ISSN: 0974-5823 Vol. 6 No. 3 October-December, 2021

International Journal of Mechanical Engineering

Analysis of Wireless Power Transfer characteristics based on the use of a superconducting wire with a round edge

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Abstract

Background/Objectives: Recently, as research on electric vehicles is progressing, battery performance is improving. Accordingly, it is necessary to improve the wireless charging system and charging technology in consideration of human convenience.
Methods/Statistical analysis: Maxwell is a software that uses the finite element method (FEM) and is capable of low-frequency electromagnetic field simulation and multi-physical analysis. By leveraging advanced electromagnetic solvers and linking them with integrated circuit and system simulation techniques, the performance of physical prototypes can be predicted. Also, in the case of the HFSS program, it is used for simulation analysis of WPT through the analysis of electromagnetic field characteristics in the MHz frequency band. For this study, the Maxwell program was used for the electromagnetic field characteristics, and the HFSS program was used to analyze the power transmission characteristics of WPT.
Findings: For the analysis of material properties of superconductors, the electromagnetic field properties were analyzed using Maxwell and HFSS programs. For the comparative analysis of the two materials, a wire length of 1.5 m was applied, and it can be seen that the current density and magnetic field strength of the superconductor are high by a difference of about 58.45 times. For the material characterization of superconductors, the electromagnetic field characteristics were analyzed. Copper was applied to the comparison target, and as a result of the analysis, it was confirmed that the magnetic field strength was about 58.45 times higher. In addition, powerless transmission by superconductors affects the frequency selective characteristic called quality factor Q. Unlike copper, superconductors have a high Q-factor of about 10^4-10^5.
Improvements/Applications: As a result, the square helical resonant coil exhibited approximately 4% higher efficiency than the round helical resonant coil with the same diameter and length.

Keywords: Resonance coil, Resonance frequency, square helical, round helical, S-parameter, Efficiency

1. Introduction

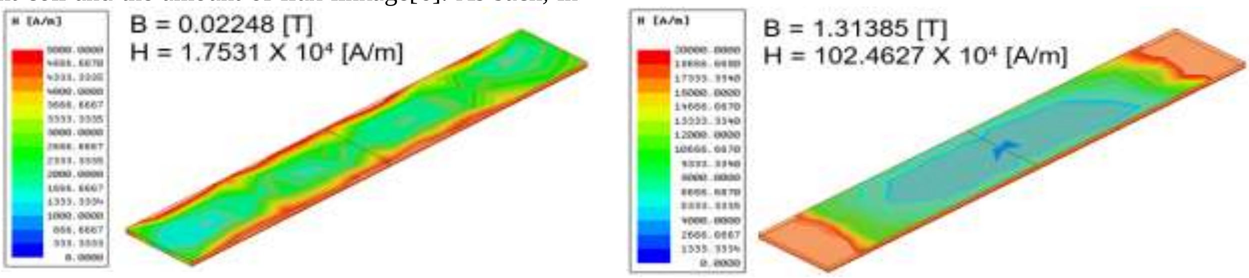
Electric vehicles are currently attracting attention for the resolution of fossil fuel depletion and other environmental problems. The improvement of the distance that can be driven during one full charge, such as charging while driving an electric vehicle, securing battery performance, and improving charging speed, is mainly studied. The charging system is applied not only to conventional wired charging, but also to wireless charging in pursuit of convenience. The wired charging system accounts for the highest proportion of the current charging methods due to its simple structure and high power transfer efficiency, but it has the problems of disconnection and terminal breakage. On the other hand, the wireless charging system uses a wireless charging panel rather than a direct connection with a plug, so that damage to terminals and disconnections is relatively small. In addition, multiple units can be charged multiple times from one transmission coil, and user convenience can be maximized through wireless charging using space. Such a wireless charging system has a magnetic induction method and a magnetic resonance method. In the case of the magnetic induction method, power is transmitted by contacting the transmitting coil and the receiving coil within a few mm. This method does not require resonance, and when power is applied to the transmitting coil, power is transferred to the receiving coil through magnetic induction, which has the advantage of high efficiency. The magnetic resonance wireless charging method has the advantage of being able to charge from a distance, but has the disadvantage of low efficiency. For this reason, research and demonstration of resonance-type wireless charging systems are being conducted in various fields to increase the efficiency while increasing the distance[1,2].

