

## 초전도 코일을 적용한 무선전력전송 시스템 효율 향상

### Efficiency Enhancement of a Wireless Power Transmission System Applying a Superconducting Coil

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**Abstract** - Due to high oil prices, environmental pollution, the study of electric vehicles have been actively promoted. Charger for the electric vehicle is being developed using wireless rather than cable options. In this paper, we got more efficiency from using a superconducting transmission coil compared to using a normal coil. We implemented a wireless power transmission system using a magnetic induction at a frequency of 63.1 kHz. For comparison, a transmitter was designed using a superconducting coil and a normal coil. In addition, a receiver used a normal coil to apply for electric vehicles. The applied voltage and current were 12 V and 5 A. Efficiency at a distance of 40 ~ 80 mm was measured. As a result, the superconducting transmission coil had a higher efficiency than the normal transmission coil. However, the receiving coil should be normal conductor for stable operation considering that it was put in moving electric vehicle. The efficiency was increased to 44 % at a distance of 40 mm when the diameter of normal receiving coil was 120 mm.

**Key Words** : Superconductor, Magnetic Induction, Wireless Power Transmission, Normal conductor, Electric Vehicle

#### 1. Introduction

During the development of wireless communication over the last twenty years, every could make calls and surf the internet using mobile phones and IT devices anywhere. However, electronic devices used in a space, for example, home or office, still depend on cables for power supply. Power supply by means of cables limits the places in which electronic devices can be used and is unattractive. People are highly interested in studying wireless power transmission (WPT) for use as a power supply. WPT is implemented in three manners [1]. The first method is microwaves. It relies on a several GHz band to transmit high power energy to receivers, and is used for artificial satellites and for military purposes [2]. However, this method is disadvantageous in terms of harmful effects on human bodies, effects of a surrounding environment on transmission efficiency, and great dimensions of transmit-receive antennas by using high frequencies. The

second method is magnetic resonance electromagnetic waves. However, this method is in early which is being studied by an MIT research team [3]-[4]. The magnetic resonance method matches the resonant frequency in the transmitter and the receiver to transmit stages of development. The last method is magnetic induction[5]. The magnetic induction method is harmless to human bodies and is highly efficient. In addition, it is used in electric toothbrushes and smartphone chargers, as well as in electric vehicle chargers. Our research team has aimed to replace the transmission coils for wireless power transmission of the magnetic induction method by a superconductor in order to enhance efficiency. Superconductors have a property allowing them to exhibit zero resistance at very low temperature. Because of this zero resistance, superconductors can increase the magnitude of current density by at least 10 times in comparison to normal conductors. Superconductors show less ohmic loss than normal conducting coils for high frequency, and do not show magnetic saturation in a strong magnetic field. Because of these advantages, by applying the superconductor to the transmission unit, rapid charging is expected to be possible in the future. Our research team applied this to a superconducting transmission coil and compared it with the normal coil of a magnetic induction WPT system. Their efficiencies were analyzed.

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2. Detailed description

2.1 Analysis of magnetic induction-type WPT system

The WPT of the magnetic induction is a method in which a magnetic field is generated around the coil causing current to flow and transfers power by generating electricity. The WPT that our research team implemented was operated at 63.1kHz. The diameter of transmission and receiving coil was designed to be 150, 120, 100 mm, respectively. The distance between the transmission and receiving coils for power transmission was 40 ~ 80mm. Fig. 1 shows the circuit of the magnetic induction method for wireless power transmission.

Inductive voltage,  $V$ , is proportional to the value of the inductance of that conductor that occurs when a magnetic field passing through the conductor is changed as a function of time. Therefore, the voltage,  $V_R$ , induced in the receiving unit is determined by the mutual inductance  $M_{TR}$  between the inductance  $L_T$  of the coil in the transmission unit and  $L_R$  in the receiving unit  $L, L_R, L_T, M_{TR}, k$  in formulas 1, 2, and 3 are respectively the inductance, the receiving inductance, the transmitting inductance, the mutual inductance between the receiver and transmitter, and the magnetic inductive coupling coefficient between transmission coil and receiving coil. In order to increase the efficiency of a wireless power transmission, as in the above formula, the inductance  $L_R$  of the receiving unit and the magnetic inductive coupling coefficient  $k$  should be increased. To increase the mutual inductance between the coils of the transmission and receiving unit, the induced voltage should be increased. Efficiency was calculated as in formula 4.

