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Analysis of the Superconducting Wireless Power Transmission System Characteristics according to the Number of Turns of the Coil

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Abstract – Studies have been actively conducted on the magnetic-resonance wireless power transmission (WPT) for commercialization. Such studies are essential for improving the transmission efficiency. In the magnetic-resonance WPT, the inductance (L) and capacitance (C) vary significantly depending on the design of the coils, and the efficiency sharply changes accordingly. To address this problem, studies on the coil design are required. In this study, the S-parameter characteristics according to the number of turns of the coil were analyzed to improve the efficiency of the superconducting WPT. Superconducting coils were designed, and the reflection coefficient (S_{11}) according to the turns was analyzed. It was confirmed that the power transmission characteristics were improved as the reactance approached 0 Ω

Key Words : Renosnace, Superconductor, S-paramter, S_{11}

1. Introduction

The wireless power transmission (WPT) technology is the most desired technology these days, when convenience and practicality are actively pursued. The need for the WPT technology has been boosted by the advancement and distribution of various electronic devices, such as smartphones, tablet PCs, and laptops, in particular. The WPT technology has been researched on more actively ever since the research team led by Professor Marine Soljacic at MIT in the United States proposed the magnetic-resonance WPT technology in 2007. This technology transmits power using the resonance of the transmitter and receiver coils. The technology is not harmful to the human body and enables multiple charging, long-distance transmission, and high positional freedom between the transmitter and receiver coils. Depending on the coil design, however, the inductance (L) and capacitance (C) vary significantly, which may cause the efficiency to change sharply. To address this problem, studies on the coil design are necessary.

The purpose of this study was to analyze the reactance of a WPT system by measuring its inductance and capacitance according to the number of turns of the coil, and to design coils with high efficiency by analyzing the correlation between the reactance value and the S-parameter characteristics.

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2. Theory

2.1 Resonance

For the magnetic-resonance WPT, the inductance and capacitance are very important elements. Inductance is the inductive capacity and represents the ratio of the counter electromotive force generated due to the electromagnetic induction caused by the current change in a circuit. Capacitance is the electrostatic capacity and represents the ratio of the quantity of electric charge accumulated when a voltage is applied.

When a frequency is applied to an LC circuit, the inductance and capacitance repeat the processes of accumulating and releasing energy in the electric and magnetic fields. During these processes, a certain frequency is selectively blocked or passed. This phenomenon is called "resonance," and the frequency at which resonance occurs is called

"resonance frequency" (F_r), which can be calculated using equation (1). As shown in equation (1), the resonance frequency is determined by the inductance and capacitance.

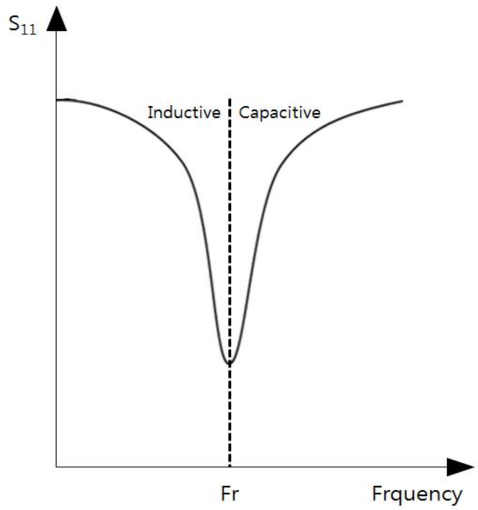

Fig. 1. Correlation between inductance and capacitance

$$The\,resonance\,frequency = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

If the inductance or capacitance has a higher force than the other during resonance, energy is deflected, and loss occurs. When they have the same force, force equilibrium is achieved, and no loss occurs. In other words, when the reactance, which is the imaginary part of the impedance, is zero, the inductance and capacitance reach force equilibrium, resulting in no loss. The impedance of a WPT system can be calculated using equation (2). The impedance is determined by the resistance of the coil (R), the reactance of the inductor (X_L), and the reactance of the capacitor (X_C).

$$Z(\Omega) = R+X = R+X_L+\frac{1}{X_C} = R+j\omega L+\frac{1}{j\omega C} \tag{2}$$

Fig. 1 shows the correlation between inductance and capacitance. When the inductance and capacitance exhibit the same magnitude, selective characteristics occur in a certain interval, resulting in the best S-parameter characteristics.

2.2 Inductance of a helical coil

Inductance is a very important element for magnetic-resonance WPT. It varies according to the coil winding method used, as shown in equation (3).