To realize high power transfer efficiency for the wireless charging system, the magnetic resonance method has been applied[3-5]. This method enables high-efficiency power transfer by matching the resonance frequencies of the transmitter and receiver coils. The power transfer efficiency of the wireless power transfer (WPT) system with the magnetic resonance method is determined by the shape of the resonant coil and the amount of flux linkage[6]. As such, in this study, the use of a square helical resonant coil was proposed to increase the amount of flux linkage of the resonant coil and to ensure a constant magnetic field distribution. A WPT system with AirFuel Alliance-certified 6.78 MHz-resonance-frequency square helical resonant coils was constructed using a High-Frequency Structure Simulator (HFSS), and it was compared with the wireless charging system with the existing round helical resonant coils[7]. Moreover, to examine the effect of the inductance change due to the coil length on the power transfer efficiency, the constructed system was compared with the wireless charging system with round helical resonant coils of the same length.

2. Main Body

2.1. *Superconductor material properties*

For the analysis of material properties of superconductors, the electromagnetic field properties were analyzed using Maxwell and HFSS programs. Table 1 shows the parameters in which material properties are input to implement a superconductor in the simulation. In Fig. 1 (a) and (b), the electromagnetic field characteristics of copper and superconductor can be confirmed, respectively, and the average is calculated through equation (1). For the comparative analysis of the two materials, a wire length of 1.5 m was applied, and it can be seen that the current density and magnetic field strength of the superconductor are high by a difference of about 58.45 times.



(a) Electromagnetic properties of copper wire rods **(b)** Electromagnetic properties of superconducting wire

Figure 1. Electromagnetic properties of wire rods according to material

$$\frac{integrate}{integrate(Surface(WireRod,)\ 1)} \qquad (1)$$

Table 1: Copper and superconducting material properties parameters

Name	Copper		Superconductor	
	Value	Units	Value	Units
Relative permittivity	1	-	1	-
Relative permeability	0.999991	-	1.135523	-
Bulk conductivity	58,000,000	siemens/m	825,000,000,000	siemens/m
Magnitude	0	A_per_meter	-876	kA_per_meter
Young's modulus	120,000,000,000	N/m^2	147,000,000,000	N/m^2
Poisson's ratio	0	-	0	-
Magnetic Saturation	0	tesla	0	tesla
Lande G Factor	2	-	2	-
Delta H	0	A_per_meter	0	A_per_meter
Thermal conductivity	0	W/m・C	0	W/m・C

2.2. *WPT resonance frequency*

in the magnetic resonance method

WPT using the magnetic resonance method transfers power at a specific frequency. This frequency is referred to as resonance frequency, which is determined by the electromagnetic energy accumulation and emission of the inductor and the capacitor, as shown in equation (1). The resonance circuit can be designed largely through the series and parallel resonance methods. In the case of series resonance, a specific frequency band is passed. In the case of parallel resonance, on the other hand, a specific frequency is blocked. Series resonance is used for WPT to transfer the resonance frequency band. The impedance of the series resonance circuit is defined as shown in equation (2). In this instance, the point at which the imaginary numbers impedance becomes zero is the resonance frequency, which is defined as shown in equations (3) and (4).

$$Z = R + jX = R + j\omega L + \frac{1}{j\omega C} \tag{2}$$

$$X = \omega L - \frac{1}{\omega C} = 2\pi f L - \frac{1}{2\pi f C} = 0 \tag{3}$$

$$\text{Resonance frequency} = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

