Experimental Verification of Wireless Charging System for Vehicle Application using EDLCs

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***Abstract*— This paper discusses an vehicle application which uses electric double layer capacitors (EDLCs) as a power source. EDLCs are charged through a rapid charger by using wireless power transmission. In this paper, as vehicle application, the electric assisted bicycle is considered. First, the antenna for the wireless power transmission and the charger are introduced. Next, this paper compares the volume and the power loss of the three kinds of DC-DC converters which are a buck-type, a boost-type and a buck-boost type for the charging and discharging of EDLCs. As a result, such as an electric assisted bicycle for small-capacity system, the boost-type is small. On the other hand, such as electric vehicles for large-capacity system, the buck-type is small. Finally, the proposed system is experimentally verified as a prototype. As a result, the proposed system can shorten to 1/4 the charging time of the conventional system.**

Keywords*— Vehicles, Supercapacitors, Inductive power transmission, DC-DC power converters

I. Introduction

Recently, in consideration of global warming, the vehicle application system using battery has been studied actively [1]. The vehicle application uses a lithium-ion battery as an energy source. The lithium-ion battery is suitable for a long assist time owing to high energy density. However, the lithium-ion battery is the short lifetime and it needs long charging time.

On the other hand, the kHz-class wireless charging system using rapid rechargeable electric double layer capacitors (EDLCs) which has long cycle life has been developed for vehicular applications [2]. This system uses EDLCs instead of the lithium-ion battery. In this system, a disadvantage of low energy density of EDLCs is solved by frequent fast wireless charging. However, the kHz-class antenna for wireless power transfer is large and heavy because of a large core. On the other hand, the MHz-class antenna for wireless power transfer for the purpose of weight reduction and miniaturization of the antenna has been studied [3].

The authors have been proposed an electric assisted bicycle with EDLCs and MHz-class wireless charging system as a vehicle application [4]. This system has two concepts as follows; First, it is assumed that the EDLCs are used as only the assist of starting acceleration and slopes for the electric assisted bicycle in order to suppress the total energy of the EDLCs; Second, the wireless power transfer system is applied to rapid charger for the EDLCs because of small capacity and the short charging time. However, the MHz-class wireless charging for EDLCs has not been actually verified in terms of transmission efficiency of the antenna, an efficiency and a volume of an interface power converter for EDLCs.

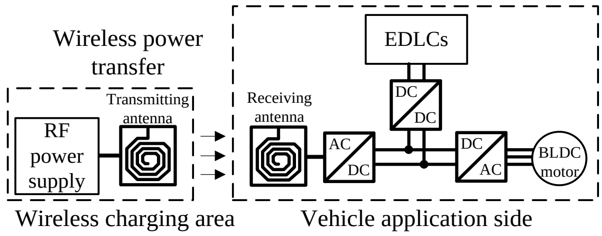


Fig. 1. Configuration of the proposed system.

This paper evaluates three items as follows in order to clarify advantages of MHz-class wireless charging for EDLCs;

1) The antenna using a print circuit board (PCB) and charger design for the wireless power transmission,

2) The circuit topology of the interface DC-DC converter for EDLCs in the proposed system configuration in terms of the volume and efficiency corresponding to output power,

3) The comparison of the charging time of the proposed system and the conventional system.

Also, the wireless power transfer system has problems that the voltage of the receiving antenna is varied by variation of the coupling factor and a load. Therefore, a control method for charging controlling an input impedance of the receiving side to constant value by using a DC-DC converter is proposed. The effectiveness of the proposed control is experimentally verified.

II. PROPOSED SYSTEM CONFIGURATION

Fig. 1 shows the configuration of the proposed system. The proposed system uses a Radio Frequency (RF) power supply at the input stage of the transmitting antenna for wireless power transmission [5-9]. Also, the proposed system comprises a rapid rechargeable AC-DC converter and EDLCs in the latter part of the receiving antenna. The EDLCs are charged when the vehicle application stops on the wireless charging area. Also, the voltage of EDLCs is controlled to be constant by the DC-DC converter when the motor is driven.

