Effects and Design Considerations of Inserted Resonator to Improve Efficiency Including Rectifying Circuit for Superconducting Wireless Power Transfer System for Electric Vehicle

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Abstract. The wireless power transfer (WPT) technology based on strongly resonance coupled method realizes large power charging without any wires through the air. Recently, the WPT systems have started to be applied to the wireless charging for electrical vehicles (EVs) because of their advantages compared with the wired counterparts, such as convenient, safety and fearless transmission of power. However, it has obstacles to commercialize such as delivery distance and efficiency. To solve the problems, we proposed the technical fusion using HTS antenna in the WPT system, it is called as, superconducting wireless power transfer for electric vehicle (SUWPT4EV) system. Since the superconducting wire has merits a larger current density and higher Q value than normal conducting wire, the HTS antenna enables to deliver a mass amount of electric energy in spite of a small scale antenna. Thus, SUWPT4EV system has been expected as a reasonable option to improve the transfer efficiency of large electric power. Authors already demonstrated the efficient effects for inserted resonator using simply copper tube wires, which structure is helix type of multi layers. In this study, as a practical approach, authors evaluated the SUWPT4EV system with inserted copper type resonator, which structure is a rectangular shape of single layer to reduce installation volume. Based on the evaluation results, authors deduced the practically alternative structure for the inserted resonator to reduce the installation space as well as to improve transmission power, compared with non-resonator SUWPT4EV system under radio frequency (RF) power of 370 kHz below 500 W.

1. Introduction
Magnetically coupled resonators, each comprising a coil in series with a capacitor, were historically first used for wireless power transfer (WPT) by Nikola Tesla in the late 1800s. Nowadays, the WPT technology has been interested again because it is offers the promise of cutting the wires, allowing users to seamlessly recharge them portable devices as safely as power is transmitted through the air. On 2007 the researchers from MIT proposed resonance coils of the same resonant frequency to transfer wireless power over a distance of meters. The experimented efficiency was about 40% at a distance of 2 m with 13.56MHz power source. 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 [1]. As one of applications, the WPT systems have started to be applied to the charging of...
Electrical vehicles (EVs) because of their advantages compared with the wired counterparts, such as no exposed wires, safety, convenient charging and fearless transmission of large power. However, limited distance and efficiency of the WPT system has been major obstacles in commercialization service [2],[3]. To overcome mentioned problems, we already proposed the combinations of WPT technology with HTS antenna for EV system [4], it is called as, superconducting wireless power transfer for EV (SUWPT4EV) system, which enables to transfer larger power efficiently compared with normal conducting antenna [5], [6]. Fortunately, since superconducting wire has a larger current density and higher Q value, HTS antenna can deliver a mass amount of electric energy in spite of a small scale antenna [7],[8]. On the other hand, in the superconducting equipment, a cooling vessel is a requisite subsystem, which is a main obstacle for installation space and handling to commercialize in the EV charging system. However, as even a normal conducting antenna coil for large power transfer should be installed underground due to safety and maintenance, the underground cooling vessel for HTS antenna doesn’t put obstacle in the wireless EV charging system anymore.

Authors already confirmed the efficient effects of efficiency improvement for an inserted resonator, which structure is multi layers made by tube type copper wire, between HTS antenna (Tx) and copper receiver (Rx) [9]. In order to adopt the resonator practically, the installation volume of inserted resonator should be reduced. In addition, as the strongly thermal energy of inserted resonator is inevitably generated, the cooling subsystem for the resonator should be considered. In this study, as a practical approach, authors propose an inserted resonator, which structure is single layer to reduce installation volume, between antenna Tx and receiver Rx coils in order to reduce the installation space. As the inserted single layer resonator can be installed in the inside of cover at cooling vessel easily, the unavoidable thermal energy of inserted resonator can be easily cooled with HTS antenna as shown in Figure 1. In this paper, we examine the improvement effects of efficiency and delivery distance using inserted single layer resonator in the SUWPT4EV system compared with non-resonator charging system at the same experimental sequence. The performance is carried out with the RF input power of 370 KHz from 100 to 500W at 40 cm distance. Based on the evaluation results, authors propose alternative structure for the single layer inserted resonator to reduce the installation space as well as to improve transmission power.