Fig. 2 shows the parameters of a helical coil. D denotes the coil diameter, H the coil height, p the coil pitch, and N the number of turns of the coil [1-3].

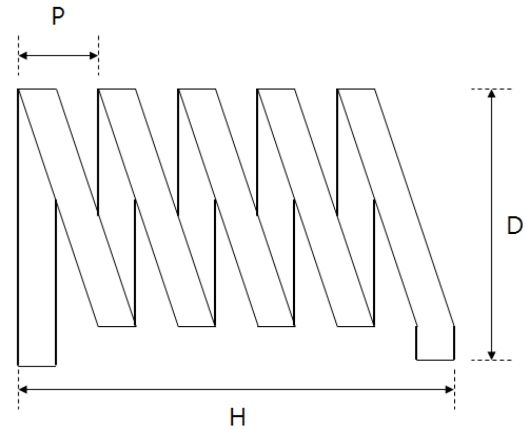

Fig. 2. Parameters of a helical coil.

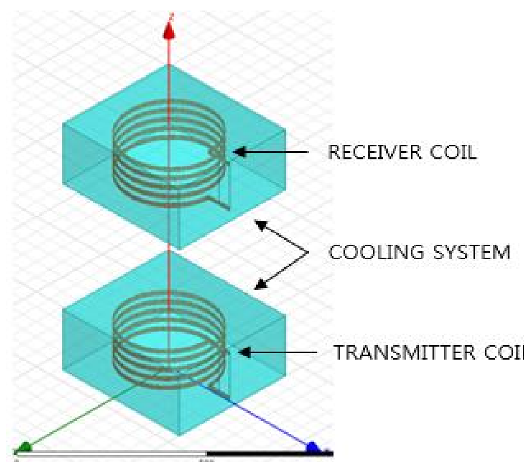

Fig. 3. Modeling of the transmitter and receiver coils.

$$L(\mu H) = \frac{D^2N^2}{0.45D+H} \tag{3}$$

3. SIMULATION DESIGN AND ANALYSIS

3.1 Experimental design

6.78 MHz was selected as the resonance frequency. A superconductor was used as the material of the coils. Table 1 shows the coil design parameters. The diameter and pitch were fixed at 300 and 22.5 mm, respectively, and the reflection coefficient (S_{11}) was measured while the number of turns was increased by one turn, from two to nine turns. The transmitter and receiver coils were designed in the same way because they have the same resonance frequencies when their shapes and dimensions are identical [4-5].

Table 1 Parameters of the superconducting coils

N (turn)	2	3	4	5	6	7	8	9
H (mm)	45	67.5	90	113	135	158	180	203
D (mm)	300							
p (mm)	22.5							
Fr (MHz)	6.78							

3.2 Simulation results

Based on the design values in Table 1, each inductance value was calculated using equation (3). The calculated inductance value was substituted into equation (1) to obtain the capacitance value for resonance at 6.78 MHz.

Modeling was performed, as shown in Fig. 3, using the High-Frequency Structure Simulator (HFSS) software based on the design values in Table 1, and each inductance value was measured. Fig. 4 shows each inductance value measured using HFSS.

Table 2 compares the calculated and measured inductance values. It was confirmed that a slight difference of 0.02 μH on average occurred.

Table 2 Inductance and capacitance by the number of turns

N (turn)	L (μH) by HFSS	L (μH) by calculation	C (pF)
2	2	1.97	279.7
3	3.96	3.94	140
4	6.31	6.3	87.5
5	8.95	8.95	61.6
6	11.8	11.81	46.7
7	14.85	14.84	37.1
8	18	18	30.6
9	21.26	21.26	25.9

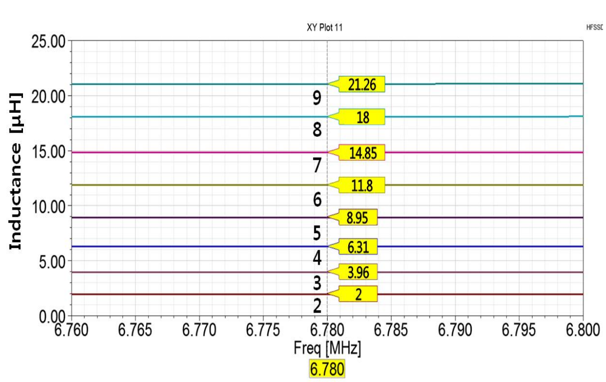

Fig. 4. Inductance according to the number of turns of the coil determined using HFSS

