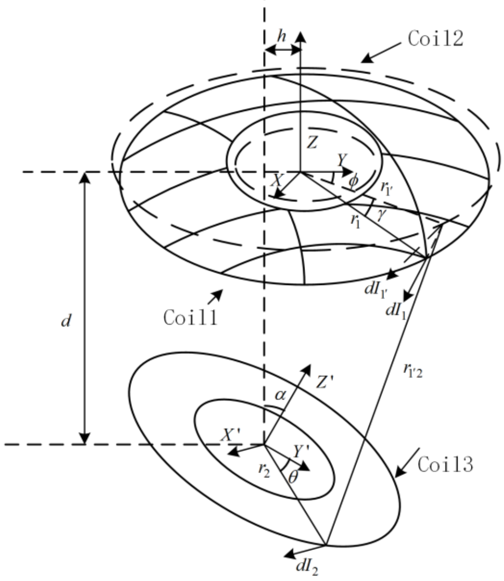


Figure 5: Coil models in different spatial positions.

The parametric equation for $dI_{1'}$ in the Cartesian coordinate system is:

$$\begin{cases} x_1 = r_1 \sin\phi \\ y_1 = r_1 \cos\phi \\ z_1 = r_1 \tan\gamma \end{cases} \tag{6}$$

The parametric equation for dI_2 in the global coordinate system is:

$$\begin{cases} x_2 = r_2 \sin\theta \\ y_2 = r_2 \cos\alpha \cos\theta - h \\ z_2 = -r_2 \sin\alpha \cos\theta - d \end{cases} \tag{7}$$

According to the formula for the distance between two points in space, $r_{1'2}$ can be calculated as:

$$\begin{aligned} r_{1'2} = {} & r_1^2 + r_2^2 + \left(r_1 \tan\gamma\right)^2 + h^2 + d^2 + 2h\left(r_1 \cos\phi - r_2 \cos\theta \cos\phi\right) + \\ & 2d\left(r_1 \tan\gamma + r_2 \sin\phi \cos\theta\right) - 2r_1 r_2 \left(\sin\phi \sin\theta + \cos\theta \cos\alpha \cos\phi - \tan\gamma \sin\phi \cos\theta\right) \end{aligned} \tag{8}$$

From the above equation, the mutual inductance between multi-turn coils at any deflection angle can be given as follows:

$$M = \frac{\mu_0 n_1 n_2}{4\pi} \oint_{c_1} \oint_{c_2} \frac{dI_{1'} dI_2}{r_{1'2}} \tag{9}$$

To further illustrate the mutual inductance coupling principle of the magnetic coupling mechanism with compensation coils, the topology of the mutual inductance circuit corresponding to the three-coil structure is shown in figure 6.

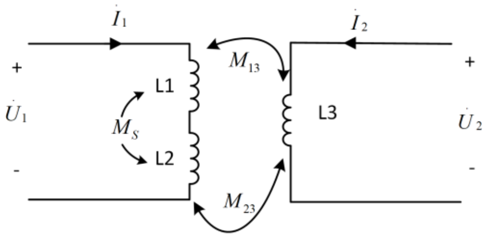


Figure 6: Coupled coil circuit topology.

For the voltages shown in the figure 6:

$$\begin{aligned} U_1 &= j\omega L_1 I_1 + j\omega L_2 I_1 - 2j\omega M_S I_1 + j\omega M_{13} I_2 - j\omega M_{23} I_2 \\ &= j\omega I_1 \left(L_1 + L_2 - 2M_S\right) + j\omega I_2 \left(M_{13} - M_{23}\right) \end{aligned} \tag{10}$$

Then the values of self-inductance and mutual inductance of the primary side can be obtained as:

$$L = L_1 + L_2 - 2M_{12} \tag{11}$$

$$M = M_{13} - M_{23} \tag{12}$$

In general, the coil mutual inductance coefficient is highest at forward alignment and decreases gradually at deflection. This is due to the fact that the most magnetic flux is interchained when orthogonal and the magnetic flux density decreases when deflected. When the coil is deflected, the mutual inductance M_{13} and M_{23} both decrease with the deflection, and the equivalent mutual inductance $M\left(M_{13} - M_{23}\right)$ can be maintained constant if the attenuation of M_{13} and M_{23} can be maintained uniformly within a certain deflection range.

4. Simulation and analysis

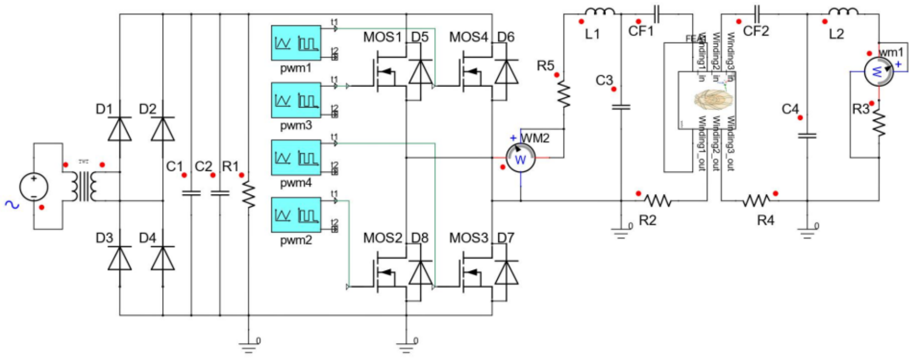


Figure 7: WPT system hardware control circuit.

