Transfer Efficiency and Cooling Cost by Thermal Loss based on Nitrogen Evaporation Method for Superconducting MAGLEV System

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Abstract. This paper presents the feasibility of technical fusion between wireless power transfer (WPT) and superconducting technology to improve the transfer efficiency and evaluate operating costs such as refrigerant consumption. Generally, in WPT technology, the various copper wires have been adopted. From this reason, the transfer efficiency is limited since the copper wires of Q value are intrinsically critical point. On the other hand, as superconducting wires keep larger current density and relatively higher Q value, the superconducting resonance coil can be expected as a reasonable option to deliver large transfer power as well as improve the transfer ratio since it exchanges energy at a much higher rate and keeps stronger magnetic fields out. However, since superconducting wires should be cooled indispensably, the cooling cost of consumed refrigerant for resonance HTS wires should be estimated. In this study, the transmission ratios using HTS resonance receiver (Rx) coil and various cooled and non-cooled copper resonance Rx coils were presented under non cooled copper antenna within input power of 200 W of 370 kHz respectively. In addition, authors evaluated cooling cost of liquid nitrogen for HTS resonance coil and various cooled copper resonance coils based on nitrogen evaporation method.

1. Introduction

Wireless power transfer technologies are spreading in application fields from transferring a few milli-watts of power in biomedical applications [1] up to hundreds of watts of power in automotive applications [2]. Currently, WPT systems with several kilowatts output, intended to wireless power charging devices for transportations such as electric vehicles, trains and underwater ships. 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 and cost [3], [4].

Generally, as the WPT system adopted normal conducting wire, the size of antenna is too large to be equipped to deliver the large power promptly due to the intrinsically property of the normal conducting wire. As well as, as the copper resonance keep relative low Q factor, the exchanges energy rate is limited. The high Q factor 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 magnetic fields out in the peripheral regions. From this reason, the WPT technology has been required for diffusion of various wires to maximize Q value of resonance coils with stability [5]-[7]. As a reasonable approach, the superconducting wire is a noble option in order to improve transfer efficiency and extend the transfer distance with high stability under high power operation. Fortunately, since the superconducting wires keep enough current density and higher Q value, it enables to exchange a massively electric power in spite of a small scale coil as well as to improve the efficiency. From this reason, superconducting resonance coils are promisingly highlighted in the electric vehicle and superconducting MAGLEV as an antenna (Tx) and receiver (Rx) coils, respectively [8]-[12]. As the superconducting wires should be cooled indispensably, the cooling cost of resonance coils should be considered to commercialize. Generally, as the cooling cost of superconducting wires is caused by AC losses, which are the sum of magnetization losses and transport current losses during AC charging. Total power dissipation is indirectly and relatively easily estimated by evaporation of liquid nitrogen compared with voltage terminal or pick-up coils [13].

In this study, operating characteristics for various copper types (solid, litz, tape wires) and HTS Rx coils, which are cooled by liquid nitrogen, are evaluated with RF generator of 370 kHz within 200 W. In addition, power dissipations of HTS, copper cable, solid, litz and tape resonance wires by AC loss are estimated using the nitrogen evaporation method. Based on the total evaporation rate, relatively consumed comparison of liquid nitrogen for various wires is presented.

2. Mechanism and properties

2.1. Structure and mechanism

Figure 1 shows the conceptual design of wireless power charging (WPS) system in MAGLEV train of EDS technology with superconducting magnet. The antenna (Tx) at MAGLEV system, magnetically-coupled multi resonance antennas, which consist of normal conductor and are used in as transmitter via optimizing resonance capacitances according to the positions of receiver (Rx) coil. Phased-multi Tx coils are also implemented that can localize and track the receiver with high power transmission efficiency even when Tx and Rx coils are misaligned. The structure of resonance wireless charging unit of SUWPT system consists of four components as follows; RF source (Vs), impedance matching (IM) circuit, antenna (Tx) coil, and receiver (Rx) coil including load (RL), as shown in Figure 2 (a). 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. 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. Once resonance coupling condition between Tx and Rx coils is broken, the transmitting waves are reflected back into Tx, and then those cause thermal heating problem. Thus, the IM circuit, which consists of LC resonant circuit, comes into play when electromagnetic wave cannot be sufficiently reduced using capacitors and inductors; it suppresses unnecessary frequency, effectively.

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

\[ Q = \frac{\omega L}{R} = \frac{2\pi f L}{R} = 2\pi f \frac{\text{Energy stored}}{\text{Power loss}} \]  

where \( f \) means resonant frequency. The maximized Q value of superconducting wires can be realized based on the optimized joint technique. Stored energy is \( LI^2/2 \) and power dissipation is \( RI^2 \). The Q factor is proportional to stored energy but inversely proportional to power dissipation.