2.3. *Quality factor of wireless power transmission using superconductors*

As for the quality factor, Q means signal selectivity at a specific frequency. As the value of this quality factor increases, the bandwidth of the resonant frequency becomes narrower. Unlike copper, superconductors have a high Q-factor, and a coefficient of about 10^4 to 10^5 can be obtained[8,9]. Therefore, as shown in equation (5), the larger the Q-factor value, the higher the resonance frequency characteristic and the higher the power transmission efficiency.

$$Q = \frac{f}{\Delta f} = \frac{\omega L}{R} = \frac{2\pi f L}{R} \tag{5}$$

2.4. *Inductance of the resonant coil*

Fig. 2 shows the structure of the helical resonant coil. The inductance of such coil is determined by the coil's diameter (D) and height (H) as well as by the number of turns (N), as shown in equation (6)[10]. The inductance of the helical resonant coil due to its structure affects the resonance frequency and efficiency of WPT. In addition, as the inductance increases, the mutual inductance (M) also increases, as shown in equations (7) and (8). This increases the degree of coupling (k) of WPT. The efficiency of wireless power transmission is determined by the coupling coefficient, which is the degree of mutual coupling, and the mutual inductance. When the length of one side of a square helical is called'A' and the radius of a round helical is called'B', the square helical is as wide as $a^2 - \pi r^2$, and the flux linkage increases. Therefore, the mutual coupling becomes higher than that of the round helical.

$$L[nH] = \frac{D^2 \times N^2}{0.45D + H} \tag{6}$$

$$L = \frac{d\phi}{di} \tag{7}$$

$$M = k\sqrt{L_1 L_2} = \frac{\phi}{I} = \frac{BS}{I} \tag{8}$$

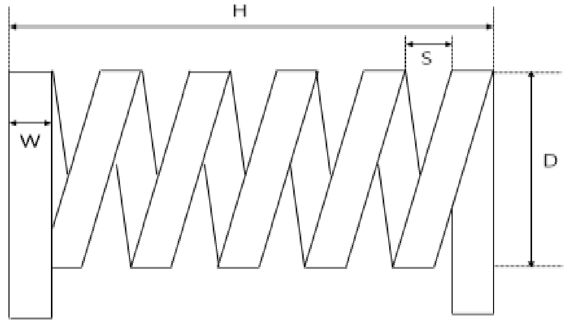
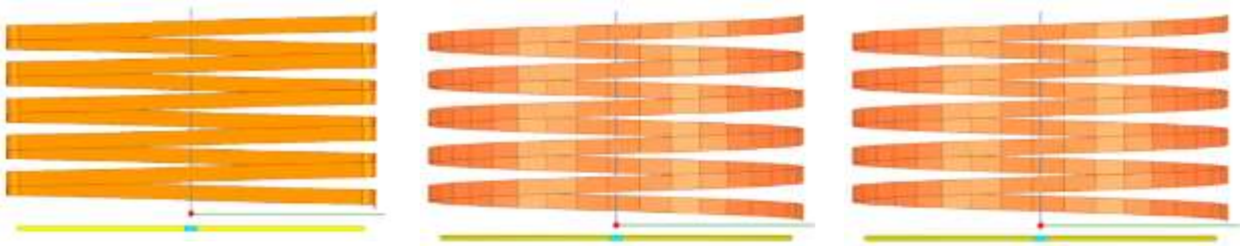


