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초전도 코일을 적용한 무선 충전시스템 특성

Characteristics of Variable Wireless Charging System Applying Superconducting Coils

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(In-Sung Jeong · Hyo-Sang Choi)

Abstract – Interest in wireless power transfer (WPT) has been growing recently due to the rapid increase in the use of electronic devices. Wireless charging systems are currently being applied to mobile phones and many studies are being conducted to apply wireless charging systems to various devices. The current wireless charging systems are capable of 1:1 charging. For wireless charging, when the devices with the same resonance frequency are present in the vicinity, the charging efficiency may be significantly lowered due to frequency interference or the wireless charging systems may stop operating. In this paper, variable capacitors were applied to a superconducting WPT system to solve the frequency interference among multiple devices with the same frequency. When a wireless charging system was performing 1:1 operation, the frequency of the other devices was varied using variable capacitors. As a result, it was confirmed that the highly efficient WPT is possible without frequency interference even when multiple receivers are present.

Key Words : Wireless Power Transfer (WPT); Superconducting coil, Resonance frequency, Selectivity of frequency

1. Introduction

The interest in electric vehicles (EVs) has been increasing rapidly due to the impending exhaustion of fossil fuels and the environmental pollution caused by toxic emissions. As EVs are driven by electric motors, they do not need fossil fuel, which can also solve the problem of gas emissions. Therefore, the use of EVs is recommended worldwide. To succeed in commercializing EVs, however, the issue concerning the battery and charging method should first be solved. EVs can currently travel up to 300 km with a single battery charge, but EVs cannot be commercialized unless and until the issue concerning the battery charging system is addressed. The present EVs depend on the wired charging method, but insufficient charging stations have been installed due to the inconvenience associated with the use of cables, the potential electric shock hazards, and the restrictions involved in the installation of charging stations. The desire to address these concerns has increased the interest in the wireless charging method. As such method does not directly use cables, it can address the issues of charging inconvenience and electric shock hazards. The problem of space limitation can be solved as well because such charging system can be installed and used in public parking lots. A high-efficiency wireless charging system (WCS) using superconducting coils was proposed. As superconducting coils have zero resistance at a critical temperature, they can increase the overall charging efficiency of the WCS by minimizing the loss caused by the conventional coils used in the general WCS[1-5]. This highly efficient superconducting WCS was applied to EV. The same resonance frequency produced by Tx and Rx coils was applied to the ground and the EV respectively. At this point, depending on the type of EV, the level of elevation of vehicles is different. In this case, the mutual inductance changes between the Tx and Rx coils. The resonance frequency is determined by the inductance (L) and capacitor (C). Interchanges between the Tx and Rx coil will alter the value of the L and the resonance frequency. When the impedance miss matching occurs to the electric device, wireless power transmission efficiency is drastically reduced.

In this paper, the variable capacitor was applied to the wireless charging system to address these problems. The variation of inductance and the mutual inductance was analyzed according to distance between the coils and EV. To maintain constant resonance frequency, C value was varied according to variation of L value. With these results, the characteristics of superconducting wireless power transfer were analyzed