III. DESIGN OF ANTENNA FOR WIRELESS POWER TRANSMISSION AND CHARGER

A small receiving antenna is preferred in order to mount the vehicle application. Therefore, the authors have been proposed a formula spiral antenna made of a printed circuit board, which is flat, compact and easy design.

A. Design of Wireless Charger

Fig. 2 shows the structure and equivalent circuits of the transmitting antenna for wireless power transmission. The connection point of the short type and open type is the output of a RF power supply. For the receiving antenna, the equivalent circuit is the same. The antenna has a two-layer structured wiring in order to increase the inductance value.

Fig. 3 shows the design flow chart of the charger and the antenna for the wireless power transmission. From Fig. 3, the charging power *P* is determined by the charging time *T* and the charging energy *E*. The antenna is designed from the specifications of the antenna size D_{omax} and the charging power *P*. The charger considers the short charging time and the volume of power conversion system for the charging power. In this paper, the specification example of the system is designed as follows.

1) The target of charging time *T* is 60 sec,

2) The charging energy *E* is supplied to 56.5 kJ. This energy is the maximum energy in the proposed system. Also, the EDLCs are used product of Nippon Chemi-Con Corporation [10].

In addition, the average output power of the charger *E*/*T* is approximately 1 kW. If the discharging power is less than 1 kW, the size of the circuit becomes large when the charging circuit combines with the discharging circuit. Therefore, the charging control should be placed in RF power supply of the power transmission side of the wireless power transfer system. On the other hand, if the discharging power is more than 1 kW, the size of the circuit does not become large when the charging circuit combines with the discharging circuit. So, a compact system can be realized. Therefore, bi-directional system for charging and discharging is designed in this paper.

Also, the antenna size D_{omax} depends on the mounting position of the power receiving side. The antenna for wireless power transmission is experimentally compared between the short type and open type with the same size.

B. Comparison of Transmission Efficiency

Fig. 4 shows the system configuration of the experiments. Arbitrary frequency is output using a function generator. The output power cannot output 1 kW (The average output power of the charger) because of capacity limit of RF power supply. Therefore, the output of the RF power supply is scaled to 100 W (10% of 1 kW). Reflected power P_R is measured using a power meter in the front stage of the power transmission antenna. Also, the antenna of short type is connected in series

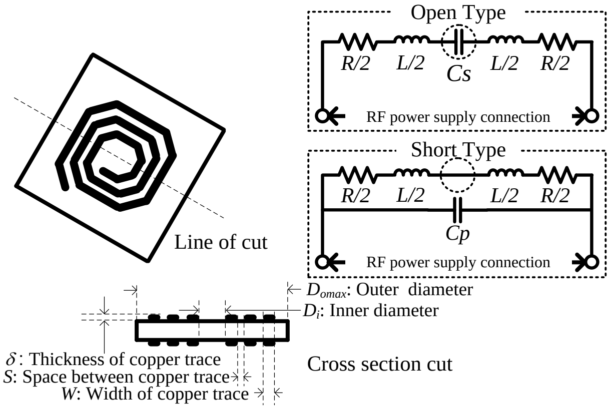


Fig. 2. Structure of the antenna for wireless power transmission.

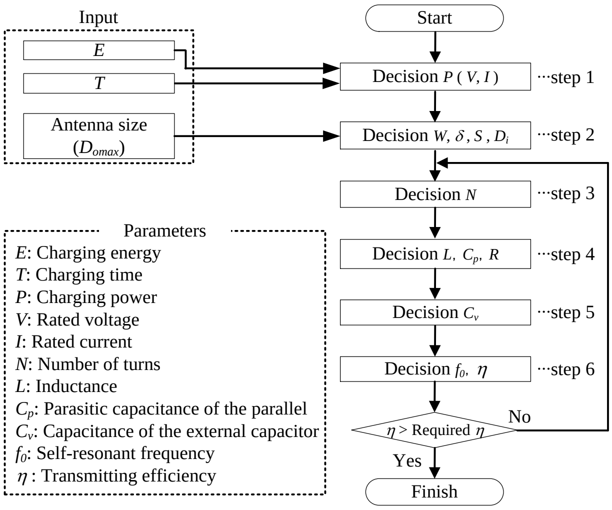


Fig. 3. Design flow chart of charger and antenna for wireless power transmission.

