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Wireless Rapid Charger of Super Capacitor

***Abstract**. The fundamental characteristics of the wireless rapid charger of super capacitor is investigated by experiments and simulation. This system is composed of the resonant half bridge inverter and the noncontact transformer. Based on the results, the frequency control method that can do the wireless rapid charge regardless of the relative position of the windings of the noncontact transformer is proposed. It can meet the resonance requirement and large charging current can be acquired by detecting the current of the primary switch and controlling the frequency of the inverter.*

***Streszczenie.** Badano eksperymentalnie i podczas symulacji numerycznych charakterystyki bezprzewodowego systemu szybkiego ładowania superkondensatora. System składa się z mostkowego przekształtnika rezonansowego i bezstykowego transformatora. Na podstawie wyników zaproponowano nową częstotliwościową metodę sterowania ładowarką, niezależnie od wzajemnej pozycji uzwojeń bezstykowego transformatora. Metoda zapewnia wysoki prąd ładowania dzięki detekcji prądu przełącznika pierwotnego oraz kontroli częstotliwości przekształtnika. (**Bezprzewodowy system szybkiej ładowarki superkondensatora**)*

Keywords: wireless power transmission, resonant technique, super capacitor, inverter.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

The energy transmission by the magnetic induction is an important technology, it contributes to making of various electric equipment cordless. It has been used for the wireless electric power transmission to IC card and the IC tag, etc., and it had tried to be used for the noncontact charger of the batteries of electric vehicles [1]. Especially, this is thought to be one of the promising technologies as a security precaution to the leak accident at rain in the electric vehicle when it is charged in the outdoors. Our research group proposed the non-contact charge system using a self-oscillated Class C converter by magnetic coupling [2]. We have done various reports since then about wireless power transmission, such as a noncontact charger of soft switching for which the inductor-commutation was used, and a noncontact charger for electric vehicles [3, 4, 5, 6, 7, 8]. Here, the electrochemical cell including the lithium-ion battery is a main current as the battery for the electric vehicle. However, this cell has the disadvantage in which it is weak in the rapid charge and discharge by large current. On the other hand, super capacitors (electric double layer capacitor) with an excellent rapid charge and discharge characteristics have been examined [9, 10, 11]. The research of using this device as an energy storage element had started [12], and we also have reported the applied research about this device [13, 14, 15, 16]. The electrical bus that makes the super capacitor a power source has already been operated in Shanghai in China. However, the energy density of the super capacitor is lower than that of the electrochemical cell. Therefore when the voltage of the capacitor is decreased, the pantograph is raised and capacitors are charged in the bus stop (charge point) that the passenger gets on and off. Here it will be possible to charge rapidly with a super capacitor of the electric vehicle easily only by parking to the shop front or the garage if the wireless charge technology could be used. It will be opened from the trouble when the plug is connected by the hand by this technology. We have been researching the wireless power transmission that uses the resonance technology for the half bridge inverter and the noncontact transformer [8]. However, when this system is applied to charge of a super capacitor, the fundamental characteristics, such as a relation of the resonance conditions, the composition of the noncontact transformer and the charging time of the super capacitor are not known well yet. In this paper, these problems are investigated by experiments and simulation, and moreover, based on the results, the control method of the inverter is proposed.

Wireless resonant power transmission circuit

The circuit for charging of a super capacitor that uses the wireless resonant power transmission is shown in Fig. 1. The half bridge inverter is on the primary side. The super-

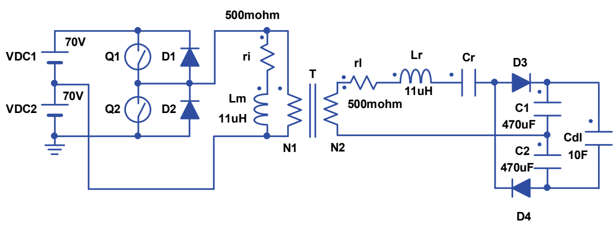


Fig.1. Wireless resonant power transmission circuit.

capacitor C_{dl} is charged with the voltage doubler circuit on the secondary side. The feature of the circuit is that the capacitor C_r for the resonance and the secondary winding of the transformer are connected with the series.

