pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.20, No.1, (2018), pp.23~27 https://doi.org/10.9714/psac.2018.20.1.023

Efficiency evaluation and characteristics of receiver coil under different inserted resonance coils in wireless power charging system for MAGLEV

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(Received 5 February 2018; revised or reviewed 28 March 2018; accepted 29 March 2008)

Abstract

As the wireless power transfer (WPT) technology based on strongly resonance coupled method realizes large power charging without any wires through the air, there are advantages compared with the wired counterparts, such as convenient, safety and fearless transmission of power. From this reason, the WPT systems have started to be applied to the wireless charging for various power applications such as train, underwater ship, electric vehicle. This study aims for the effect and characteristics of different inserted resonance coil between Tx and Rx coils for charging system of superconducting magnetic levitation (MAGLEV) train. The transfer efficiency and effect are evaluated with helix type, rectangular type copper resonance coil, and HTS resonance coil under bulb and HTS magnet load, respectively. The input power is adapted with radio frequency (RF) power of 370 kHz below 500 W.

Keywords: electromagnetic resonance coupling, HTS resonance antenna, large transfer power

1. INTRODUCTION

Historically, magnetically coupled resonators, each comprising a coil in series with a capacitor, were first used for wireless power transfer (WPT) by Nikola Tesla in the late 1800s. Wireless power systems are slowly emerging in a variety of applications such as passive RFID system, inductively coupled methods and resonance wave structures. As a drawback, inductive coupling requires the coils to be very close to the object under charge for successful induction [1]. Recently, Marin Soljačić proposed resonance coils of the same resonant frequency to transfer wireless power over a distance of meters [2]. This pioneer technique enables to transfer electric power at source power of 13.56 MHz with a power transfer efficiency of 40 % within 2 m. Even though it takes an advantage of large air gap, it has not shown the brightness for commercial grade products in the power applications due to efficiency [3]. The advantage of such a method is that resonant circuits interact with each other so much more strongly than they do with non-resonant objects that power losses are negligible due to absorption in stray nearby objects [4]. Generally, as the WPT system adopted normal conducting wire, the size of antenna is too large to resonators exchange energy at a much higher rate than they lose energy due to low damping ratio for each resonance coil as well as they are possible to keep much stronger intrinsically property of the normal conducting wire. As well as, as the copper resonance keep low Q factor, the exchanges energy rate is limited [5-6]. The high Q factor magnetic fields out in the peripheral regions. From this reason, the WPT technology has been required for diffusion of various wires. As a reasonable approach, the superconducting wire is a noble option in order to improve transfer efficiency and extend the transfer distance. Fortunately, since the superconducting wires keep enough current density and higher Q value, it enables to exchange a massive electric power in spite of a small scale coil as well as to improve the efficiency [7].

The MAGLEV, which levitates the vehicle by magnetic force and propels it with linear synchronous motor (LSM), has already accomplished the maximum speed up over 600 km/h in the Japanese Maglev, MLX. The MAGLEV systems, which are spotlighted as future green transportation systems, can be the application of the wireless power transfer technology [8]. Especially, the super high speed MAGLEV using high temperature superconducting (HTS) magnet has drawn attention as next generation transportation since superconducting magnet can keep mighty levitation force [9]. Generally, the HTS magnet has been supplied by conventional electric power persistently to keep fixed levitation gap and low irregularity tolerance. However, a large thermal loss is indispensably caused by power transfer wires and joints [10] in the superconducting MAGLEV train, which system, with a linear synchronous motor, for instance, requires primary windings distributed along the track, resulting in substantial increase in the construction and maintenance cost. Placing windings on the mover plus a proper WPT system considerably reduces the cost. A suitable structure for high power WPT systems should be designed to satisfy

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the best performance and meet the requirement of the application. Recently, as it makes possible a convenient power charging system based on multi-coil array [11]. The high performance multi-coil Tx coil enhances power transfer efficiency and longer distance. The MAGLEV systems inherently have advantages in higher efficiency due to smaller air gap for wireless power transfer system between guidance and train, and almost no lateral displacement as well as increased attractiveness, and reduced management costs [12].