$$V = L \frac{di}{dt} \tag{1}$$

$$v_R = L_R \frac{di_R}{dt} + M \frac{di_T}{dt} = M \frac{di_T}{dt} \mid \frac{di_R}{dt} = 0 \tag{2}$$

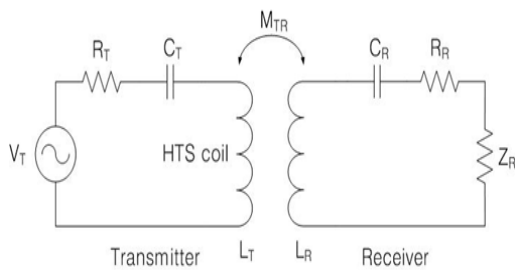


그림 1 자기유도방식 무선전력전송 시스템의 회로도  
 Fig. 1 Circuit diagram of magnetic induction-type WPT

$$M = k \sqrt{L_T L_R} \tag{3}$$

$$\eta = \frac{P_o}{P_i} \times 100[\%] = \frac{V_o \times I_o}{V_i \times I_i} \times 100[\%] \tag{4}$$

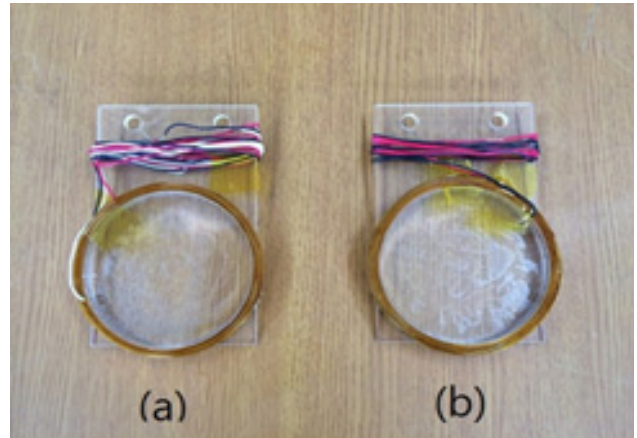


그림 2 송신코일 및 수신코일(a) 초전도 코일 (b) 상전도 코일  
 Fig. 2 Transmission and receiving coil (a) superconducting coil (b) normal conducting coil

2.2 Design of transmission and receiving coil

To increase the efficiency of the wireless power transmission, resistance became zero at cryogenic temperature in superconductor which used in a transmission coil. In order to use in an electric vehicle for the future, a receiving coil was designed by a normal coil because the moving electric vehicle didn't have a cryogenic bath or cooler for the stable operation. For the miniaturization of the system, the spiral winding method was selected. As shown in Fig. 2, coils were fabricated by winding superconducting and normal coils with an inner diameter of 150, 120, 100 mm, respectively. The turn number was 18-turn winding in each coil.

2.3 Test result

For comparison and analysis, the transmission and receiving coils were designed as a superconductor and normal conductor. For the test, liquid nitrogen was put in a container manufactured to keep the superconductivity at a very low temperature. In addition, when applied to wireless charging in an electric vehicle, the efficiency corresponding to the change in size of the receiving coil was analyzed. Fig. 3 is a graph of WPT efficiency by changes of the conductor. Tx means transmission unit and Rx is receiving unit. The diameter of transmission and receiving coils was fixed to be 100 mm.

Transmission efficiency of wireless power transmission

was 10% in the distance of 40 mm and it was very low, when transmission and receiving coils were normal conductor.

