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Design Considerations of Cooling Vessel to Improve Power Charging under Magnetic Shielding Structure in Wireless Power Charging System in Magnetic Levitation Train

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The wireless power transfer (WPT) using magnetic resonance coupling method has been known to have the advantage of being able to transfer power across large air gap with considerably high efficiency. As well as, as such a method can eliminate the physical contact loss in the system, it provides an ideal solution for the problem of contact losses in the power applications. From these reasons, WPT technology has started to be applied to the wireless charging for various power applications such as transportations (train, underwater ship, electric vehicle). In the high speed superconducting magnetic levitation (MAGLEV) train, antenna (Tx) coils, which are installed both sides of train, are placed on the guidance rail, as well as, superconducting receiver (Rx) coils can be installed in traveling train. In the superconducting system, a cooling vessel, which is made by steel materials, is a requisite subsystem. However, since the steel materials can shield electromagnetic field, the structure design of cooling vessel can affect the transfer efficiency. In this study, we presented transfer efficiency and operating characteristics from copper Tx to superconducting Rx coil under different structures of cooling vessel with radio frequency power of 370 kHz below 500 W.

Keywords : electromagnetic shielding, superconducting magnetic levitation train, wireless power charging system

1. Introduction

The Maglev, which levitates the vehicle by magnetic force and propels it with linear synchronous motor (LSM), has already accomplished the maximum speed up to 581 km/h in the Japanese Maglev, MLX [1]. The MAGLEV systems, which are spotlighted as future green transportation systems, can be the application of the wireless power transfer technology [2]. Especially, the super high speed MAGLEV using superconducting magnet has drawn attention as next generation transportation since superconducting magnet can keep mighty levitation force. Generally, the superconducting 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 in the superconducting MAGLEV train [3-6]. Especially, the super high speed MAGLEV using high temperature superconducting (HTS) magnet, compared with low temperature superconducting (LTS) coils, has drawn attention as next generation transportation since superconducting magnet can keep mighty levitation force [7]. 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 [8-10] 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.

Recently, the wireless power transfer (WPT) technology has been interested because it is offers the promise of cutting the wires, allowing users to seamlessly recharge them portable devices as safely as power is transmitted

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through the air. The researchers from MIT proposed resonance coils of the same resonant frequency to transfer wireless power over a distance of meters on 2007. The experimented efficiency was about 40 % at a distance of 2 m with 13.56 MHz power source [3, 4]. Such an exploring research has been promisingly emerged in a variety of applications such as consumer electronics, medical devices, and transportation charging system since there is the desire to use seamlessly recharges them in order to offer the possibility of connector-free devices [5, 6]. As one of applications, the WPT systems have started to be applied to the charging of electrical high speed magnetic levitation (MAGLEV) train because of their advantages compared with the wired counterparts, such as no exposed wires, safety, convenient charging and fearless transmission of large power. From these reasons, authors suggested wireless power charging (WPC) system to MAGLEV train to reduce construction and maintenance costs. However, in the superconducting system, a cooling vessel, which is made by steel materials, is a requisite subsystem. Since the steel materials can shield electromagnetic field, the structure design of cooling vessel can affect the transfer efficiency. In this study, authors investigated operating characteristics from copper antenna (Tx) coil to HTS receiver (Rx) coil under different structures of cooling vessel, which consists of steel materials, with radio frequency (RF) power of 370 kHz, 500 W.