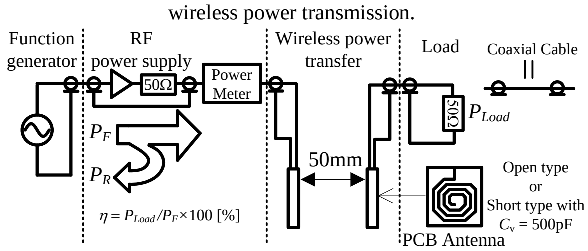


Fig. 4. System configuration of the experiments.
The system of the experiment circuit is matched at 50Ω.

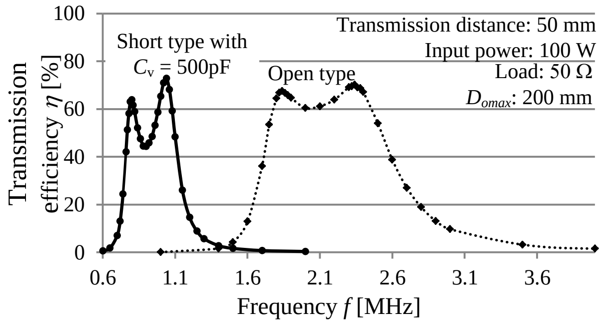
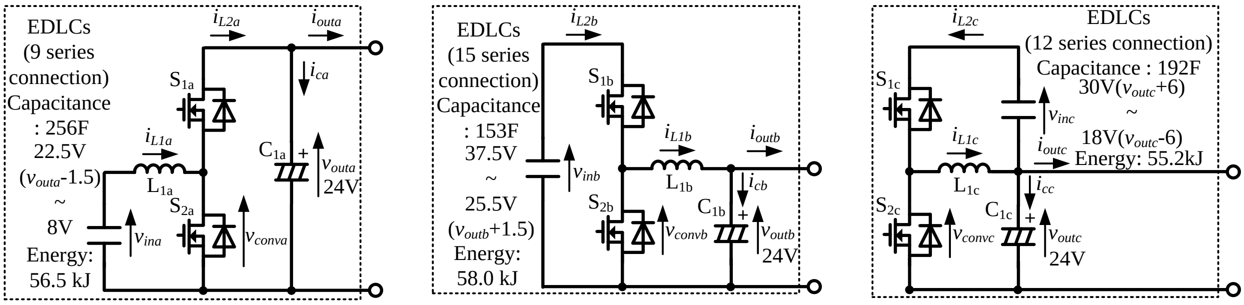


Fig. 5. Experimental results of the frequency characteristics of the transmission efficiency.

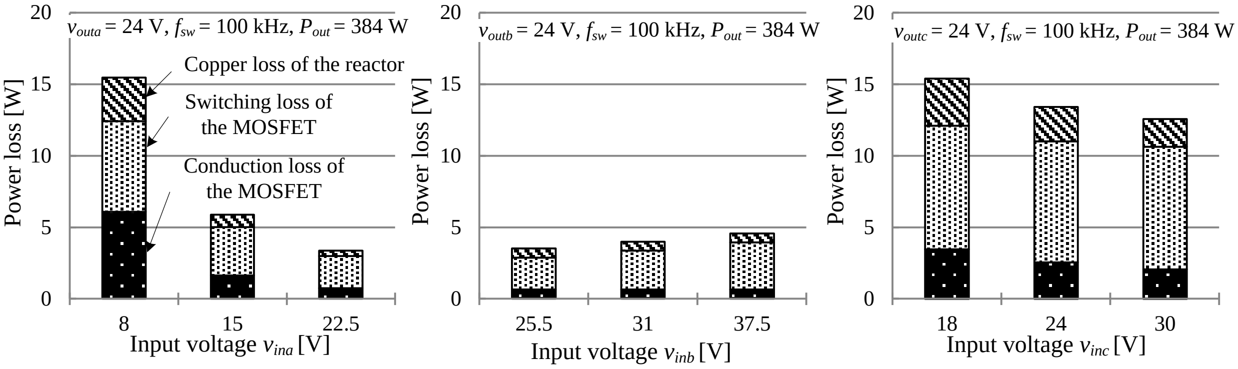
with the capacitor of capacitance 500 pF.