2. Mechanism and properties

2.1. Structure and mechanism

As shown in Fig. 2, the basic principle of SUWPT4EV system with inserted resonator via coupled magnetic resonance is proposed. Such a system consists of RF power source (Vs), HTS Tx coil, normal conducting resonator Sx coil, normal conducting Rx coil, rectifying circuit and load. If the distance between Tx and Rx is broadened, the phases of voltage and current waves for each coil are proportionally
shifted. That is, the resonance coupling for each coil doesn't match due to varying distance. Thus, the shifted phase of transmitting wave causes reactive power loss (thermal loss). From this point of view, the Sx coil plays a role to keep strong resonance coupling and reduce phase shift between Tx and Rx, which associates with techniques to improve efficiency and expand distance. The inductance of Tx coil, \( L_2 \) and capacitor \( C_2 \) constitute a source resonance circuit to generate an alternative non-radiative magnetic field corresponding to \( L_3 \) and \( C_3 \) resonance circuit. In theory, when the oscillation of source resonance circuit is tuned with receiver resonance circuit, the resonance current is highest and then induced magnetic field intensity of Rx coil is maximized. In the system, a variable distance of \( d_{12} \) takes a role to tune resonance coupling between Tx and Rx coils. When the inductor \( L \) and capacitor \( C \) in resonance circuit is determined, the circuit resonance frequency \( f \) could be calculated from Equation (1):

\[
f = \frac{1}{2\pi \sqrt{LC}}
\]

(1)

The transfer efficiency can be explained by quality factor \( Q \). Higher \( Q \) indicates a lower rate of energy loss relative to the stored energy of the resonator; the oscillations die out more slowly. The magnetic resonant coupling contains creating an LC resonance, and transferring power with electromagnetic coupling. The \( Q \) value is defined by this ratio. 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:

\[
Q = \frac{1}{R} \sqrt{\frac{L}{C}} = \frac{\omega L}{R} = \frac{2\pi f L}{R} = \frac{2\pi f}{\text{Energy stored}} \frac{\text{Power loss}}{f R L}
\]

(2)

Figure 2. Schematic diagram of superconducting wireless power transfer (SUWPT) system with three-separate resonance coils.

Figure 3 shows the equivalent circuit of SUWPT4EV with inserted resonator system. The \( R_1, R_2, R_3, I_1, I_2, I_3 \) are the internal resistance and induced current of three-separate resonance coils, respectively. \( M_{ij} \) and \( k_{ij} \) means mutual inductance and coupling coefficient between coupling coils. They are calculated as [7]

\[
k_{xy} = \frac{M_{xy}}{\sqrt{L_x L_y}}
\]

