Wireless charging system load characteristic analysis and optimal load condition of autonomous Underwater robot

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Abstract. Autonomous underwater robots mainly obtain energy supplement through Wireless Power Transmission (WPT). Magnetic coupled resonant wireless charging is achieved through magnetic field coupling, with no direct connection on electricity, and can achieve intelligent control, autonomous charging, flexible and safe, frictionless wear. Based on the underwater robot wireless charging system, this paper proposes a high efficiency energy conversion technology for receiving end of wireless charging system. Though analysis of load change to effect the transfer characteristic of wireless charging system and wireless charging system optimal load conditions, this paper lays the foundation of the optimal load for subsequent research real-time tracking control, ensures the reliability of the charging system of underwater robot and improves the efficiency of wireless charging system.

1. Introduction

The safe and efficient operation of the charging system is the premise of ensuring the work of the robot. The traditional contact charging caused by frequent plugging and the sealing problem of underwater application all affect the safety of its underwater application. Due to the special working environment, wireless charging has a good applicability to underwater robots. Numerous and extensive research have been done on wireless charging in both military and civilian fields[1]. The US Navy developed wireless charging systems for submarines, and electric vehicle companies developed wireless charging systems for electric vehicles.

Radio energy transmission can be divided into three types: microwave type, electromagnetic induction type, magnetic coupled resonant type[2]. The basic principle of the microwave type is electromagnetic radiation, with a long transmission distance but a low transmission efficiency. Electromagnetic induction transmission efficiency is high, but close transmission distance and high charging location. The magnetic coupled resonant has the advantages of transmission distance and transmission efficiency[3].

For magnetically coupled resonant wireless charging, the transmission distance and the load conditions are different under different working conditions[4]. Since the transmission characteristics of wireless charging system are greatly affected by transmission distance and load conditions, it is necessary to study the energy conversion technology at the receiving end of the robot charging system[5].

1.1. Wireless charging system modeling

The wireless charging system stimulates the resonant magnetic field, and the receiving terminal receives the energy from the power supply terminal, but it generally receives high-frequency AC power and a low voltage, while what is required for the inspection robot power battery charging is DC.
power, so it cannot be directly charged. The function of the receiving terminal is to convert the high-frequency AC power into the DC current for the robot charging. In this paper, the full-bridge rectifier circuit is selected to achieve larger average output current and smaller current pulsation. In addition, buck-Boost voltage lifting DC converter circuit is adopted in this paper, and its structure is shown in the figure 1.

![Figure 1 Schematic diagram of a four-switch buck-Boost circuit](image1)

![Figure 2 equivalent transformation plot of the two coil](image2)

Assuming the circuit is ideal circuit and each component is ideal component, the inspection robot load is equivalent to resistance $R_O$ to simplify the analysis. The charging voltage at both ends is $U_O$. The coil includes the rectified filter circuit, BUCK-BOOST circuit and load equivalent to resistance $R_S$. The rectified output voltage is $U_S$. The resonant coil accepts voltage is $U_S$. The duty cycle of the MOS tube is $d$, cycle is $T$. According from the voltage relationship of BUCK-BOOST circuit in BUCK mode $U_S=(1/d )U_O$. Let $k=U_S/U_O$, according to the relationship between input and output voltages of BUCK-BOOST circuit in different modes, we can know $U_S=kU_O$, which can be obtained from the energy conservation law: $U_S^2 = U_O^2 R_O$. Thus, the impedance transformation relation $R_S= k^2R_o$ is obtained.

The charging load of inspection robot can be transformed from $R_O$ to $R_S$ by impedance transformation, so the optimal load can be obtained by impedance transformation for different charging requirements in this way.

### 2. Load characteristic analysis and the optimal load condition

In the case of resistive load, inductive load and capacitive load, the transformation relationship between the input impedance of WPT system and the equivalent impedance of the inspection robot charging is analyzed. Based on this, the influence of load change on the energy transmission characteristics of the system is studied. Finally, the optimal load condition of the system is obtained. It lays a foundation for the research of optimal load real-time tracking control and dynamic adjustment strategy of inspection robot charging load.

#### 2.1 Analysis of resistance load characteristics

For the two-coil structure, when the load is pure resistive impedance, i.e. $Z_L=R_L$, and the two coils are resonant. The function of transmission efficiency and load can be derived to obtain the following formula:

$$ R_L = \sqrt{R_o^2 + \frac{R_o \omega^2 M^2}{R_S + R_t}} $$

(1)

From formula (1), the optimal load value of the efficiency is related to the resonant frequency and the coupling coefficient. The coupling coefficient is generally related to the transmission distance, coupling area, coil parameters, so for a specific coupling coefficient, at the resonant frequency, the transmission efficiency of the system will reach the maximum value.
Give parameters conventional assignments respectively, the relationship between load resistance and transmission efficiency under different coupling coefficients by MATLAB simulation as shown in Figure 3.