Fig. 5 shows the experimental results of the frequency



(a) Boost-Type. (b) Buck-Type. (c) Buck-boost Type.

Fig. 6. Investigated circuit configuration.
The energy of EDLCs for a circuit of three types is designed with the same energy.
As shown in Fig. 9, a BLDC motor is connected to the output of the DC-DC converter.



(a) Boost-Type. (b) Buck-Type. (c) Buck-boost Type.

Fig. 7. Results of power loss analysis of the three kinds of DC-DC converters.
The power loss is neglected iron loss of the reactor, the conduction loss of the diode, recovery loss.

characteristics of the transmission efficiency. The power is amplified by the amplifier. The antenna is designed according to the flowchart of Fig. 4. From Fig. 5, it is confirmed that the short type can realize the low resonance frequency compared to the open type at the same transmission efficiency and antenna size. In general, if resonant frequency is the low frequency, the efficiency of RF power supply is high. Therefore, the short type can be high efficiency of the system than the open type. So, the proposed system is adopted the short type. In Section 5, the antenna is redesigned in order to use the inexpensive low voltage RF power supply.

IV. Design of the Interface Converter for EDLCs

A. Comparison of Circuit Configuration

Fig. 6 shows the circuit configuration of three kinds of DC-DC converters. This paper investigates the interface DC-DC converter which a buck-type, a boost-type and a buck-boost type for EDLCs. In this paper, when the voltage of EDLCs is smaller than the output voltage of the DC-DC converter, it is defined as a boost-type. The number and the output voltage range of the EDLCs are designed when the charging and discharging energy of EDLCs meet more than 53.0 kJ. Thus, the DC-DC converters are designed that the charging and discharging energy of EDLCs is as follows: the energy of the boost-type, buck-type and buck-boost type are 56.5 kJ, 58.0 kJ and 55.2 kJ, respectively. In addition, the specification of the input voltage of the DC-AC converter is 24 V (V_{outa}, V_{outb}, V_{outc}), and the output voltage of the DC-DC converter is controlled to 24 V at constant. Further, the reactors of all types are designed to the current ripple value (1.5 A) as same as the buck-type. Therefore, the reactors of all types are designed that the current ripple of the reactor meets less than 1.5A. On the other hand, the smoothing capacitor is designed from the allowable ripple current.

In this system, the load of BLDC motor is changed. It is necessary to increase the capacitance of the smoothing capacitor in order to reduce the variation in the output voltage of the DC-DC converter owing to load variations. However, the volume of the smoothing capacitor should be reduced in terms of volume implementation. Therefore, when the load fluctuations occur, it is important to reduce the volume of the smoothing capacitor by implementing the fast control response of the output voltage [11].

B. Comparison of Power Loss

Fig. 7 shows the power loss analysis of three kinds of DC-DC converters when the voltage of the EDLCs V_{in} is changed. The power loss is analyzed under the conditions that the output power of the DC-DC converter is 384 W. It is noted that dead time is neglected. As shown in Fig. 7, it is confirmed that the switching loss and the conduction loss of the MOSFET dominates the total loss in the boost-type. Also, it is confirmed that the switching loss of the MOSFET is dominates the total losses in the buck-type and buck-boost type. This is because the input current of the boost-type is increased owing to the input voltage, which is lower than the buck-type and buck-boost type.

C. Comparison of Total Volume

Fig. 8 shows the relationship between the total volume and the output power for the three kinds of DC-DC converters. It is noted that the power loss is maximum for the voltage of EDLCs in Fig. 7. In addition, the volume of the Fig. 8 is the sum of volume of EDLCs and DC-DC converter (Reactor, Heat sink, Electrolytic capacitor).