Figure 2. Inductance of the helical resonance coil

2.5. *Resonant coil design using HFSS / Maxwell*

Fig. 3 shows the 3D modeling of the WPT resonant coil, and Table 2 shows the design parameters of cases 1, 2, and 3. The resonant coils were designed based on cases 1, 2, and 3. Case 1 represents a square helical resonant coil. A 10mm round helical resonant coil was applied to reduce the concentration of the electric field on the vertex. Case 2 represents a round helical resonant coil. To compare the efficiencies of WPT by the cross-sectional area of the resonant coil, all the conditions except for the cross-sectional area were designed to be the same. Finally, case 3 represents a round helical resonant coil with the same length as the square helical resonant coil. This is to compare the transfer efficiencies when the total lengths of the square and round helical resonant coils are the same. For electric vehicles, the average height of the bottom of the car body from the ground ranges from 220 to 250 mm. Therefore, the distance between the transmitter and receiver coils was set to 250 mm in this study. The inductances of the designed resonant coils were measured using simulation software. To generate resonance at 6.78 MHz according to the measured inductances, capacitances were applied, as shown in Table 3.



(a) Square helical coil with 5550 mm length and 5 turns

(b) Round helical coil with 4732.38 mm length and 5 turns

(c) Square helical coil with 5980.02 mm length and 6.3 turns

Figure 3. Coil modeling of cases 1, 2, and 3

Table 2: Design parameters for each coil shape

Category	CASE 1	CASE 2	CASE 3
Shape	Square	Round	Round
Number of turns	5	5	6.3
Pitch (P)	30 mm	30 mm	30 mm
Width (W)	12 mm	12 mm	12 mm
Thickness (T)	1 mm	1 mm	1 mm
Coil height (H)	163 mm	163 mm	201 mm
Diameter and length (D)	300 mm	300 mm	300 mm
Total coil length (L)	5980.02 mm	4732.38 mm	5980.02 mm

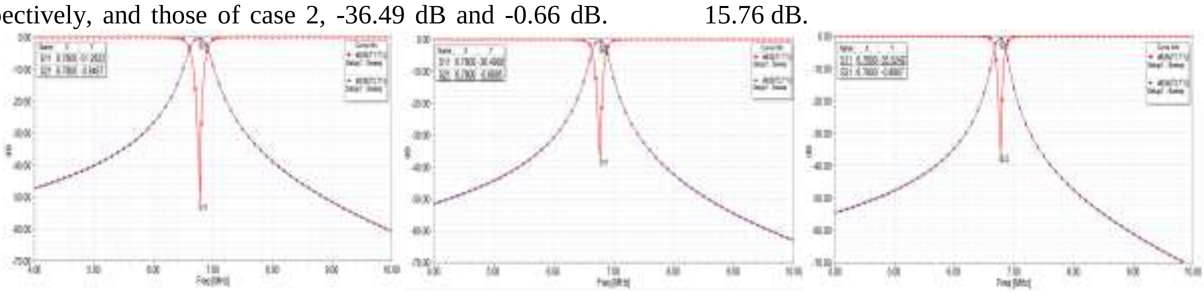
Table 3: Inductance and capacitance for each case

Category	CASE 1	CASE 2	CASE 3
Shape	Square	Round	Round
Number of turns	5	5	6.3
Inductance	9.94 μH	8.17 μH	11.34 μH
Capacitance	55.44 pF	67.45 pF	48.59 pF

3. Simulation analysis

3.1. *S - parameters of resonance coil*

Fig. 4 shows the S-parameters of cases 1, 2, and 3. S11 represents the reflection coefficient, and S21, the transfer coefficient. As a results of cases 1, 2, and 3. The S11 and S21 of case 1 were found to be -51.28 dB and -0.64 dB, respectively, and those of case 2, -36.49 dB and -0.66 dB. Finally, case 3 exhibited -35.52 dB for S11 and -0.88 dB for S21. The efficiency of WPT increases as the reflection coefficient decreases and as the transfer coefficient becomes closer to 0. As a result of S-parameter analysis, it can be seen that case 1 had the closest transmission coefficient to 0 with a difference of -0.02 dB to 0.22 dB. and the reflection coefficient was the lowest with a difference of -14.49 dB to -15.76 dB.