The transformer T is expressed by the excitation inductance L_m, the leakage inductance L_r and the ideal transformer of winding N_1 and N_2 as shown in Fig. 1. T is the air-core transformer that is composed of the spiral windings as shown in Fig. 2, and the gap of the windings is g, and the distance from the center of the windings is d, respectively.

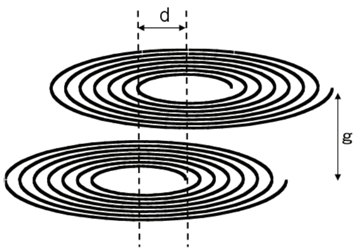
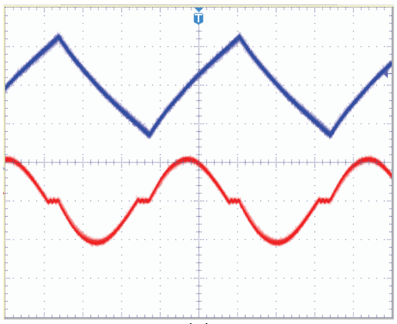


Fig.2. Air-core spiral transformer

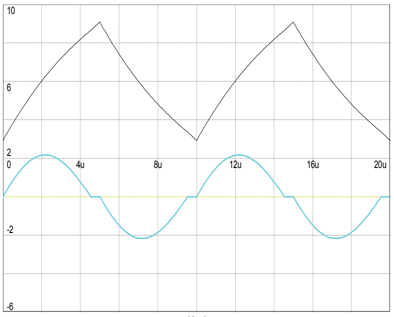
Here, power transmission can be made by the series resonant circuit of L_r and C_r. Moreover, the switching loss can be reduced because the soft switching that uses the exciting current of the transformer can be achieved by installing the dead-time in the driving waveform of the switch Q_1 and Q_2 of the inverter.

Experiment and simulation

In the experiment, the switching frequency of the inverter is 100kHz and the duty ratio is fixed to 50%. The winding of the transformer is N_1=N_2=17, the outer diameter of each spiral coil is 48mm and the self inductance of each winding is 11μH. Fig. 3(a) is the experimental waveform of the current of the windings of the transformer. The upper waveform is the current of the primary winding and the



(a)



(b)

Fig.3. Waveforms of (a) Experiment and (b) Simulation (Top trace: current of primary winding (10A/div, 2μs/div); bottom trace: current of secondary winding (2A/div, 2μs/div).

lower one is that of the secondary one. The waveforms simulated by SCAT (Switching Converter Analysis Tool) [17] are shown in Fig. 3(b). Both waveforms are corresponding well. As for the current of the secondary winding, the resonating appearance is understood though the current of the primary winding has changed in most straight lines according to the excitation inductance. Fig. 4 is the experimental result that shows the relation between the resonant capacitance C_r and the time to charge with the voltage of the super capacitor of 10F from 0 to 2.5V.

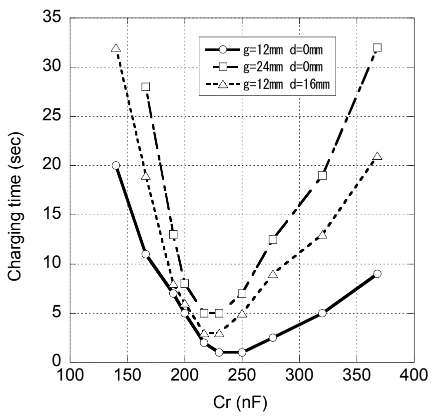


Fig.4. Charging time versus resonant capacitance with air-core transformer.