In this paper, CSPI (Cooling System Performance Index), which is a reciprocal of the product of the volume and the thermal resistance, is introduced to estimate the volume of cooling system. The CSPI indicates the cooling performance per unit volume of the cooling system. It means that a high performance cooling system shows high CSPI. Therefore, the cooling system is miniaturized when CSPI become higher. The volume of the cooling system $vol_{cooling}$ is given by (1) from the relationship between the power loss and the rise in temperature [12].

$$vol_{cooling} = \frac{1}{R_{th} \times CSPI} = \frac{P_{loss}}{\left(T_j - T_a\right) \times CSPI} \qquad (1)$$

where R_{th} is the thermal resistance of the cooling system, T_j is the junction temperature of the switching device, T_a is the ambient temperature, P_{loss} is the power loss of the switching device.

In this paper, the reactor is designed by the Area Product concept [13] using a window area and a cross-sectional area. Then volume of the reactor vol_L is given by (2).

$$vol_L = K_v \left(\frac{2W}{K_u B_m J} \right)^{\frac{3}{4}} \qquad (2)$$

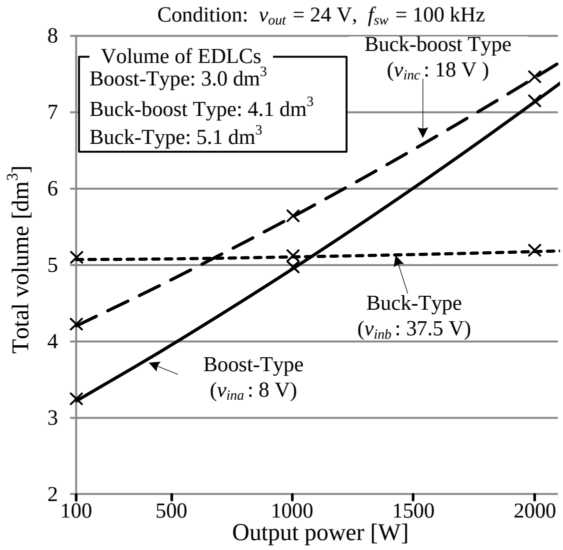
where K_v is the constant value depending on the shape of cores, W is the maximum energy of the reactor, K_u is the occupancy of the window, B_m is the maximum flux density of the core, and J is the current density of the wire.

The capacitor volume is calculated based on commercially available electrolytic capacitors [14]. The volume of the electrolytic capacitor is proportional to the rms value of the ripple current of the electrolytic capacitor. The volume vol_{CE} of the electrolytic capacitor is given by (3).

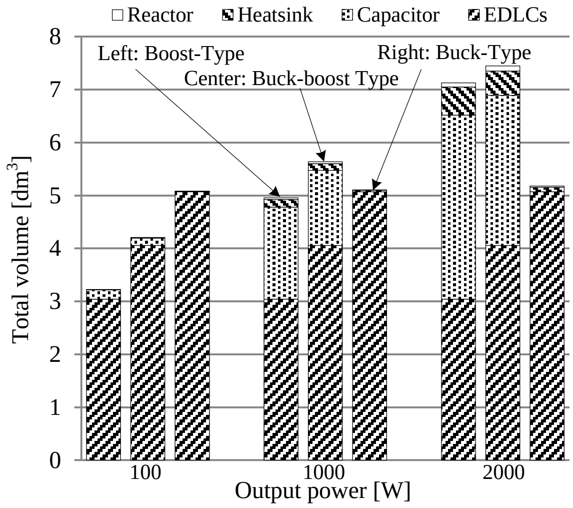
$$vol_{CE} = \gamma_{VCE}^{-1} I_{CRMS} \qquad (3)$$

where $\gamma^{-1}_{\mathrm{VCE}}$ is the proportionality factor between the rms value of the ripple current and the volume, and I_{CRMS} is the rms value of the ripple current of the electrolytic capacitor.

From Fig. 8(b), around the output power of 100 W, the volume of the EDLCs is dominant in the converter of all types. The number of EDLCs for the boost-type is the fewest in all of other DC-DC converters. Therefore, the volume of the boost-type is the smallest. However, if the output power is 1.1 kW or more than 675 W, the volume of the buck-type is smaller than that of the boost-type and the buck-boost type. For the boost-type and the buck-boost type, the ripple current of the smoothing capacitor is increased when the output power is increased. Therefore, the ratio of the volume of the smoothing capacitor is increased. On the other hand, for the buck-type,



(a) Total volume.