2. Structure and Mechanism

2.1. Structure of Wireless Power Charging (WPC) System for Superconducting Magnetic Levitation (MAGLEV) Train

Fig. 1 shows the conceptual design illustration of wireless power charging (WPS) system in MAGLEV train of EDS technology with superconducting magnet. It is composed by impedance matching (IM) subcircuit, Tx coils, magnetically-coupled HTS Rx coils and HTS magnet. The input AC power provide DC power to superconducting magnet through rectifier unit. The IM subcircuit can play a role to keep strong resonance coupling between Tx and Rx coils even changing interval. The magnetic resonant coupling contains creating an LC resonance, and transferring power with electromagnetic coupling. The general definition of the quality factor is based on 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:

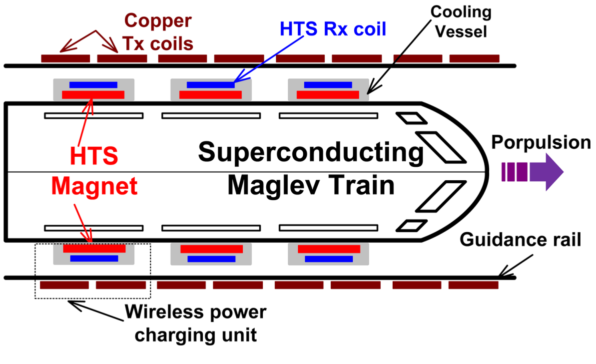


Fig. 1. (Color online) Illustration of superconducting wireless power charging (WPC) system for EDS-based superconducting magnetic levitation (MAGLEV) train.

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{\omega L}{R} = \frac{2\pi f L}{R} = 2\pi f\,\frac{Energy\ stored}{Power\ loss} \qquad (1)$$

Fig. 2 shows the schematic diagram of wireless charging unit with Tx coils. If it keeps strong resonance coupling between Tx and Rx, the transfer efficiency at Rx coil is maximum. At that time, minimized thermal losses at Tx coil are generated due to relatively lower reflected power. That is, the strong resonance coupling can improve transfer efficiency. On the other hand, if the resonance coupling is weakened or misaligned, the increased thermal loss is generated in Tx coil as well as the efficiency is decreased at Rx coil. The symbols of k_{12} and M_{12} mean the coupling coefficient and mutual inductance of both coils, respectively. The variable L_{X1} and C_{Y1} coupling play a role as an impedance bridging for varying impedances due to changing distance between coils. The efficiency of the power transfer depends on their quality factor Q and coupling coefficient k. The antenna coil forms a series RL circuit and the Q factor is expressed as:

$$Q = \frac{\omega L}{R}\,\omega\left(\frac{Maximum\ energy\ stored}{Average\ power\ dissipated}\right) = \frac{2\pi f L}{R} \qquad (2)$$

Coupling coefficient k_{xy} between different coupling coils and mutual inductance M_{xy} of both coils are calculated as [9]

$$k_{xy} = \frac{M_{xy}}{\sqrt{L_x L_y}},\ M_{xy} = \frac{|L_x - L_y|}{4} \qquad (3)$$

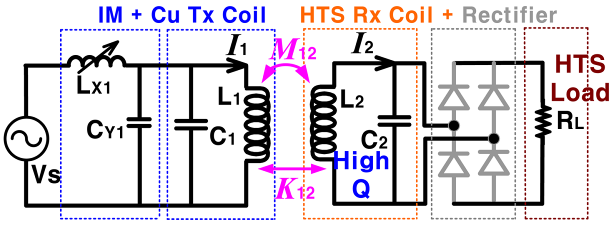


Fig. 2. (Color online) Schematic diagram of wireless charging unit with permanent magnet including rectifying sub-circuit in the Maglev train.

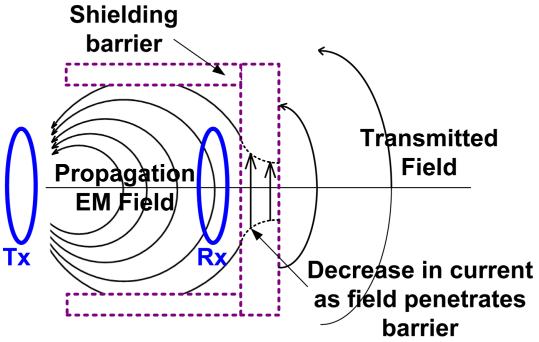


Fig. 3. (Color online) Schematic diagram of electromagnetic (EM) field shielding by shielding barrier in the resonance coupled coils.