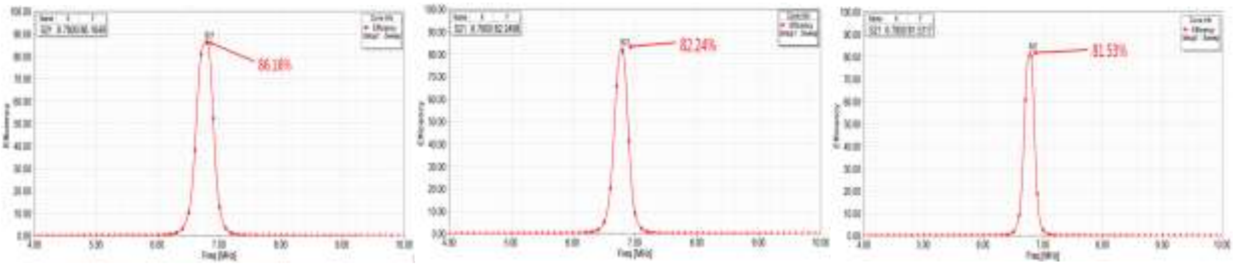


(a) 5980.02 mm, 5 turns square coil S-parameter **(b)** 4732.38 mm, 5 turns round coil S-parameter **(c)** 5908.02 mm, 6.3 turns round coil S-parameter

Figure 4. S-parameters of cases 1, 2, and 3

3.2. *Efficiency of resonance coil*

Fig. 5 shows the efficiencies of cases 1, 2, and 3. As mentioned above, M, which is the degree of mutual coupling between coils, affects the efficiency by equations (6) to (8). To improve this coupling, the flux linkage can be affected by changing the shape of the coil. The S-parameter is expressed using the coupling properties of the designed coils in the simulation program, and the efficiency of power transfer between the coils can be calculated as shown in equation (9) using this. The efficiencies of cases 1, 2, and 3 were measured to be 86.16%, 82.24%, and 81.53%, respectively. comparing case 1 and case 2, the difference between S21/S11 is -0.02 dB/-14.79 dB, showing an efficiency difference of about 3.92%. when case 1 and case 3 are compared, it can be seen that the difference between S21/S11 is about 4.63% due to -0.22 dB/-15.76 dB.



(a) 5980.02 mm, 5 turns square coil S-parameter **(b)** 4732.38 mm, 5 turns round coil S-parameter **(c)** 5908.02 mm, 6.3 turns round coil S-parameter

Figure 5. Efficiencies of cases 1, 2, and 3

$$(\mathrm{mag}(S(T_2, T_1)))^2 \times 100 \quad (9)$$

3.3. *Magnetic field distribution of resonance coil*

Table 4 shows the magnetic field distributions of cases 1 and 2. Case 3 was excluded because it exhibited the lowest efficiency due to the increase in the number of turns. For case 1, the magnetic field value was approximately 0.62 A/m at the center and approximately 0.5 and 0.89 A/m at the ends of the coil, respectively. For case 2, on the other hand, the magnetic field value was approximately 0.76 A/m at the center, but it decreased to approximately 0.1 A/m at both ends. Moreover, the average intensity of the magnetic flux was 0.65 A/m for case 1 and 0.41 A/m for case 2. Therefore, the difference in cross-sectional area between cases 1 and 2 caused a difference in magnetic flux distribution. It also affected the average intensity of the magnetic flux. Finally, the currents of the resonant coils were obtained through the integration of Fig. 5. In addition, the results were divided by cross-sectional area to obtain the current densities of the resonant coils. The analysis results revealed that case 1 had an approximately 0.093 A higher current and a 0.723 A/m2 higher current density than case 2.