The parameters are the gap g and the distance d of the windings of the air-core transformer. The displacement of g is 1/4 of the outer diameter 48mm, and that of d is 1/3 of that, respectively. It is understood from this figure that the charging time shortens extremely for specific C_r. This is because it meets the resonance requirement of the following equation.

$$f = 1/2\pi\sqrt{L_r C_r} \quad (1)$$

where: f – switching frequency of the inverter, L_r – leakage inductance of the noncontact transformer, C_r – resonant capacitance.

The rapid charge is possible since large resonant current flows in the resonance point. Fig. 4 also shows that the charging time becomes long as the gap g or the distance d increases. In this system, the charging time changes notably by the relative position of windings.

On the other hand, the air-core transformer has the problem that the leak of the magnetic flux is large, although there is no core loss. Therefore, magnetic shielding is required to actually use. Then, the ferrite-cores are arranged on the outside of the spiral coils for magnetic shielding as shown in Fig. 5, and the same experiment is conducted.

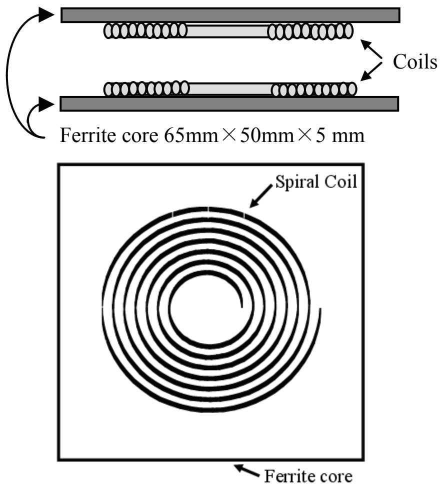


Fig.5. Spiral coils with Ferrite cores.

The self inductance of each winding is 16μH due to the ferrite-core although both the windings of the transformer and the outer diameter of each spiral coil are the same as those of the air-core one. Fig. 6 shows the charging time versus resonant capacitance C_r with ferrite-core transformer.

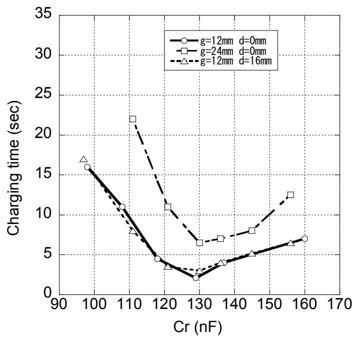
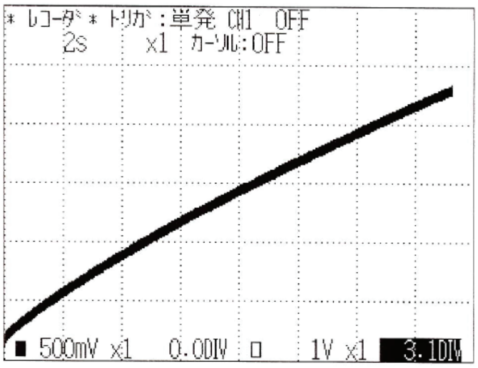
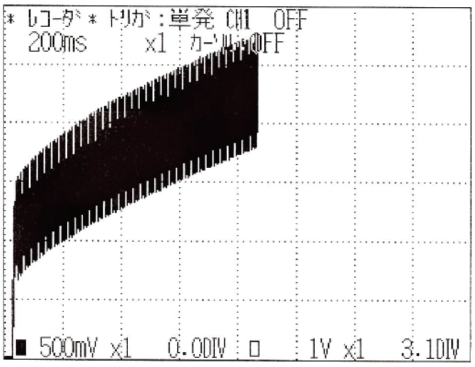


Fig.6. Charging time versus resonant capacitance with ferrite-core transformer.