In order to verify the anti-deflection of the unmanned surface vehicles wireless charging system based on the arc three-coil magnetic coupling mechanism, as shown in figure 7, a co-simulation study was carried out by using the maxwell and simplorer modules of Ansys software equipped with a wireless power transfer system, and the specific parameters of this circuit are shown in Table 1.

Table 1: Design parameter

Parameter	Value	Parameter	Value
L_p	$554\,\mu h$	C_{f2}	$55.124\,nF$
L_s	$94\,\mu h$	U	$100\,V$
L_1	$30.4\,\mu h$	f	$85\,Khz$
L_2	$30.4\,\mu h$	C_1	$115.32\,nF$
C_{f1}	$6.69\,nF$	C_2	$116\,nF$

Under different deflection angles, the effective voltage, current and apparent power of the system change rule is shown in figure 8, when the deflection angle is about 15 degrees, its output apparent power is the highest. This is caused by the inconsistency of the decay rate of the reverse magnetic field and the original magnetic field with the change of angle, but with the increase of the angle, its apparent power slowly decreases, and the apparent power generated at the deflection angle of 0 degrees is nearly the same. The apparent power output fluctuation of the WPT system with the arc three-coil structure is about 14% and the efficiency is about 91%.

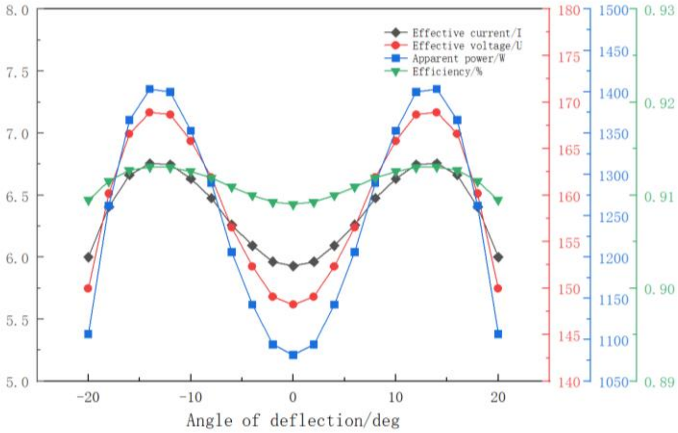


Figure 8: Output characteristic change curve.

In order to verify the anti-deflection capability of the wireless charging system with the arc three-coil magnetic coupling mechanism, the wireless charging system equipped with curved uncompensated coils and planar triple-coil magnetic coupling mechanism is compared with the design proposed in this paper. As shown in figure 9, it can be seen that the output active power of the WPT system equipped with the arc three-coil magnetic coupling mechanism is about 1KW, and the transmission power of the system can meet the design requirements.

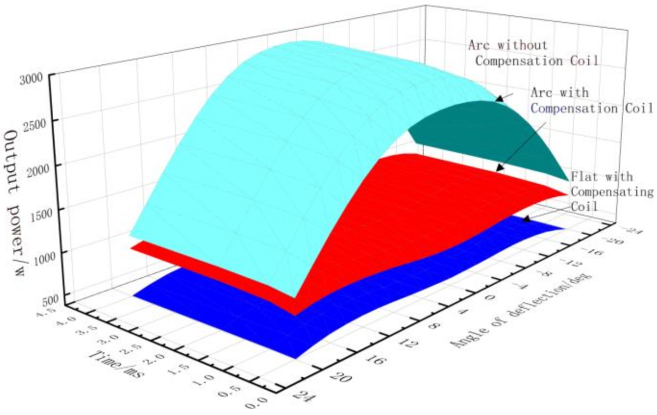


Figure 9: Power output change curve.

Compared with the forward alignment case, the power variability of the uncompensated coil magnetic coupling mechanism reaches 62% at a deflection angle of nearly twenty degrees, while the power variability of the WPT system with the arc three-coil magnetic coupling mechanism is only 9%. Compared with the traditional magnetic coupling mechanism, the design of the arc three-coil magnetic coupling mechanism can effectively enhance the system's deflection resistance and improve the system's transmission performance.

5. Conclusions

In order to solve the problem of output power fluctuation and transmission energy efficiency degradation of wireless charging system for unmanned surface vehicles caused by wind and wave disturbances in the marine environment, this paper proposes a anti-deflection wireless charging system for unmanned surface vehicles based on the arc three-coil magnetic coupling mechanism, which shapes a more homogeneous magnetic field by adding the compensation coils, thus stabilizing the output power of the wireless charging system. In this paper, firstly, the equivalent circuit of the WPT system is established. Then the arc three-coil magnetic coupling mechanism is proposed and its anti-deflection characteristics are theoretically analyzed. Compared with the magnetic coupling mechanism in the traditional anti-deflection WPT system, the arc three-coil magnetic coupling mechanism does not need to add an independent coupling path, which reduces the difficulty of the system control strategy. It not only ensures excellent coupling performance in forward alignment, but also has better anti-deflection characteristics. The final construction of the WPT system with a coupling pitch of 80 mm, in the range of deflection –20° to 20° , the output power of the system is about 1 KW, the power change rate is 9%, and the transmission efficiency of the system is not less than 91%.

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