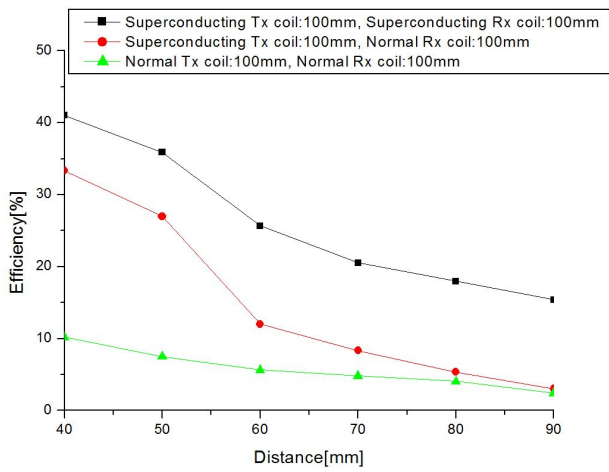


그림 2 전도체 변화에 의한 무선전력전송의 전송 효율  
 Fig. 2 Transmission efficiency of WPT coils by changes of the conductor

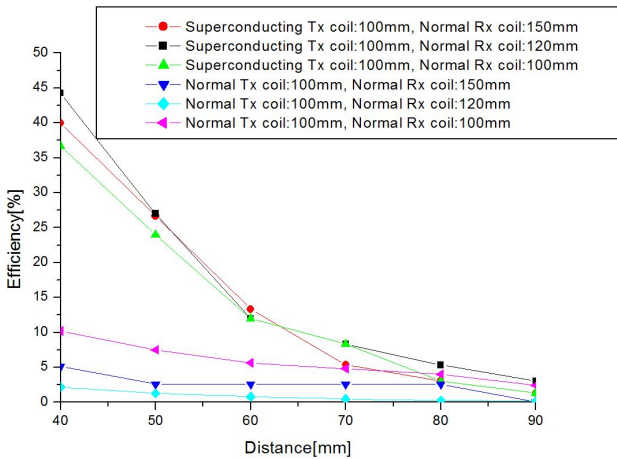


그림 3 수신코일의 직경에 따른 무선전력전송의 전송 효율  
 Fig. 3 Transmission efficiency of WPT by change in the winding diameter of the receiving coil

When we changed the transmission coil into a superconductor, its efficiency was increased to 33 % under the same condition. Finally, its efficiency showed 42 % as transmission and receiving coils were all changed into the superconducting unit. We considered that it was because magnetic inductive coupling coefficient  $k$  was increased by high magnetic flux generated from high current density of the superconductor. However, the efficiency was exponentially lowered after the distance of 40 mm. In

general, mutual inductance of above formula (3) is reduced exponentially according to the distance between transmission and receiving coils. We found that this was directly related to the efficiency. So, magnetic inductive coupling coefficient  $k$  was increased by high current density of a superconductor. In case that both transmission and receiving coils were a superconductor, the efficiency was maximized. However, when considering that the WPT system of our research team will be applied to electric vehicle, we chose transmission coil of a superconductor and receiving coil of a normal conductor.

Fig. 4 shows the efficiency of wireless power transmission according to the change in the winding diameter of the receiving coil. When diameter of the normal receiving coil was 120 mm under the condition of same superconducting transmission coil, the efficiency was 44 % at the distance of 40 mm between transmission and receiving coils. Trend of efficiency was reduced exponentially after the distance of 40 mm. This is related to the reduction of mutual inductance and magnetic flux linked between transmission and receiving coils. Deviation of efficiency by diameter of a receiving coil became decreased according to increase of applied distance. In addition, when transmission and receiving coils were normal conductor, the efficiency was less than 10 % but it was relatively high in case of same size at the diameter of transmission and receiving units.

### 3. Conclusion

In this study, a superconducting coil was used in the transmission unit to enhance the efficiency of magnetic induction-type wireless power transmission. When a superconducting coil was applied to the transmission unit, efficiency of wireless power transmission was very high as 40% at the distance of 40 mm between transmission and receiving coils. The efficiency was exponentially lowered when distance increased. This is directly related to the mutual inductance and magnetic flux linked between transmission and receiving coils. In case of superconducting coil, mutual inductance and magnetic flux is relatively high because of its high current density. When we applied normal receiving coil with a diameter of 120 mm in the transmission coil of 100 mm, its efficiency was enhanced. It was thought that magnetic inductive coupling coefficient  $k$  was increased by linkage of generated flux. Our research team will overcome the shortcomings of the magnetic induction system such as mismatch of coil array and dependency of transmission distance by applying various

superconducting transmission coils in future studies.

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