Like the case of the air-core transformer, this figure shows that the charging time shortens extremely for specific C_r and it becomes long as the gap g increases. However, unlike the case of the air-core, it turns out that there is little change of the charging time by the distance d. This is the advantage and it is considered to be an effect by the ferrite-core. However, cautions are required since aggravation of the charging efficiency by the core loss is expected.



(a)



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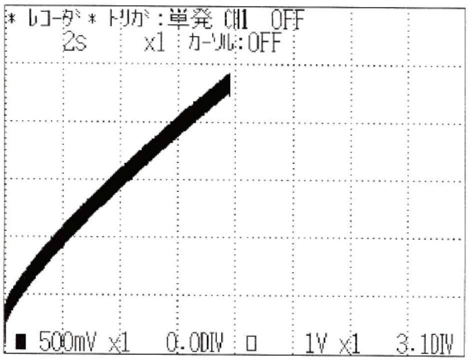
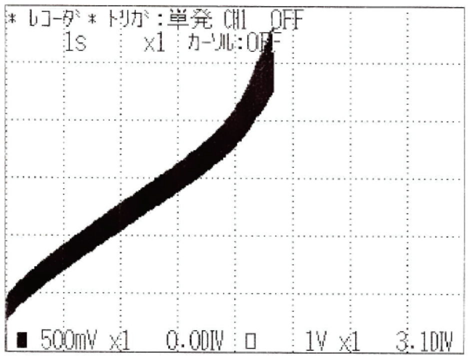


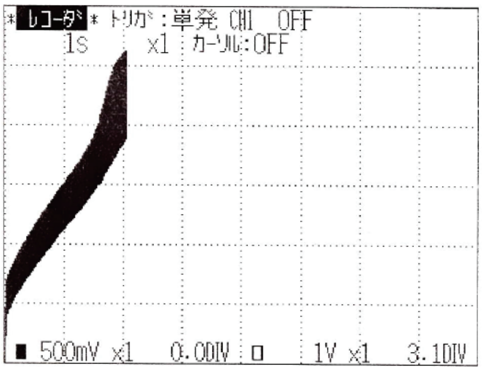
(c)

Fig.7. Charging voltage of super capacitor versus time with air-core (a) C_r=156nF, (b) C_r=253nF, (c) C_r=362nF (Magnitude: 0.5V/div, Time: 2s/div for (a) and (c), 0.2s/div for (b)).

Here, Figs. 7 and 8 show the change of the charging voltage of the super capacitor to time for the air-core and the ferrite-core transformer, respectively. In Fig. 7(b), it is in the state that the resonant condition (C_r=253nF) is almost satisfied and it is not satisfied with both Figs. 7(a) and 7(c). The swing of the voltage of high frequency is large in Fig. 7(b) because the internal resistance of the super capacitor becomes dominant in the resonant condition. However, the average voltage is increasing in monotone with the air-core transformer. On the other hand, the tendency of the rise of the charging voltage has changed on the way in Fig. 8 with the ferrite-core. Bordering on Fig. 8(b) with which it is satisfied of resonance condition (C_r=129nF), the tendencies of the voltage change clearly differ by the resonant capacitance C_r. One of the causes is considered that the operating point of the inverter changes every moment according to the voltage of the super capacitor. This phenomenon needs to be solved for utilization of the rapid charge system.



(a)



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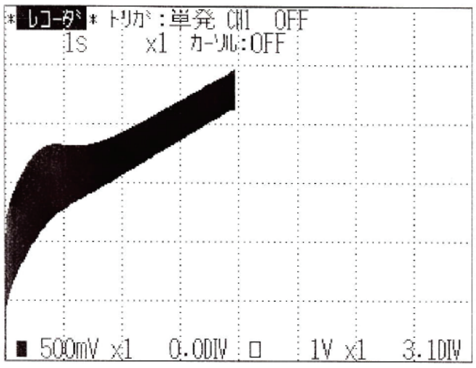

(c)

Fig.8. Charging voltage of super capacitor versus time with ferrite-core (a) C_r=118nF, (b) C_r=129nF, (c) C_r=137nF (Magnitude: 0.5V/div, Time: 1s/div).