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2. Theory

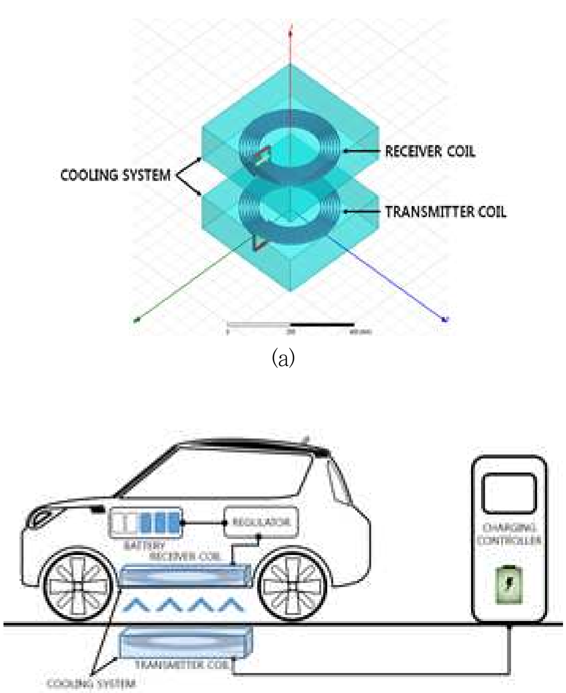
2.1 Resonance frequency

When two objects share the same frequency, energy is transferred between them. This frequency is called “resonance frequency.” The transmitter and receiver coils of WCS should be designed to share the same frequency to facilitate energy exchanges. Therefore, the resonance frequency is the key to wireless charging. Equ. (1) represents the resonance frequency. Such frequency consists of the inductance (L) and capacitance (C). The values of L and C can be adjusted to create selectivity at specific frequencies [5].

$$Wireless\,charging\,frequency = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

2.2 Experiment design

Fig. 1 (a) shows a WCS that adopted high-frequency structure simulation (HFSS). Fig 1 (b) represents a superconducting wireless filled system on EV vehicles. The Tx coil was applied to the ground and the Rx coil was applied to the underside of the vehicle. The spiral type coil was applied for downsize the volume to place in the underside of the vehicle.



(a)

(b)

Fig. 1 (a) The modeling of the transmitter and receiver coils (b) The WCS modeling applying in EV

Two transmitter and receiver coils made of a superconducting material were designed. The selected resonance frequency was 350 kHz, within the frequency band range recommended by WPC (325-450 kHz), which allows the avoidance of interference between high-frequency communication bands and reduces the adverse effect on the human body. Table 1 shows the coil design parameters. The diameter and pitch of the coils were selected considering the specifications of an actual EV. The transmitter and receiver coils were made with the same shape. As the superconducting coil has zero resistance below the critical temperature, the impedance matching of the transmitter and receiver coils was made 0 Ω. In WCS, L stands for the wireless charging coil. First, the wireless charging coil was designed, and the L value was measured through HFSS. Then the C value capable of resonating at 350 kHz was calculated using Equ. (1).

Table 1. Parameters of Superconducting coil

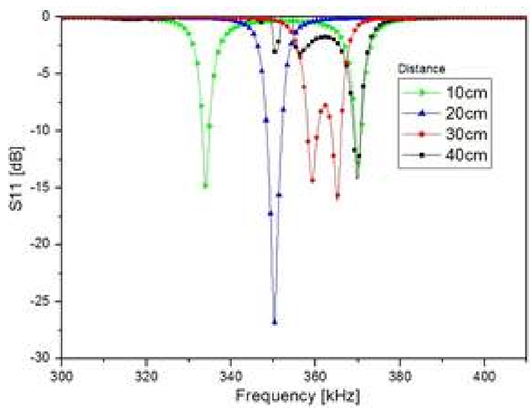
Parameters	Value
Material	Superconductor
Diameter	20 [cm]
Pitch	1 [cm]
Height	1.2 [cm]
Inductance (L)	16.73 [μH]
Capacitance (C)	12.36 [nF]
Impedance matching	0 [Ω]