Table 3 Reactance of the resonance coil by the number of turns

N (turn)	$X_L(\Omega)$	$X_C(\Omega)$	X (Ω)
2	85.16	83.97	1.19
3	168.61	167.76	0.85
4	268.67	268.41	0.26
5	381.08	381.27	-0.19
6	502.43	502.92	-0.49
7	632.29	633.05	-0.76
8	766.41	767.52	-1.11
9	905.22	906.8	-1.58

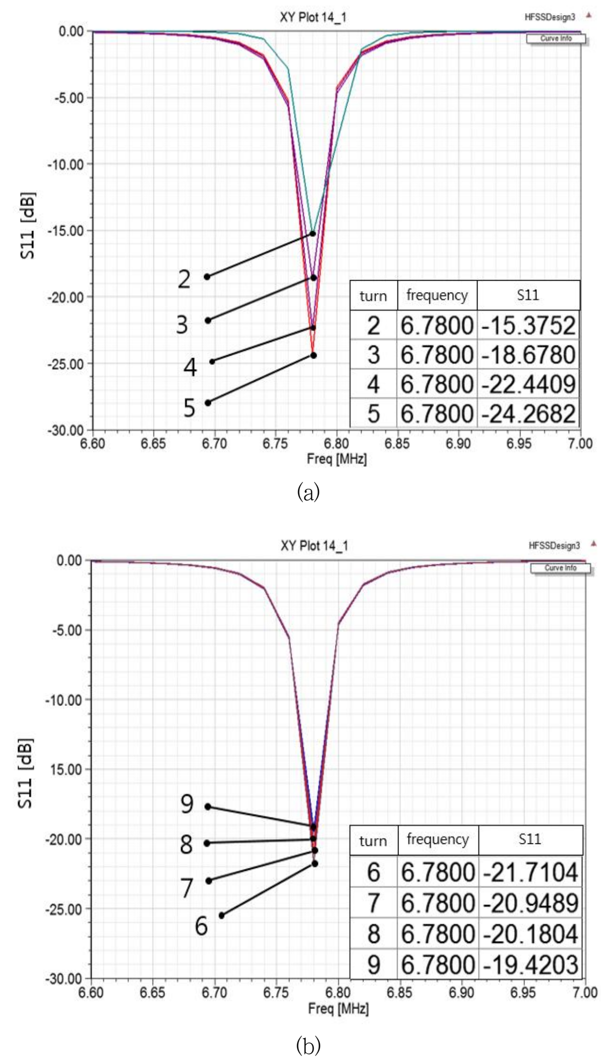

Fig. 5. S_{11} according to the number of turns of the coil: (a) 2-5 turns; and (b) 6-9 turns.

WPT systems can transmit power without any loss when the reactance is 0 Ω. The 0 Ω reactance can be achieved if the number of turns is determined considering the detailed units when the coils are designed. As the commonly used number of turns was selected, however, the reactance was close to 0 Ω.

The reactance of the WPT system was calculated by substituting the inductance values measured and the capacitance values in Table 2 into equation (2). The reactance values for two to nine turns were 1.19, 0.85, 0.26, -0.19, -0.49, -0.76, -1.11, and -1.58 Ω. The reactance value of -0.19 Ω at five turns was the closest to 0 Ω.

Based on the WPT system designed above, S_{11} was measured according to the number of turns of the coil. Fig. 5(a) is the S_{11} graph for two to five turns. Resonance occurred at 6.78 MHz, and the values of S_{11} were -15.37, -18.67, -22.44, and −24.26 dB. Fig. 5(b) is the S_{11} graph for six to nine turns. Likewise, resonance occurred at 6.78 MHz, and the values of S_{11} were -21.71, -20.94, -20.18, and -19.42 dB. S_{11} decreased for two to five turns and increased from six turns. At five turns, when the reactance was closest to 0 Ω, S_{11} also exhibited the best characteristic value of −24.26 dB.

4. Conclusion

In this study, superconducting wireless power transmission (WPT) coils were designed using the High-Frequency Structure Simulator (HFSS) software. For the coil design, the coil diameter, coil height, coil pitch p, and distance between the coils were fixed, and S_{11} was analyzed according to the number of turns of the coil. At five turns, when the reactance (-0.19 Ω) was closest to 0 Ω, S_{11} exhibited the best power transmission characteristic value of −24.26 dB.

The magnetic-resonance WPT technology can be commercialized if the efficiency problem is addressed. If the efficiency can be maximized through the optimal design proposed in this study, the magnetic-resonance WPT technology can be commercialized earlier and applied to various areas.

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