Analysis and experimental study of wireless power transfer with HTS coil and copper coil as the intermediate resonators system

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Intermediate resonator (repeater) between transmitter and receiver can significantly increase the distance of wireless power transfer (WPT) and the efficiency of wireless power transfer. The wireless power transfer via strongly coupled magnetic resonances with high temperature superconducting (HTS) coil and copper coil as intermediate resonators was presented in this paper. The electromagnetic experiment system under different conditions with different repeating coils were simulated by finite element software. The spatial distribution patterns of magnetic induction intensity at different distances were plotted. In this paper, we examined transfer characteristics with HTS repeating coil and copper repeating coil at 77 K and 300 K, respectively. Simulation and experimental results show that HTS and copper repeating coil can effectively enhance the space magnetic induction intensity, which has significant effect on improving the transmission efficiency and lengthening transmission distance. We found that the efficiency and the distance of wireless power transfer system with an HTS coil as repeater is much higher by using of copper coil as repeater.

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1. Introduction

In recent years, wireless power transfer technology became a hot research spot. Especially, near-field non-radiative wireless power transfer (WPT) using magnetic resonant coupling was appeared, as they are less sensitive to surroundings and safer for humans [1,2]. The basic principle of magnetic resonances technology is that two separate coils with same resonance frequency are possible to form a resonant system based on high frequency magnetic coupling and exchange energy in a high efficiency [3]. It has been demonstrated with experiment that, two resonators of the same resonant frequency exchange energy efficiently in their non-radiative field in midrange [4]. With technology of magnetic resonant coupling, the effective transmission distance of WPT system can be greatly extended compare to the system based on technology of inductive coupling. But the efficiency still drops rapidly as the distance continue to increase. Thus, researchers proposed [5] placing intermediate resonator in the magnetic resonant coupling wireless power transfer system. Repeater can receive the magnetic field from transmitter coil and then relay the magnetic field to the receiver coil which could enhance the magnetic coupling at the longer distance and improve the transfer efficiency.

The WPT system which included one repeater or more repeaters had been researched and got a good effect [6,7].

The high temperature superconducting (HTS) technology has been applied to wireless power transfer technology recently, because it enables the wireless power transfer system more efficient and more compact [8–10]. Wireless power transfer system aim at a higher efficiency, so HTS technology becomes more important in wireless transfer system. Kim et al. in Korea [8], Zhang et al. in China [10] and Raymond et al. in USA [11] have constructed WPT system which researched on wireless power transfer use HTS wire instead of copper wire in different respects. Such designs have analyzed the problems of using HTS. However, there are also a lot of problems need to resolve.

In this paper, we investigated a kind of system architecture with three coils. In the system, the repeater is copper tape coil or HTS tape coil. We simulated the magnetic field intensities of different repeating coils at different distance. We measured the output voltage of the receiver coil in different temperature and with different repeating coil.

2. Theoretical analysis of magnetically coupled resonant WPT with repeater

The idea behind the magnetically coupled resonant WPT system is to exchange energy efficiently by creating a strong magnetic cou-
Fig. 1. Equivalent circuit diagram of WPT system with three coils.

Fig. 2. Sketch of the magnetically coupled resonant wireless power system (a) Material of repeater is HTS (b) Material of repeater is copper.

coupling between two objects that are tuned to resonate at the same frequency. This phenomenon occurs between the current carrying coils through their varying or oscillating magnetic fields. In this paper, the system of coupled resonant WPT architecture with three coils which consist of a transmit coil intermediate resonator and a receive coil, showed in Fig 1. From Fig. 1, it can be seen that when a transmit coil loaded with a capacitor is fed by the input energy, it will oscillate to produce a magnetic field. The energy will transfer back and forth between the induced magnetic field in the inductor and the electric field across the capacitor at the operating frequency. Due to the resistive and radiation losses, this oscillation disappears at a rate determined by Q factor. When the intermediate coil and receive coil are tuned at the same frequency, the intermediate coil receive the magnetic field from transmit coil and relay the field to receive coil. So the receive coil cuts enough of the induced field in transmit coil which results in the absorption of more energy rather than losing in each cycle. Thus, most of the energy can still be exchanged. Fig 2 shows a WPT system with a repeater. In Fig. 2(a), the repeater is HTS tape coil; In Fig. 2(b), the repeater is copper tape coil. In order to analyze the magnetically coupled resonant WPT system with intermediate resonator, coupled mode theory (CMT) [12] and circuit theory (CT) were employed in this paper.

2.1. Coupled mode theory

Coupled mode theory is basically a physical theory to analyze the energy exchange between resonant objects in strong coupling regimes. According to coupled-mode theory, the physical processes of power transferring in wireless power transfer system with repeater can be described as:

\[ k_{23}^2 |a_3(t)|^2 = \Gamma_1|a_1(t)|^2 + k_{12}^2 |a_2(t)|^2 \]

\[ k_{23}^2 |a_2(t)|^2 = (\Gamma + \Gamma_w)|a_3(t)|^2 \]

where \( k_{12} \) is the coupling rate between transmit coil and intermediate resonator coil, \( k_{23} \) is the coupling rate between intermediate resonator coil and receive coil, \( a_1(t), a_2(t) \) and \( a_3(t) \) represent energy amplitude of the transmit coil, intermediate resonator coil and receive coil. \( \Gamma \) is the rate of intrinsic decay due to the coil’s (transmit coil intermediate resonator coil and receive coil) ohmic and radiative losses, respectively, \( \Gamma_w \) represents the additional energy decay rate due to the load. So the transfer efficiency expression of this system can be described as follows:

\[ \eta = \frac{\Gamma_w|a_3(t)|^2}{\Gamma_1|a_1(t)|^2 + \Gamma|a_2(t)|^2 + (\Gamma + \Gamma_w)|a_3(t)|^2} \]

where \( \Gamma_1|a_1(t)|^2 \), \( \Gamma|a_2(t)|^2 \) and \( \Gamma|a_3(t)|^2 \) represents the transmit coil intermediate resonator coil and receive coil energy decay rate. \( \Gamma_w|a_3(t)|^2 \) is the energy which transfer from source to load, also represent energy decay rate due to the load.

Thus, the inherent loss in different material of repeater for field enhancement plays a decisive role in the final ability to increase WPT. We can see that in order to improve the system transmission efficiency, we need to reduce the energy decay rate of intermediate coil and improve the coupling rate. It can be seen from formula (2) the efficiency would increase if one WPT system can reduce energy decay rate. And the smaller the resistances (ohmic loss), the lower the energy decay rate, the higher the efficiency. In Fig. 2 the repeater is made of superconductors, the efficiency will be higher because of the low loss of superconductor. By comparing Fig. 2(a) and Fig. 2(b), the efficiency of WPT system in Fig. 2(a) will be higher than the WPT system in Fig. 2(b).

2.2. Circuit theory

CMT is suitable for analyzing the energy exchange process between resonators, but its concepts are obscure. Rather, circuit theory based on mutual inductance model is more straightforward and qualitative.

A WPT system with repeater is basically constituted by a transmit coil intermediate coil and a receive coil. The equivalent circuit
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