3. Experimental

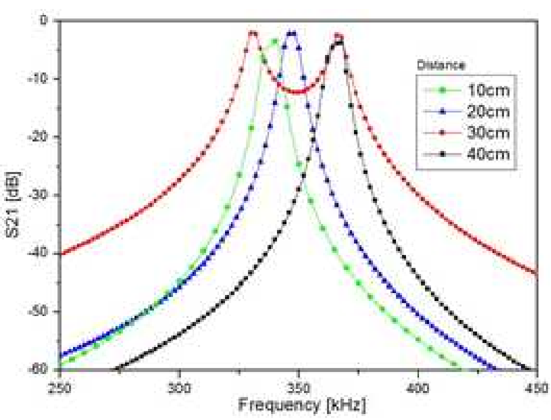
3.1 Mutual inductance

Fig. 2 shows the changing S-parameter of the WCS when the transmitter and receiver coils were placed at 10, 20, 30, and 40 cm, respectively. When applying a wireless charging system to the EV and the ground, the distance variation according to the lower height of the EV is unavoidable. Therefore, it is essential to analyze the characteristics of the wireless charging system according to the distance variation. Fig. 2(a) is a graph of the reflection coefficienct(S11). At the 20cm interval, it was resonated at 350 kHz, thereby confirming that it was about −27.1 dB. The reflection coefficients, however, were -0.5, -0.3, and -3 dB, respectively, at the 350 kHz frequency when the distance was 10, 30, and 40 cm, confirming that the signals of the transmitter coil were not transmitted properly but bounced back. Fig. 2(b) is a graph of the transmitting coefficient (S21) when the distance was changed at the same intervals as in Fig. 2(a). The transmitting coefficients for the different distances were -22, -1.87, -12, and −31 dB, respectively. As with the case of S11, the majority of the signals were not transmitted to the receiver coil.

$$Wireless\,charging\,frequency = \frac{1}{2\pi\sqrt{(L \pm M)C}} \quad (2)$$



(a)



(b)

Fig. 2. S-parameters according to the changing distance of the wireless charging system (a) S11 (b) S21

Resonance could occur in the other frequency band. When the power frequency applied to WCS is 350 kHz, a significant amount of efficiency loss is expected at distances other than 20 cm. It was confirmed that the frequency is divided according to the changing distance between the transmitter and the receiver.

The frequency selection changes according to the distance between the transmitter and receiver coils due to the mutual inductance. The inductance of each coil occurring between the two coils affects the resonance frequency. Equ. (2) is a resonance frequency equation that considers the mutual inductance.

The clearance of the vehicle from the ground depends on the vehicle type. As such, the distance between the transmitter and receiver coils of WCS also changes. Therefore, the mutual inductance of the two coils should be considered when applying WCS to an EV.

3.2 Variable wireless charging system

Fig. 3 shows the proposed variable WCS. First, a WCS that resonates at 350 kHz was designed. To change the capacitor value according to the change in the mutual inductance, capacitors were connected in parallel using a switching system. The spacing between the Tx and the Rx coils varies from 20, 30 and 40 cm. The reason is that the height of the lower part varies depending on the size of the EV. Variation, Medium-sized car, Sports utility vehicle were selected for the (simulation, experiment).

Table 2 shows the mutual inductance according to the distance, which was calculated using the data in Fig. 2. The mutual inductance was calculated using Equ. (2). The 20 cm standard, which demonstrates the resonance characteristics at 350 kHz, was adopted. Considering the L and M values, the capacitance at 350 kHz is the figure with a 350 kHz resonance frequency.

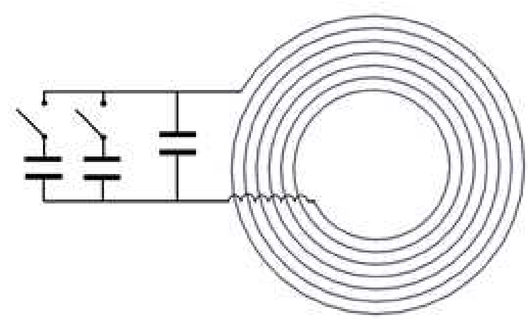


Fig. 3. Superconducting coils schematic with a variable capacitor

Table 2 Mutual-inductance & Capacitance according distance

Distance	20 [cm]	30 [cm]	40 [cm]
Wireless charging Frequency	350 [kHz]	362 [kHz]	371 [kHz]
Inductance & Capacitance	16.73 [uH] & 12.36 [nF]		
Mutual Inductance	0 [uH]	-1.09 [uH]	-1.94 [uH]
Capacitance at 350kHz	12.36 [nF]	13.22 [nF]	13.89 [nF]