This paper describes the performance for WPT system combined with high Q of HTS wire via resonant coupling method. The transfer characteristics using HTS and copper resonance coils are compared with various cases with inserted copper and HTS resonance (Sx) coil at 77 K. The RF generator is 370 KHz, below 500 W.

2. MECHANISM

Fig. 1 shows the conceptual design illustration of wireless power charging (WPS) system in MAGLEV train of EDS technology with superconducting magnet is presented. It is composed by Tx coils at the guidance rail of the MAGLEV, magnetically-coupled Rx coils, which consist of HTS and are used in as a receiver, provide DC power to superconducting magnet through rectifier unit. The structure of resonance type WPT system consists of four components as follows; RF source, IM circuit which is fabricated by variable LC resonance unit, antenna (Tx) coil, inserted resonance (Sx) and receiver (Rx) coil including HTS magnet, as shown in Figure 1. The transferred power is allowed by selected resonance condition for each coil, which contains creating an LC resonance. The resonant degree of coupled coils can be easily variable corresponding to different distance and external factors. Once resonance coupling condition between Tx and Rx coils is broken, the transmitting waves are reflected back into Tx coil and then those cause heating problem. Thus, the inserted IM circuit plays a major part in the needed band of frequencies to be passed, while it rejects in the all others band. Especially, the T type LC resonant circuit comes into play when electromagnetic wave cannot be sufficiently reduced using capacitors and inductors; it suppresses unnecessary frequency, effectively.

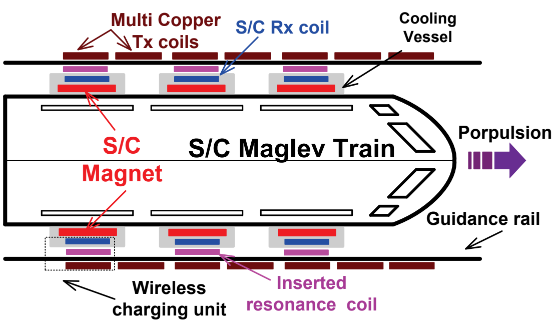


Fig. 1. Illustration of wireless power charging system for superconducting MAGLEV with inserted resonance coil.

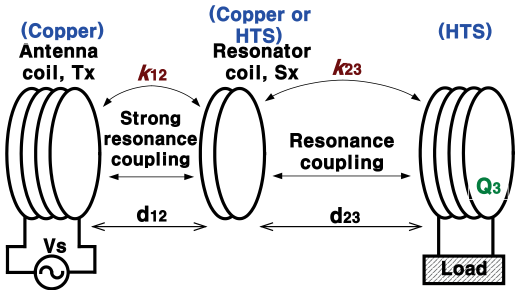


Fig. 2. Illustration of resonance type wireless power transfer (WPT) system with inserted resonance coil.

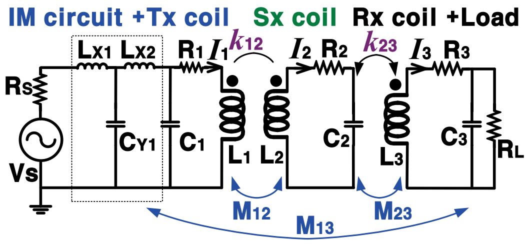


Fig. 3.Equivalent circuit diagram of resonance type WPT system of Fig. 2.