Figure 2 (b) shows the equivalent circuit of the resonance type WPT system. Variable inductances \( L_{x1} \)
and $L_{N2}$ are changed to select the resonance frequency of input source corresponding to LC coupled degree and distance of Tx and Rx coils. Using element circuit analysis, currents of primary and secondary coil are expressed as

\[ I_1 = \frac{(1 + k_{12}^2 Q_{s2}) V_s}{(1 + k_{12}^2 Q_{s2}) R_s} \quad I_2 = \frac{k_{12} \sqrt{Q_{s2}}}{1 + k_{12}^2 Q_{s2}} \frac{jV_s}{R_s R_{L}} \]

2.2. Thermal loss of resonance coil

The cooling cost of superconducting wires is caused by AC loss, which is the sum of magnetization losses and transport current losses during AC charging. In addition, in the SUWPT system, the resonance coupling coil also can cause thermal loss depended on the LC resonance condition. The LC resonance of Tx and Rx coils constitute a source resonance circuit to generate an alternative non-radiative magnetic field in the resonance coupling coils. In theory, when the oscillation of source resonance circuit is tuned with receiver resonance circuit, the resonance current is highest. That means thermal loss is minimized in the Tx and the transfer efficiency is maximized. On the other hand, if LC resonance coupling is weakened or enlarged air gap with Rx resonance circuit, resonance current is reflected back into Tx. And then, the thermal loss of Tx coil is maximized. Thus, in this study, the consumed evaporation rates of various Rx coils are examined by liquid nitrogen evaporation method in the next section.

2.3. Nitrogen evaporation method

The measurement device using the nitrogen evaporation method was developed as a practical way to measure AC losses in HTS coils, and is being verified for its measurement accuracy. Compared to conventional electrical measurements, the nitrogen evaporation method has the following beneficial features: Firstly, the amount of AC loss, equivalent to the amount of released gas, can be directly

![Figure 1. Illustration of superconducting wireless power charging (WPC) system for electrodynamic suspension (EDS)-based superconducting MAGLEV train](image1)

![Figure 2 (a). Illustration of simplified circuit model of resonant type superconducting WPT (SUWPT) system](image2)

![Figure 2 (b). Equivalent circuit diagram of resonance type SUWPT system](image3)
detected. Secondly, there is no specific limitation on shape and size of coils. Thirdly, any calibration is made possible directly by using a heater. The power dissipation by nitrogen evaporation method can be expressed by [14]

\[ Q_i = \frac{P}{h_L} \]  

(4)

Where liquid nitrogen boil-off rate \( Q_i \), power dissipation \( P \), the latent heat of vaporization of liquid nitrogen \( h_L \).

3. Experimental setup and results

In this experiment, authors focused on power transfer characteristics, thermal distributions, transfer ratio and evaporation rate of LN2 for cooled Rx resonance coils. In Figure 3, the Q value of various resonance coils at 77 and 300 K, respectively, is presented under different frequencies. The cooled copper solid, litz, and tape resonance coils are apparently improved over two times compared with non-cooled circumstance since the resonance coils are stabilized by lower resistance. As the high Q and transfer efficiency are correlated, the cooling condition has a direct influence on transfer ratio. In Figure 4, the strong resonance circumstance between Tx and Rx coils for solid, litz and tape wires is

**Figure 3.** Measured results of Q value for copper cable, solid, litz, tape and HTS wires within 1 MHz: (a) with 77 K, (b) with 300 K.

**Figure 4.** Photograph of experimental performance and measured thermal distributions for coupled Tx, and Rx coils by thermo-graphic camera at 300 K. The input power is 200 W of 370 kHz RF generator: (a) copper solid wire, (b) litz wire (c) tape wire.
Figure 5. Photograph of experimental performance and setup: (a) experimentally structural elements, (b) experimental setup of non-cooled performance (c) experimental setup of cooled Rx for solid, litz and tape coils (d) experimental setup of HTS coil.