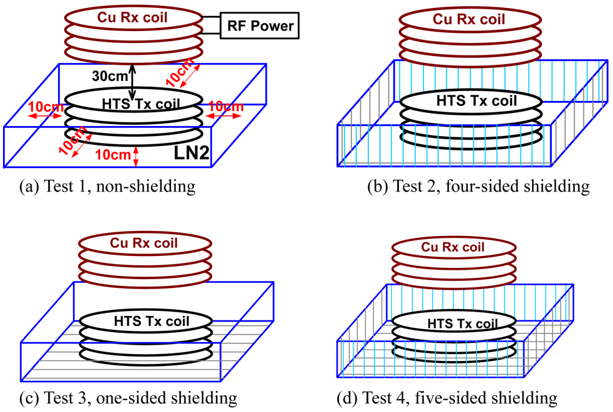
2.2. Thermal Distribution of Resonance Coils by Electromagnetic Shielding barriers

As the electromagnetic (EM) field is propagated to the direction of perpendicular, the maximized transfer efficiency is achieved by the straight array of Tx and Rx coils as shown in Fig. 3. The radiated EM field is generated by the action of driving a current through a wire which acts as a transmitting antenna as an emitter of EM interference and as a receptor with regard to EM susceptibility. A common method of eliminating the possibility of the emitter is by the use of a shielding barrier. When an EM field is impinged on a conductive shielding barrier, currents are caused to flow in the barrier. As the field penetrates the barrier, the current is attenuated (i.e., reduced in amplitude as illustrated in Fig. 3) by skin effect. The power of the field as it leaves the barrier is approximately equal to the current squared times the impedance of the barrier. The currents flow in the shielding barrier as a function of the radiated field being impinged on the barrier. When the current crosses a seam in the barrier, a voltage is created across the seam, where the value of the voltage is equal to the current times the impedance of the seam The shielding barriers, which are made of conductive materials, are the practice of reducing the EM field since these can absorb the EM field. That is, the transfer efficiency can be affected by structure shielding barriers. The cooling vessel, which is generally made by stainless materials, is requisite for HTS Rx coils at MAGLEV train, Even though glass fiber reinforced plastic (GFRP) materials are usefully adopted in the only lid to maximize the efficiency in the cooling vessel, the full-sided of the vessel is difficult to commercialize due to the cost and low cooling efficiency. From this reason, the effective design of cooling vessel should be considered to improve the transfer efficiency.

3. Experimental Setup and Results

3.1. Experimental setup

Authors examined transmission wave properties from room temperature to very low temperature without connectors based on magnetically resonance coupling under different shielding conditions. The experimental sequences of four different test are shown in Fig. 4. The surrounding space of cooling vessel from Rx coil keeps 10 cm and the antenna and receiver resonance coils are collinearly installed. We adopted the usable frequency range at 370 kHz. The rating power of fabricated RF power amplifier source is 200 W and reflect power limit is 100 W. The output resolution is below 1 W. As an HTS coil and copper wire have different material resistance for each other, it effectively can tune the impedance matching using the variable resistance and inductance. The measured impedance and inductance of antenna and receiver coils are 22 W and 9.2 μH, respectively. We adopted 1 mm Mu metal as a shielding barrier, which is a nickel–iron soft magnetic alloy with very high permeability suitable for shielding sensitive electronic equipment against static or low frequency magnetic fields. It has several compositions. One such composition is approximately 77 % nickel, 16 % iron, 5 % copper and 2 % chromium or molybdenum. Mu metal typically has relative permeability values of 80,000-100,000 compared to several times of ordinary steel. The high permeability of Mu metal provides a low reluctance path for magnetic flux, leading to its use in magnetic shields against static or slowly varying magnetic fields. Magnetic shielding made with high permeability alloys like Mu metal works not by blocking magnetic fields but by providing a path for the magnetic field lines



(a) Test 1, non-shielding (b) Test 2, four-sided shielding

(c) Test 3, one-sided shielding (d) Test 4, five-sided shielding

Fig. 4. (Color online) Schematic illustration of experimental setup with different structure of electromagnetic shielding using steel plate: (a) non-shielding, (b) four-sided shielding, (c) one-sided shielding, (d) five-sided shielding.