In the WPT technology, the transfer efficiency is generally determined by quality factor Q, which is defined by the ratio of apparent power to the power losses in a device. The antenna coil forms a series RL circuit and the Q factor is expressed as:

$$Q = \frac{\omega L}{R} = \frac{2\pi f L}{R} = 2\pi f \frac{Energy \quad Stored}{Power \quad Loss} \tag{1}$$

Where f means resonant frequency. The maximized Q value of superconducting wires can be realized based on the improved joint technique. Another important parameter which determines the type of waves is the frequency $\boldsymbol{f}$ in hertz of the oscillations. The frequency determines the wavelength $\boldsymbol{\lambda}$ of the waves which carry the energy across the gap, is expressed as :

$$\lambda = \frac{c}{f} \tag{2}$$

Where $\boldsymbol{c}$ is the velocity of light. Figure 2 shows the equivalent circuit of the resonance type WPT system. The symbols of L_1 and L_2 mean the self-inductances of separated antenna & receiver coils. Capacitors C_1 and C_2 are employed to improve the coupled degree. Variable inductances L_{X1} and L_{X2} are changed to select the resonance frequency of input source corresponding to LC coupled degree and distance of Tx and Rx coils. M_{ij} and k_{ij} means mutual inductance and coupling coefficient between coupling coils. They are calculated as

$$k_{xy} = \frac{M_{xy}}{\sqrt{L_x L_y}} \tag{3}$$

When the distance between the Tx and Rx coils is much larger than the diameter of the coils, very little power is transferred even though the Tx and Rx coils keep strong impedance matching. The transmitted power is exponentially decreased in the expanding distance and then the thermal loss of Tx coil is rapidly caused since transmitting waves are reflected back into Tx coil. Therefore, as the range of electromagnetic fields depends on the size and shape of the Tx coil, these techniques should be considered to reduce transmission loss in the design of resonance coils.

3. EXPERIMENTAL SETUP RESULTS

In this experiment, since the impedances of HTS and copper wires are different at 370 kHz, IM sub-circuit, which consists of the supplement of the variable inductors and capacitor, plays a key role to keep strong resonance coupled conditions for each coil, practically. The four bulbs of 30 W bulb are attached in the receiver coil as a load in order to confirm the transfer power. The RF input power of 500 W, 370 KHz is used for Cases I ~ IV sequence and the different inserted resonance coil is fixed at 30 cm from Rx coil as shown in Figure 4. We adopted a cooling vessel for HTS wire made from Styrofoam.

Fig. 5 shows photograph of fabricated copper and HTS resonance coils and experimental performances of four cases. In this experiment, the size and width of the copper coil are same with HTS coil. The reflection ratio for input power keeps below 1 W in the performance. The Tables 1

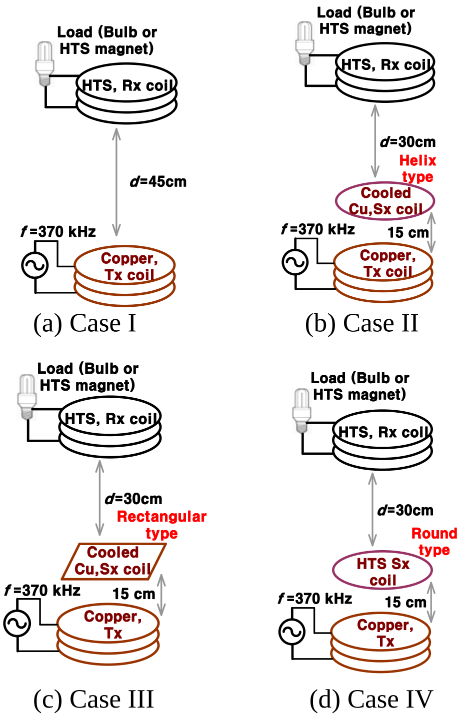


Fig. 4. Schematic illustration of four different experimental sequences of transmission mode under without inserted resonance (Sx), round shape cooled copper Sx, rectangular shape cooled copper Sx and round shape HTS Sx under HTS Rx coil, respectively.