(3)
2.2. Thermal distribution of resonance coils

Generally, the thermal coupled loss of resonance wires (copper and superconducting coils) are caused by AC loss, which is the sum of magnetization losses and transport current losses during AC charging in an AC magnetic field. The resonance coupling coil also can cause thermal loss depended on the \( LC \) resonance condition. In the case of non-resonator, the thermal loss of Tx is relatively higher than Rx coil as shown Figure 4 (a) since the transferred power is relatively small. Generally, the transferred distance corresponding to induced electro-magnetic field (EMF) by Tx coil can be depended on the diameter of Tx coil. However, the diameter of Tx coil is limitation due to restricted length and impedance of Tx coil. From these reasons, the inserted resonator, which keeps strong resonance coupling, is one of reasonable options to expand the transferred distance, since the radius of induced EMF by Tx coil can be strongly expanded using inserted resonators. As well as, in the case of inserted Sx coil, since the radius of induced EMF can be expanded, the transferred power at the Rx coil is relatively higher compared with that under non-resonator coil. However, the thermal losses of Sx and Rx are strongly caused as shown in Figure 4 (b). Since the total impedance of Sx coil, which is only connected with capacitor, is smaller than that of Rx including load. If the load is connected with Sx coil, the transferred power of Rx coil would be relatively reduced. Also, if the induced thermal loss of Sx coil can be minimized by cooling device, the transferred power at Rx coil would be maximized. That means the inserted Sx coil plays a role to preserve the induced EMF by Tx coil and thus it delivers the EMF energy to Rx coil. In the viewpoints of efficiency, the design of cooling device for inserted Sx coil should be practically considered. The experimental performance of Figure 4 is carried with RF generator 370 kHz of 200 W and it keeps reflect power below 10 W.

![Figure 3](image3.png)

**Figure 3.** Equivalent circuit diagram of SUWPT4EV with inserted resonator system of Figure 2.

![Figure 4](image4.png)

**Figure 4.** Photograph of experimental performance and thermal distributions with (a) non-resonator and (b) inserted resonator (Sx) between Tx and Rx coils at 200 W 370 KHz, respectively.
In this experiment, we examined the effects of transmission efficiency and delivery distance with inserted resonator antenna including rectifying circuit of the SUWPT4EV system. The rectangular shape of Rx coils is required. The rectangular shape of Sx coil plays a role to keep strong resonance coupling. The transferred power at Rx coil with inserted Sx coil is higher over 25 % compared with non-Sx coil. In other words, the transferred distance can be expanded by inserted resonator due to keep strong resonance coupling. The transferred power at Rx coil with inserted Sx coil is higher over two times compared with non Sx coil. In other words, the transferred distance can be expanded by inserting resonator antenna including rectifying circuit of the SUWPT4EV system. The rectangular shape of Rx coils is required.

3. Formatting the text

3.1. Structure and mechanism

In this experiment, we examined the effects of transmission efficiency and delivery distance with inserted resonator antenna including rectifying circuit of the SUWPT4EV system. The rectangular shape of Rx coils is required. The rectangular shape of Sx coil plays a role to keep strong resonance coupling.

Figure 5 shows the measured results of voltage and current waves for different intervals between Tx and Rx coils with 200W of 370 kHz RF generator under including Sx and non Sx coils, respectively. The intervals d is changed from 5 cm to 20 cm between Tx and Rx coils. The reflected power rates keep below 1 %, which is indicated in the protection device of RF generator. Definitely, the strong resonance waves with resonator Sx coil can spread far away compared with non-Sx coil under same conditions. As well as, the amplitudes of transferred voltage and current waves at Rx coil were markedly reduced depended on enhancing intervals as shown in (a) and (b). On the other hand, in the case of including Sx coil, the amplitudes of transferred voltage and current waves were slowly reduced corresponding to enhancing intervals as shown in (c) and (d). Obviously, the amplitude of transferred voltage and current waves at d= 20 cm under including Sx coil is higher over two times compared with non Sx coil. In other words, the transferred distance can be expanded by inserted resonator due to keep strong resonance coupling. The transferred power at Rx coil with inserted Sx coil is higher over 25 % compared with non-resonator Sx coil as shown in Figure 5. Even though the inserted Sx coil plays a role to keep strong electromagnetic field, as the generation of heat for inserted resonator, the cooling device for inserted Sx coil should be considered in order to keep strong resonance coupling. Thus, the Sx coil has a benefit to expand the transfer distance. However, since the thermal loss is strongly generated in the Sx and Rx coil at the large intervals between Sx and Rx coils, the cooling device for Sx and Rx coil is required.
resonator, which is wound into one layer by helix type, was made from copper tape in order to install on the cover of cooling vessel easily. The HTS Tx and copper Rx coil are wound by helix type. The dimensional and design specifications of Tx, Sx and Rx coils and RF power are shown in Tables I and II, respectively. The rectified waves of load are measured by two pairs of fast recovery diodes. To confirm the transfer power, the multi 30 W bulbs are attached in the receiver coil as a load. The experiment is carried out below 300 W of RF input power 370 KHz for case I and II sequences. To compare transferred power ratio of cases I and II fairly, the reflect power ratio is kept below 1 %. The distances of $d_1$, $d_2$ and $d_3$ are fixed at 40, 30, 10 cm in the cases I and II as shown in Figure 6. Authors adopted a cooling box made from Styrofoam. In the next, we will fabricate the GFRP vessel and glass cover for practical approach. Apparently, it is experimentally confirmed that transmission power at Rx coil with resonator is larger than that without resonator under the same condition. That means, the resonator keeps strong resonance coupling and thus the transmission distance can be expanded.