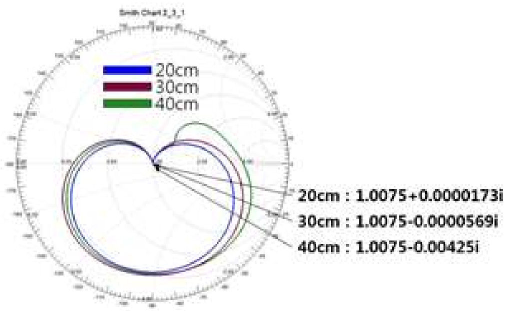


Fig. 4 Smith chart according to the distance of the variable wireless charging system (a) 20cm (b) 30cm (c) 40cm

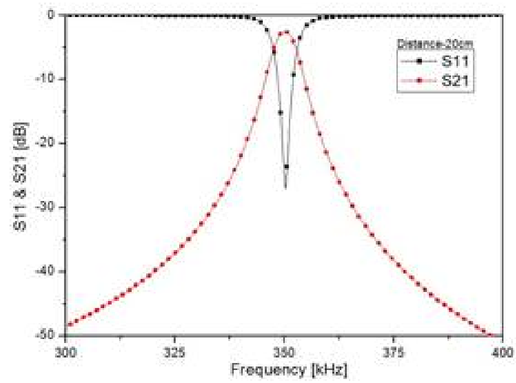
3.3 Experimental results

Fig. 4 is a Smith chart according to the distance of the variable WCS. The characteristic impedance can change according to matching of L and C values. If the L and C values is not matched, then WCS efficiency will decrease dramatically. Therefore, impedance matching is essential. When the impedance of Tx and Rx is 0 Ω, impedance matching is also 0 Ω. The impedance values at resonance point on the smith chart is 1.00075+0.0000173i, 1.0075-0.0000569i, 1.0075-0.00425i when the distance between Tx and Rx is 20, 30, 40 cm respectively. The reactance values at resonance point was close to 0Ω. So, it could be confirmed that the impedance matching is well operated. Fig. 5 shows the S-parameters of the WCS using variable capacitors. Fig. 5(a) shows the reflection and transmitting coefficients when the distance between the transmitter and receiver coils is 20 cm.

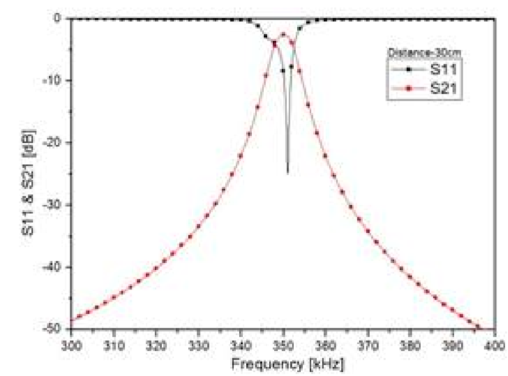
S11 is about -27.1 dB, and S21 is about -1.87 dB. The resonance frequency is 350 kHz. Fig. 5(b) shows the S11 and S21 values when the distance between the transmitter and receiver coils is 30 cm. The values are about -24.8 and -2 dB, respectively. Fig. 5(c) shows the S-parameters when the distance between the two coils is 40 cm. The reflection and transmitting coefficients are -26 and -1.91 dB, respectively.