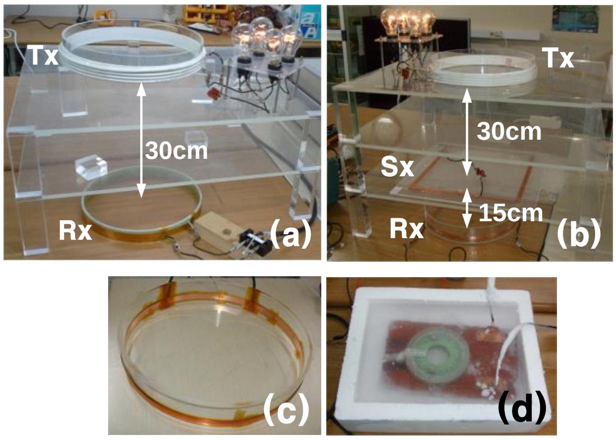


Fig. 5. Experimental performances and photographs for without Sx (a), inserted Sx (b) under 300 W of input power. The fabricated HTS Rx coil (c) and HTS magnet (d).

TABLE I
MEASURED Q VALUE OF HTS AND COPPER COILS AT 370 KHZ.

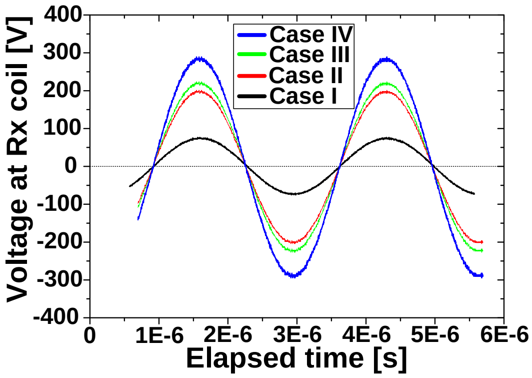
Parameters	HTS @ 77K, 370kHz	Copper (tape) @300K, 370kHz	Copper (tape) @77K, 370kHz
Resistance [mΩ]	12.28	24.47	22.68
Inductance [μH]	10.54	9.57	9.46
Q value	200	50	82

TABLE II
DESIGN PROPERTIES OF HTS AND COPPER RESONANCE COILS.

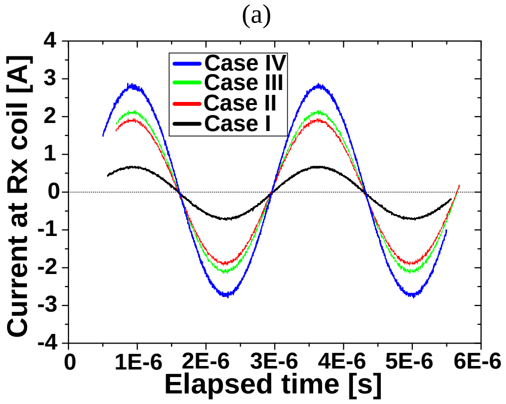
Parameters	Dimensions
HTS wire (thickness, width)	Ic = 200 A @ 77 K (0.15 mm, 4 mm)
Copper wire (thicknes, width)	(0.26 mm, 4.6 mm)
Diameter of Tx and Rx	30 cm
Inductance of HTS magnet	1.61 mH
Total turns of Tx and Rx	About 6 turns

and 2 show measured parameters and properties for Q value of resonance coils under room temperature (300 K) and liquid nitrogen circumstances (77 K), respectively. Apparently, we investigated transmission efficiency for different Q values of Tx and Rx coils using copper and HTS wires via strong magnetic resonances. The cooled copper and HTS wires are same sizes and tape types. However, the measured Q values of copper and HTS at 370 kHz are 82 and 200, respectively. Even though there is used rough superconducting joint technique with outer circuit, it is confirmed that the Q value of HTS tape wire is over two times compared with copper tape wire even cooled conditions.