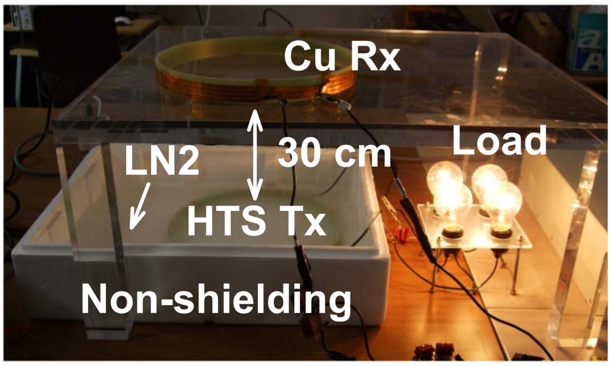


Fig. 5. (Color online) Photograph of experimental performance at Test 1 in Fig. 4 including with load of four bulbs 120 W under Styrofoam cooling vessel without non-shielding condition.

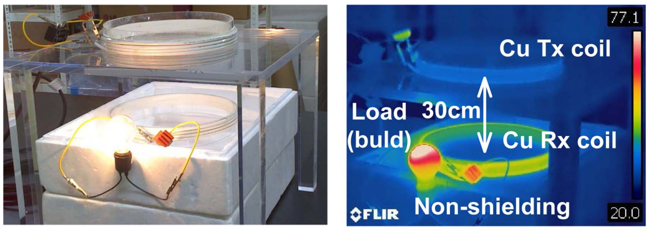
Table 1. Specification of copper tape, HTS coils and RF Power amplifier.

Parameters	Dimension
HTS wire AMSC 344S	Ic = 72 A @ 77 K
(Thickness, width)	(0.3 mm, 4.5 mm)
Copper tape coil (thickness, width)	0.5 mm / 6 mm
Total length of antenna & receiver coils	7.6 m
Diameter of bobbin of antenna & receiver coils	30 cm
RF power frequency /	370 MHz /
rating / resolution	200 W / 1 W
RF reflect power limit	100 W
No of turns in Copper, HTS	5

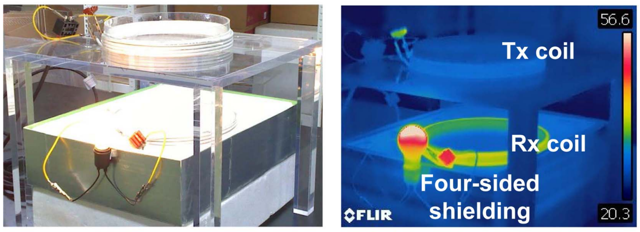
around the shielded area. Fig. 5 shows experimental performance of test 1 in Fig. 4 with input power of 300 W 370 kHz. The measured Q factor of copper of Rx coil at 300 K is 90 and HTS of Tx coil at 77 K is 170. The specification of fabricated copper and HTS resonance coils and input power is shown as Table 1.