Frequency Control

Figs. 4 and 6 show that the rapid charge of the super capacitor is possible in the resonance point. However, it is quite difficult to charge on the conditions always near resonance since the leakage inductance L_r changes with the relative position of the windings and there also is a variation in the capacitance for resonance. Therefore, it is necessary to make the state of always satisfying resonance condition for utilization. There are two methods to satisfy the equation (1) for the change of L_r; the one is changing C_r and the other is changing f. The latter is more effectual than the former because the former requires another C_r and switching element on the secondary side in order to change C_r and this is troublesome. Here, it is necessary to obtain information whether to satisfy the resonance condition to change switching frequency. Then, we propose to detect the current of the switch Q_2 on the low side of the inverter. Fig. 9 is the simulation of the averaged current of the switch Q_2 when resonant capacitance C_r is changed by SCAT. It is understood from this figure that the current of the switch is the maximum for C_r=223nF where it meets the resonance requirement (1).

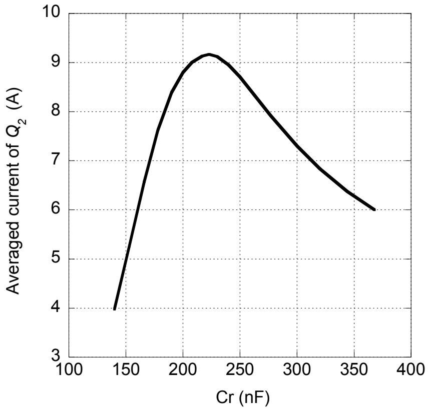

Fig.9. Simulation of the averaged current of the switch Q_2 of the inverter versus resonant capacitance in the secondary side (L_m=11μH, L_r=11μH, f=100kHz).

Fig. 10 is the simulation of the averaged current of the switch Q_2 when the switching frequency f of the inverter is changed by SCAT where L_r=13μH, C_r=223nF and resonance frequency is 93.5kHz from (1). For example, suppose that L_r=11μH, C_r=223nF and the resonance frequency was 100kHz at first from (1) as shown in Fig. 9. Then, when the relative position of the windings changes and L_r also changes to 13μH from 11μH, Fig. 10 shows that only the current of 3A is obtained if the frequency is still 100kHz. However, it turns out that the large resonant current more than 10A is obtained if the frequency could be changed near 93.5kHz. Therefore, the super capacitor can be charged rapidly if the frequency is changed by detecting the current of the switch of the inverter. This circuit configuration is easy because the control circuit can be composed on all the primary side.

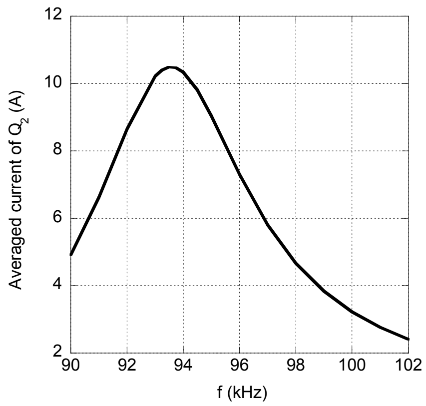

Fig.10. Simulation of the averaged current of the switch Q_2 versus switching frequency f of the inverter (L_m=13μH, L_r=13μH, C_r=223nF).

Conclusion

The fundamental characteristics of the wireless rapid charge system of super capacitors have been investigated by experiments and simulation. Based on the results, the frequency control method of the inverter has been proposed. By this method, wireless rapid charge becomes possible regardless of the relative position of the windings of the noncontact transformer. It can meet the resonance requirement and large charging current can be acquired by detecting the current of the primary switch and controlling the switching frequency of the inverter. The validity of the method has been confirmed by the simulation. The verification by the experiment is the future task.

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