Table 4: Currents and current densities of the WPT resonance coils

Category	Shape	Current $[A]$	Current density $[A/m^2]$
Case 1	Square	0.195	2.166
Case 2	Round	0.102	1.443

4. Conclusion

In this study, to maximize the efficiency of WPT (Wireless Power Transfer), the use of a spiral resonant coil close to a square was proposed and analyzed. In the case of a rectangular coil, a round was applied because current concentration occurred at the vertices and the power transmission was not performed smoothly. As a result of the simulation, it can be confirmed that increasing the inductance of the coil, increasing the number of coil turns, and increasing the coil height in order to increase the degree of mutual coupling between the coils is ineffective in increasing the efficiency. As in case 1, it is possible to maximize the efficiency by applying a round that is close to a square, suppressing the current concentration phenomenon, and increasing the cross-sectional area to increase the flux linkage. Currently, the charging system using a wireless coil is a 'coil-to-coil' transmission method, but further research on wireless power transmission is needed for research and demonstration of a 3D wireless power system that utilizes space rather than a charging panel. In the case of this paper using superconductors, it is thought that it will be used as data to solve the problem of maximizing efficiency in the future.

5. Acknowledgment

This research was financially supported by the Ministry of Trade, Industry and Energy(MOTIE) and Korea Institute for Advancement of Technology(KIAT) through the National Innovation Cluster R&D program (P0015286)

6. References

1. Elnait KEI, Huang L, Tan L, Wang S, Wu X. Resonant Reactive Current Shield Design in WPT Systems for Charging EVs. IEEE PES Asia-Pacific Power and Energy Engineering Conference(APPEEC). 2018 Dec:56-59. DOI:10.1109/APPEEC.2018.8566600.
2. Cheng Y, Tsunekawa K. Analysis and performance improvement of independent electric coupled resonance WPT system with impedance transformer. IEEE Wireless Power Transfer Conference(WPT). 2014 May;98(4):239-42. DOI:10.1109/WPT.2014.6839571.
3. Campi T, Cruciani S, Santis VD, Maradei F and Feliziani M. Numerical Analysis Applying the AMSL Method to Predict the Magnetic Field in an EV with a WPT System. IEEE Wireless Power Transfer Conference(WPTC). 2019 Feb. DOI:10.1109/WPT.2018.8639279.
4. Jeong IS, Choi HW, Choi HS and Chung DC. Analysis of S-Parameter Using Different Materials for the WPT Resonance Coil. IEEE Transactions on Applied Superconductivityin. 2018 Apr;28(3):65-72. DOI:10.1109/TASC.2018.2801299.
5. P N, Choi HS, Jeong IS, Choi HY. Analysis of Efficiency Characteristics of Superconducting Coil-Applied Wireless Power Transmission Systems by Transmission Distance. 16th International Superconductive Electronics Conference (ISEC). 2018 Mar.

DOI:10.1109/ISEC.2017.8314220.

6. Cho JH, Sun JD, Kim HG, Fan J, Lu Y and Pan S. Coil design for 100 KHz and 6.78 MHz WPT system :Litz and solid wires and winding methods. IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity(EMCSI). 2017 Oct. DOI:10.1109/ISEMC.2017.8077977.

7. Ahn DJ, Park JW and Mercier PP. A 200-kHz/6.78-MHz wireless power transmitter featuring concurrent dual-band operation. International SoC Design Conference (ISOCC). 2016 Oct. DOI:10.1109/ISOCC.2016.7799763.

8. Karalis A, Joannopoulos JD, Soljacic M. Efficient wireless non-radiative mid-range energy transfer. 2008 Jan;323(1):34-48.

9. Gu HS, Choi HS. Analysis of Wireless Power Transmission Characteristics for High-Efficiency Resonant Coils. IEEE Transactions on Applied Superconductivity. 2020 Jun;30(4). DOI:10.1109/TASC.2020.2966424.

10. Jang JY, Hur J and Kim YN. Novel Mutual Inductance Formula for the Magnetic Resonance Wireless Power Transmission System Using Helical Coil. KIEES, 2012 Jun;23(6):669-81. DOI:10.5515/KJKIEES.2012.23.6.669.