Table 1. Material properties and specifications of HTS and copper resonance coil with 77 K at 370 kHz.

| Parameters           | Impedance [Ω] | Inductance [μH] | Q  | Dimensions (thickness \( t \), width \( w \), diameter \( d \)) |
|----------------------|---------------|-----------------|----|---------------------------------------------------------------|
| HTS (YBCO copper clad) | 12.28         | 10.94           | 200| \((t: 0.2\, \text{mm}, w: 4 \, \text{mm})\)                  |
| Solid                | 23.3          | 10.41           | 90 | \((d: 1.2 \, \text{mm})\)                                    |
| Tape                 | 25.6          | 10.24           | 80 | \((t: 0.35 \, \text{mm}, w: 5 \, \text{mm})\)                |
| Litz                 | 22.8          | 10.22           | 95 | (no. of wires:150 strand)                                    |

Figure 6. Experimental results of voltage and current distributions at Rx coil in the different resonance Rx coils with input power of 200 W at 77 K:. (a) voltage wave forms (b) current wave forms.

shown under 300 K. The reflected power below 1 W is kept corresponding to input of 200 W. It is confirmed that the relatively higher heat at Rx is caused compared with Tx due to load impedance. From this investigations, authors installed experimental setup and data acquisition elements as shown in Figures 5 (a) and (b). The operating characteristics of copper solid, litz and tape resonance coils are
investigated under non-cooled circumstance and only cooled Rx, respectively, as shown in Figure 6 while HTS resonance characteristics are investigated at 77 K under conditions of Figures 5 (c) and (d). The evaporation rate of liquid nitrogen, which is preserved using Styrofoam vessel, is measured by weigh scale. Table I show design specifications and measured properties HTS and various copper resonance coils. Figures 6 (a) and (b) show measured results of voltage and current wave distributions for various resonance coils at 77 K. The advanced order of high transfer ratio for voltage and current is HTS wire, copper solid wire, litz wire and tape wire. In the amplitude of current, the differential gap is eminently widened compared with voltage wave forms. That means the HTS resonance coil can keep strong magnetically resonance coupling. In addition, its transfer intensity is higher than even cooled copper resonance coil. Especially, it is confirmed that it is advantageous for copper solid wire to transfer current wave forms compared

![Figure 7](image)

**Figure 7.** Experimental results of transfer ratio from IM circuit to Rx coil for different resonance coils with input of 100 and 200 W under 300 K and 77 K, respectively.

![Figure 8](image)

**Figure 8.** Experimental results of evaporation rate of liquid nitrogen of Rx coils and relative consumption percentage compared with fiducial point of nitrogen consumption for HTS coil with input of 100 W and 200 W: (a) evaporation rate of liquid nitrogen (b) relative comparison for HTS consumption.

with other copper resonance coils. In Figure 7, from a transfer efficiency point of view, the transfer ratio of resonance Rx coils between non-cooled copper and cooled copper including HTS coil are presented. Definitely, the transfer ratio of cooled resonance coil is enhanced over 15 % compared with non-cooled resonance coils. Based on the results, it is certified that the transfer efficiency of copper resonance coils can be effectively promoted by cooling circumstance.

In Figure 8, as a viewpoint of cost and consumption, the evaporation rate of LN2 per one hour for various resonance coils and relative consumed comparison are presented with input power of 100 W and 200 W, respectively. The consumption rate of HTS resonance coil from 100 W to 200 W is increased about 5 %, while the solid, tape and litz resonance coils are increased 10, 12 and 21 %, respectively as shown in Figure 8 (a). As well as, compared with HTS coil even under 77 K, the relative consumptions
of LN2 per one hour for copper solid, tape, litz resonance coils are higher about 11, 38 and 63 %, respectively, as shown in Figure 8 (b). The LN2 consumption rates of solid, tape, litz wires are relatively increased compared with HTS wire under increasing input power since the HTS wire keeps higher current critical point. That means thermal loss of HTS wire relatively low under critical current point due to intrinsically characteristics compared with copper material wires. The consumed LN2 of HTS, solid, tape and litz wires are 0.8, 0.9, 1.1 and 1.2 liters with input power of 100 W during one hour. On the other hand, the HTS, solid, tape and litz wires consumed 0.9, 1.1, 1.3 and 1.6 liters of LN2 with input power of 200 W, respectively. The cost of evaporated LN2 for one liter is about 0.5 dollar.

4. Conclusion
Authors successfully achieved the relative comparison for transfer ratio and consumption of liquid nitrogen between HTS and various copper resonance coils at 77 K and 300 K, respectively. It is confirmed that the HTS resonance coil has advantages of enhanced transfer ratio with stability and relatively low cooling cost of LN2 compared with cooled copper resonance coils. Furthermore, the cooling cost can be improved through the optimal design of cooling vessel in the next study. That the copper resonance coil with cooling circumstance can improve for transfer ratio is informative and interesting points. Based on the results, authors expect to apply the HTS resonance coil for superconducting MAGLEV train. In the case of wireless power charging system for superconducting MAGLEV train, the Rx resonance coil is easily installed in the train since the cooling vessel is installed in the train to cool superconducting magnet. Thus, our research target is to evaluate validity and stability of HTS resonance coils to accomplish wireless power charging system for the superconducting MAGLEV train.

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