The measured Q value for copper cable at 370 KHz, 300 K is 110. Also the Q value for cooled copper cable at 370 KHz, 77 K is 130 and 160. Also, at 370KHz, the Q value for HTS tape is 190 at the same length resonance coil.

![Figure 6. Schematic illustration of different experiment sequences for transmission mode including setup under (a) non-resonator and (b) inserted resonator, respectively](image-url)

**Table 1.** Dimensional specifications of Tx, Sx, and Rx coils

| Parameters                                      | Dimensions                                      |
|------------------------------------------------|------------------------------------------------|
| HTS wire AMSC 344S (Thickness, width)          | Ic = 72 A @ 77 K (0.3 mm, 4 mm)                 |
| Inductance and impedance of HTS Tx coil @300K, 370kHz | 7.96 [µH], 18.42 [Ω]                            |
| Cable diameter of of Rx coil                   | φ 10 mm                                        |
| Inductance and impedance of Rx coil@300K, 370kHz | 9.23 [µH], 21.42 [Ω]                            |
| Size of Sx coil (Thickness, width)              | 0.2 mm, 10 mm                                  |
| Inductance and impedance of Sx coil@300K, 370kHz | 10.43 [µH], 24.2 [Ω]                            |
| Load (bulb)Capacitor                           | 30W                                            |
| Capacitor of Sx and Rx coils                   | 18nF                                           |
Figure 7 shows experimental setup and performance sequences without rectifying circuit at input power of 200 W under the cases I and II, respectively. Apparently, it is experimentally confirmed that transmission power at Rx coil with resonator is larger than that without resonator under the same condition. That means, the resonator keeps strong resonance coupling and thus the transmission distance can be expanded.

![Experimental Setup](image)

**Figure 7.** Photograph of experimental setup and different performances without rectifying circuit in the case I and case II of Figure 6 with input of 200 W; including HTS Tx, copper Sx, Rx and load (bulb)

### Table 2. Specifications of RF power

| Parameters        | Dimensions |
|-------------------|------------|
| Frequency         | 370 kHz    |
| Harmonics         | -50dbc     |
| Rating Power      | 1 KW       |
| Output resolution | 1 W        |
| Reflect power limit | 200 W    |

3.2. Experimental results

Figure 8 (a) shows the experimental results of current and voltage distributions for HTS Tx and copper Rx in the case I at 40 cm under input power of 200 W. As surely seen, the phases of voltage and current of Rx are shifted compared with input phases of Tx coil. The shifted angle is about 79° between Tx and Rx coils. That means it is difficult to keep resonance coupling condition, if the interval is expanded between Tx and Rx coils, even though reflected energy loss is minimized. Figure 8 (b) shows measured results of current and voltage distributions for HTS Tx and copper Rx in the case II with inserted resonator under input power of 200 W. The wave shifting between Tx and Rx coils is apparently reduced due to inserted resonance. That means the inserted resonance coil keeps strong coupling easily. Thus, the inserted resonator can minimize the reactive power loss at Rx coils.