3.2. Experimental results

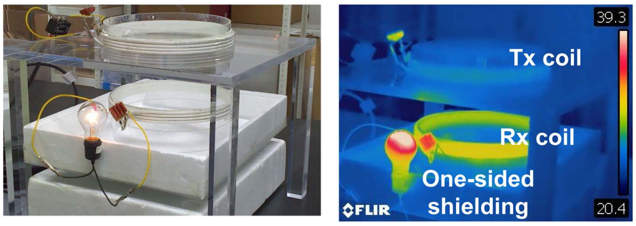
In order to confirm the shielding effects under different shielding structure of cooling vessels, authors measured thermal distributions in the resonance coils using thermographic camera as shown in Fig. 6. Certainly, the priority sequences of transfer power are as follows: Fig. 6(a) non-shielding, Fig. 6(b) four-sided shielding, Fig. 6(c) one-sided shielding and Fig. 6(d) five-sided, respectively. The peak temperature of load bulb is 77.1, 56.6, 39.3 and 36.1 in the sequences from Fig. 6(a) to (d). That means higher transfer ratios are depended on the temperature of bulb. Fig. 7 shows calculated results for the coupling coefficient *k* between antenna wire and HTS coil at interval of 30 cm based on the results of Fig. 3 and Eq. (3) under non-shielding condition of Fig. 4. Apparently, the *k* value has gradually risen corresponding to increasing frequency.



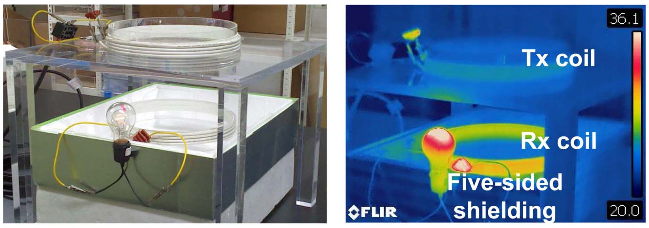
(a) non-shielding



(b) four-sided shielding



(c) one-sided shielding



(d) five-sided shielding

Fig. 6. (Color online) Photograph of experimental performance for wireless charging unit between copper cable type Tx and Rx coils under different shielding structures of cooling vessel. The input power is 150 W of 370 KHz generator:

Fig. 8 shows the experimental results of transferred waves for voltage at HTS Rx coil. Surely, as the transferred electromagnetic fields keep straight waveform, in the case of four-sided shielding, the transferred voltages are reduced about 10 %, on the other hand, the rates with one-sided and five-sided shielding structures are reduced about 74, 83 %, respectively, compared with non-shielding structure. Fig. 9 shows experimental results of current waves at HTS Rx coil from tests 1 to 4 with same power conditions. Apparently, it is evaluated that transferred rates at tests 3 and 4 are reduced more than over 60 % compared with tests 1 and 2. That means shielding of

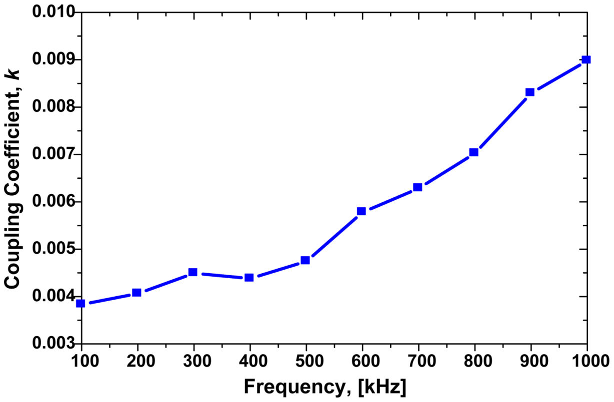


Fig. 7. (Color online) Measured results of coupling coefficient between copper Tx and HTS Rx coils using measured self-inductance of resonance coils and Equation (3) under Test 1 of Fig. 4.

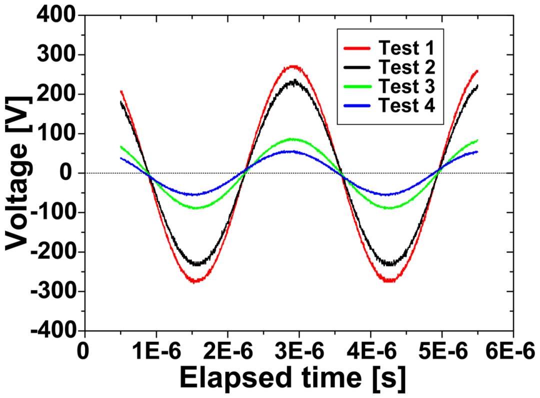


Fig. 8. (Color online) Experimental results of transferred voltage distributions at HTS Rx coil from tests 1 to 4 of Fig. 4.