From the figure 3, the figure shows that the transmission efficiency of the system increases with the load; when the coupling coefficient increases rapidly and changes gradually; each particular coupling coefficient has an optimal load value that increases with the coupling coefficient, which decreases with the transmission distance (the coupling coefficient decreases).

\[ \eta = \frac{(\omega M)^2 (R_L + j\omega L)}{(R_2 + R_L + j\omega L)(R_3 + R_1)(R_2 + R_L + j\omega L) + (\omega M)^2} \]  

(2)

The figure 4 is the effect of load receptor change on the transmission efficiency of several fixed load resistance values based on the two-coil structure. It can be seen that when the electric inductance value is very small, the load resistance value has an obvious impact on the system transmission efficiency. With the increase of the inductance value, the three curves gradually tend to coincide. At this time, the main factor affecting the size of the transmission efficiency is the load inductance value.
2.2.2 Analysis of tolerance load characteristics
For two-coil structures, when the load is a tolerance load, \( Z_L = R_L + \frac{1}{j\omega C} \). In the same way, give parameters conventional assignments respectively. It can be seen in figure 5 that the transmission efficiency of the system decreases with the load impedance capacitance value and decreases first with the load impedance value.

2.3 Optimum load characteristics at different frequencies
In order to obtain the optimal load changes with the system operating frequency under different load properties, this section is analyzed by finite element simulations under the two-coil structure. When selecting parameters, parameters other than frequency can be fixed and the effect of the three loads on the system transmission efficiency and output power can study the frequency changes alone. The simulation results are shown in the figure 6.

![Figure 6: The power changes with frequency in the three load cases](image1)

![Figure 7: The efficiency changes with frequency in the three load cases](image2)

It can be concluded from figure 6 that the operating frequency has a large power near the resonant frequency of the system, the pure resistance load adaptability to frequency change is relatively weak, the perceptual load and tolerance load are more adaptable to frequency change, so the perceptual load is more suitable for higher frequency.

It can be obtained from the figure 7 that the system efficiency fluctuates greatly with the frequency for the tolerance load, and the system transmission efficiency is low when the frequency is large. For resistive and perceptual load, the system transmission efficiency increases first and then tends to gentle. At large frequencies, the resistive load and the perceptual load can easily obtain greater transmission efficiency.

2.4 Optimum load condition
As the transmission characteristics of wireless charging system are greatly affected by transmission distance and load conditions, it is necessary to use two-port network theory to summarize the derivation method of optimal load conditions for analyzing the transmission characteristics of WPT system and further system optimization.
In this section, different equivalent circuit parameters are characterized in combination with the two-port network as shown in Figure 8.

Transmission and impedance matrix are widely used in circuit analysis, but at high frequency cases the corresponding parameter measurements become difficult. Conversely, at high frequency, the scattering matrix becomes preferred due to the presence of a network analyzer, which can measure the scattering matrix parameters in a wider frequency range. Figure 9 shows a two-port network with source and load. The power transmission efficiency of the entire system can then be expressed as:

\[ \eta_t = \frac{(1 - |\Gamma_G|^2)|S_{21}|^2 (1 - |\Gamma_L|^2)}{|(1 - S_{11}\Gamma_G)(1 - S_{22}\Gamma_L) - S_{12}S_{21}\Gamma_G\Gamma_L|^2} \]  

(3)

If both the source and the load match, yes, the reflection coefficient can be expressed as:

\[ Z_G = Z_L = Z_0 \]

\[ \Gamma_L = \Gamma_G = 0, \Gamma_{in} = S_{11}, \Gamma_{out} = S_{22} \]

(4)

Thus the relation between the transmission efficiency and the S parameter can be simplified as:

\[ \eta_t = |S_{21}|^4 \]

(5)

3. Conclusion

This paper first briefly introduces the underwater robot wireless charging system, constructs the mathematical model of the wireless charging system, and further studies the efficient energy efficiency conversion technology of the wireless charging system. This paper analyzes the relationship between the input impedance and the equivalent impedance of the underwater robot and studies the influence of the load change on the energy transmission characteristics and the system to provide a theoretical basis for an efficient and stable real-time tracking control and underwater robot charging load.

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