Table 3 Comparison of experimental results

		Normal Capacitor at 350 [kHz]	Variable capacitor at 350 [kHz]
20 [cm]	S11 [dB]	-27.1	-27.1
	S21 [dB]	-1.87	-1.87
30 [cm]	S11 [dB]	-0.3	-24.8
	S21 [dB]	-12	-2
40 [cm]	S11 [dB]	-3	-26
	S21 [dB]	-31	-1.91



(a)



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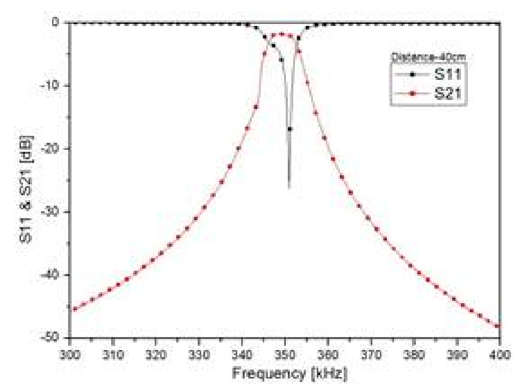

(c)

Fig. 5 S-parameters according to the distance of the variable wireless charging system (a) 20cm (b) 30cm (c) 40cm

Table 3 shows the S-parameter values according to the availability of a variable capacitor in WCS. If the height of the EV vehicle is not taken into consideration, the efficiency of the wireless charging system will decrease drastically because of discordance of resonance frequency. However, using a wireless charging system with a variable capacitor, the resonance frequency can be harmonized with the level of elevation of the EV and the ground, and wireless charging can be achieved a high efficiency.

4. Conclusion

With the increase in the number of EVs being used, the interest in wireless charging is rapidly increasing. Wireless charging is expected to play a decisive role in the commercialization of EVs because they can eliminate the inconveniences that drivers experience with the conventional wired charging system. In this study, a variable WCS using superconducting coils was proposed. In the said WCS, the transmitter and receiver coils affect the mutual inductance level. The size of the mutual inductance varies depending on the distance between the transmitter and receiver coils. In this case, the selectivity of the resonance frequency is influenced, thereby decreasing the efficiency of wireless charging. The bottom clearance of an EV differs from one vehicle to another. It causes a difference in the frequency selection of the WCS from one system to another. Therefore, inevitably, it changes the charging efficiency in the same WCS. The variable WCS can maintain constant resonance frequency characteristics by changing the capacitor value according to the mutual inductance value of the transmitter and receiver coils. As a result, it was confirmed that the frequency selectivity was kept constant even when the vehicle's bottom clearance was changed.

Furthermore, high efficiency was maintained because superconductors were applied to the WCS. It is believed that stable and highly efficient wireless charging would be feasible even in vehicles of various clearances and sizes if sufficient studies would be made on a variable WCS using superconducting coils.

감사의 글

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References

[1] Andre Kurs, AristeidisKaralis, J. D. Joannopoulos, and Marin Soljacic, Wireless Power Transfer via Strongly Coupled Magnetic Resonances, Science, pp. 83-86, 2007.

[2] SangCheol Moon, Bong-Chul Kim, Shin-Young Cho, Gun-Woo Moon, “Analysis and design of wireless power transfer system with an intermediate coil for high efficiency,” 2013 IEEE ECCE Asia Downunder, pp. 1034-1040, 2013.

[3] Rui Jin, Zhongping Yang, Fei Lin,”Mutual inductance identification and maximum efficiency control of wireless power transfer system for the modern tram,” 2017 IEEE PELS Workshop on Emerging Technologies, pp. 70-74, 2017.

[4] Kunwar Aditya, Mohamed Youssef, Sheldon S. Williamson, “Design considerations to obtain a high figure of merit in circular archimedean spiral coils for EV battery charging applications,” IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society, 2015, 005396-005401. M. Young, The Technical Writer's Handbook. Mill Valley, CA, USA: University Science, 1989.

[5] I.S.Jeong, B.I.Jung, H.S.Choi, Characteristic of wireless power transmission S-parameter for a superconductor coil, PSAC, 17(1), 2015.

[6] J. Ogawa et al., “Experimental investigation of loss characteristics with AC and DC offset transport current in HTS double pancake coil,” IEEE Trans. Appl. Supercond., vol. 22, no. 3, Jun. 2012.

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