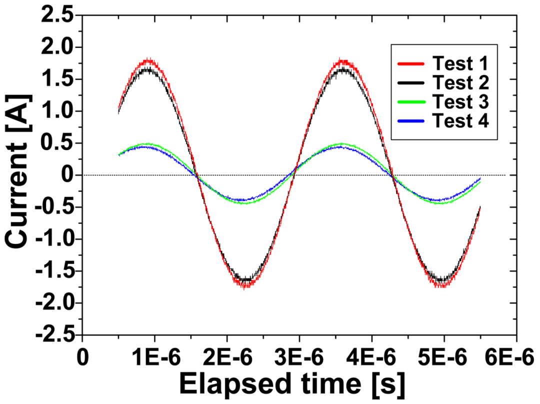


Fig. 9. (Color online) Experimental results of transferred current distributions at HTS Rx coil from tests 1 to 4 of Fig. 4.

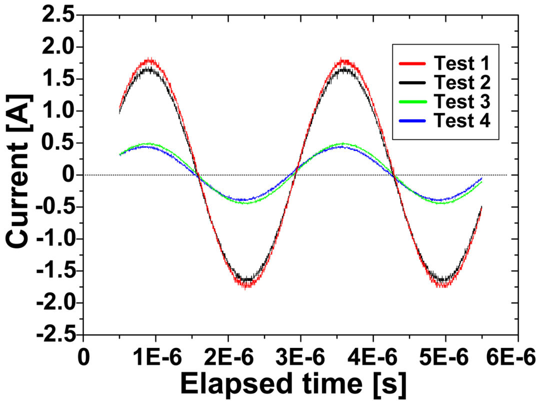


Fig. 10. (Color online) Experimental results of transferred ratios between copper Tx and HTS Rx coils from tests 1 to 4 of Fig. 4.

base plane (back side of Rx coil) absorbs effectively electromagnetic field from Tx coil. In the case of test 2, the transferred current is reduced over 10 % compared with test 1. That means, surrounding shielding structure can affect to reduce the electromagnetic field about 10 % compared with non-shielding structure.

Fig. 10 shows the measured transferred efficiency from input power to Rx coil excluding IM circuit loss to different scenario tests of Fig. 4. Certainly, the transferred efficiency with only surrounding shielding structure at test 2 is higher than over two times compared with the shielding structure of base plane. Based on the comparative analytical study of operating patterns of different shielding structures, in the viewpoint of transfer efficiency with superconducting resonance coils, it should be considered that the non-magnetic materials for cooling vessels at top cover and base plane should be included such as glass fiber reinforced polymer (GFRP) in order to maximize the transferred power.

4. Conclusions

In this paper, the transferred characteristics of wireless power charging unit for shielding structures of cooling vessel in superconducting MAGLEV train was successfully achieved. Especially, it was investigated that the reduction patterns of transfer efficiency for different shielding structures in HTS Rx coil. Based on the experimental results, it was confirmed that the transferred ratio of shielding structure including base plane is reduced over 60 % compared with surrounding shielding without base plane. As well as, the transferred ratio of surrounding shielding structure is reduced over 10 % compared with non-shielding structure. From this reason, in the viewpoint of transfer and cooling efficiency, the top cover and base plane of cooling vessel should be considered to non-magnetic materials such as GFRP. However, in the practical system, since the fabrication cost for cooling capacity with shielding structure of cooling vessel is one of major considerations to commercialize, various approaches and researches for shielding structures have been demanded. From the results, authors will be to evaluate validity and stability of optimizing design for cooling vessel of HTS Rx coils in the next study.

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