Fig. 6 shows the experimental results of voltage and current distributions of Rx coils in the different cases of Fig. 4 with input power of 300 W. Apparently, it is confirmed that the transmission power is affected by high Q value of HTS resonance coil. The transferred voltage of case IV is improved over three times compared with transferred voltage of Case I. In addition, it is confirmed that transferred ratio of rectangular shape cooled copper Sx at Case III is slightly higher than that of helix Sx coil of Case II. Apparently, the efficiency ratio under HTS Sx coil at Case IV is improved about 50 % compared with Case III. That means, the high Q, HTS Sx coil can keep stronger resonance coupling condition compared with cooled copper Sx coil. In addition, it is confirmed that the Sx coil of rectangular shape is slightly profitable compared with helix shape Sx coil.



. (a)



(b)

Fig. 6. Experimental results of voltage and current distributions at Rx coil in the different Cases I~IV of Fig. 4 under input power of 300 W.

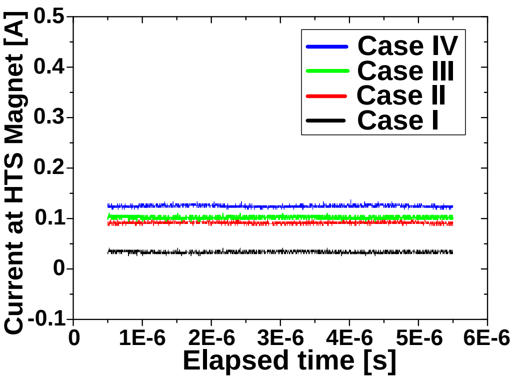


Fig. 7. Experimental results of charging current distributions at HTS magnet in the different Cases I~IV under input power of 300 W.

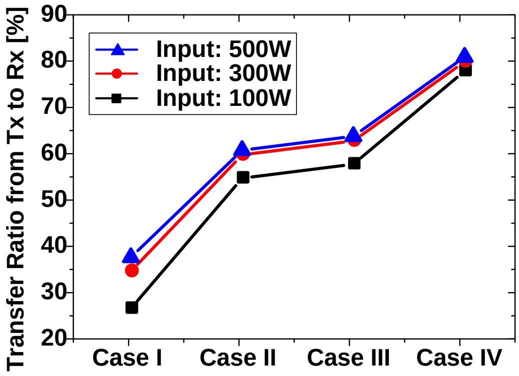


Fig. 8. Experimental results of transfer ratio between Tx and Rx in the different Cases I~IV below input 500 W.

Fig. 7 shows the experimental results of charging current at HTS magnet, which is connected with rectifying sub-circuit under different Cases of Fig. 4, below 500 W. It is confirmed that the charging currents with HTS magnet can be clearly stabilized under different inserted Sx coils with high fast full bridge rectifying sub-circuit. Fig. 8 shows the measured results of transmitted power ratio between Tx and Rx coils for various Cases I~IV below input power of 500 W. Apparently, the transferred power of Case IV is higher two times compared with Case I. As well as, the ratio with HTS Sx coil at Case IV is higher about 20 % than Case III.

4. CONCLUSIONS

We achieved the technical fusion of WPT technology with different inserted resonance coil in order to improve the delivery efficiency. The transfer ratio characteristics for high Q HTS resonance coil were successfully examined under various sequences. Authors obtained that the maximum transfer power with inserted HTS Sx is improved over two times across 30 cm distance compared with cooled copper Sx. That means high Q resonance coil can keep and spread stronger electromagnetic fields under even Sx coil. From this reason, it is confirmed that HTS Sx resonance coils are most effective among under HTS MAGLEV train charging system. Based on the fundamental approach, we reasonably evaluated such a WPT technology combined with superconducting MAGLEV to accomplish wireless high power charging system.

In the next work, authors will examine the transmission properties of shielding under different cooling vessel design since transfer ratio is depended on the design and material of cooling vessel, as well as to reduce the cooling cost for HTS Sx coils, we will examine the transmission properties and optimal cooling cost for design of various cooling vessels under over 1 kW of input power.

ACKNOWLEDOGEMENT

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by Korean Ministry of Education, (Grant No: 2017R1D1A1A09081100).

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