Figure 9 (a) shows measured results of input voltage at Tx, rectified voltage and rectified current including rectifying circuit and load under Case I. The peak voltage of Tx coil, rectified voltage and rectified current are 432 V_{peak}, 384 V_{peak} and 0.18A_{peak}, respectively. The shifted phase angle is about 79°. Figure 9 (b) shows measured results of input voltage at Tx, rectified voltage and rectified current including rectifying circuit and load under Case II. The peak voltage of Tx coil, rectified voltage and rectified current are 491 V_{peak}, 442 V_{peak} and 0.21A_{peak}, respectively. Surely, the transferred voltage and rectified current are improved over 20 % and 15 %, respectively, due to inserted resonator as shown in Figures 9. As the inserted resonator can reduce reactive power loss at Tx and Rx coils, transfer ratio can be improved effectively even though the interval is expanded between Tx and Rx coils.
Figure 10 (a) shows measured results of rectified voltage distributions at load including input power of 100, 200, 300 W, respectively, under Case I. The peak values at input 100, 200, 300 W are 250, 332, 417 V, respectively. As well as, the wave shifting is enhanced depended on increasing input powers. On the other hand, rectifying waves are stably improved under inserted resonator without wave shifting as shown in Figure 10 (b). The peak values at input 100, 200, 300 W are 251, 349, 417 V, respectively.

Figure 8. Measured results of voltage and current distributions at Tx and Rx coils, respectively, in the input power of 200 W under the (a) Case I and (b) Case II, respectively.

Figure 9. Measured results of input voltage at Tx coil and, rectified voltage and current of load at input power of 200 W under the (a) Case I and (b) Case II, respectively.

Figure 10. Measured results of rectified voltage distributions at input power of 100, 200, 300 W respectively under the (a) Case I and (b) Case II, respectively.
Figure 11. Measured results of transfer efficiency at Rx coil with 300 W under the (a) Case I and (b) Case II of Figure 7, respectively.

Clearly, in the case of non-inserted resonator, the wave shifting is gradually enlarged under increasing input power and it causes reactive losses, which generates thermal loss at Rx and Tx coils. On the other hand, waves shifting of transferred waves can be apparently reduced under increasing input power due to inserted resonator. That means inserted Sx coil has a role to keep stable transfer power including rectifying circuit under increasing input power. Figure 11 shows the measured transfer efficiency for Cases I and II of Figure 7 with 300W of 370kHz, respectively. Surely, the transfer efficiency with Sx coil at Case II is slowly decreased depended on the increasing intervals. On the other hand, the Case I is sharply decreased depended on the increasing intervals. Based on the experimental results, it is evaluated that the tape type copper Rx coil, which is installed at the outside of cover in cooling vessel, can play a role to improve the transmission efficiency easily. Thus, the copper resonator Sx coil is one of reasonable options to improve the transmitting ratio and spread the waves widely.

4. Conclusion
We point out that this study achieved wireless power transfer technology with HTS antenna coil in order to improve the delivery efficiency of the electric power for EV using inserted resonator. The properties and relations for inserted resonator between Tx and Rx coils were successfully performed. Especially, we have shown the possibility of impedance matching method for different materials (HTS and normal conductor), sizes (tape and tube types) and environments (between room temperature and low temperature) at 370 KHz resonant frequency within 40 cm. Thus, we obtained that the improved transmitting ratio of voltage and current using inserted resonator are over 25 %. That means the inserted copper resonator, which is easily installed at the cover of cooling, is one of reasonable options to improve the transmitting ratio even for superconducting antenna conditions. However, since it is confirmed that the inserted resonator can generate heating loss at Sx as well as Rx coils, the design of cooling device for inserted Sx coil should be considered to improve transfer efficiency. The economic efficiency of cooling vessel should be investigated under structural design in the next. Our research target is to evaluate such a transfer technology to EV fast and high power charging system.

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