(b) Ratio of the volume.

Fig. 8. Relationship between the total volume and the output power for the three kinds of DC-DC converters.
In this figure, it is noted the voltage of EDLCs at the maximum power loss is considered.

the ripple current of the smoothing capacitor does not depend on the output power. Therefore, when the output power is increased, the volume of heat sink and reactor which is very small compared to the volume of the EDLCs is increased. However, the volume of the converter does not increase too much. Furthermore, if the output voltage of the DC-DC converter is set to over 24 V, the cross over point of the volume of three kinds of DC-DC converter is shifted toward high output power. The reason is that the volume of the capacitor is decreased depends on its ripple current according to the high output voltage of the DC-DC converter. Also, the boost-type is the most compact in the power capacity (384W) of the electric assisted bicycle. Also, even if the energy of the EDLCs is small capacity further, the boost-type is the most compact. Therefore, the boost-type is adopted in the proposed system.

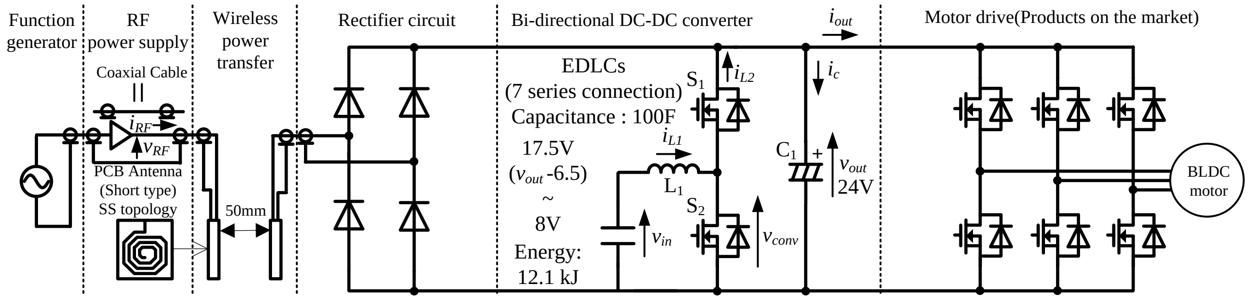


Fig. 9. The entire circuit diagram of the proposed system.
The proposed system is designed based on the system design to chapter 5.
The semiconductor switches are silicon MOSFETs.

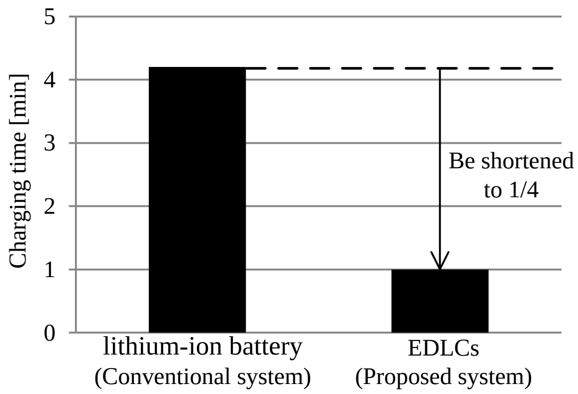


Fig. 10. Comparison of the charging time for charging the 12.1kJ of the proposed system and conventional system.

V. WIRELESS CHARGING VERIFICATION OF SYSTEM

A. Design of the Whole System

Fig. 9 shows the circuit diagram of the entire system based on the system design to chapter 4. By the system design, the total volume of boost type is minimum in three kinds of DC-DC converters at the maximum power (384W) of electric assisted bicycle. Therefore, boost type is adopted for the bi-directional DC-DC converter. In the antenna for wireless power transmission, the short type can be high efficiency of the RF power supply than the open type. Therefore, the antenna of short type is adopted. The running distance of a slope is more than 200 m as prototype specifications in this paper. Thus, the energy of the EDLCs (Nippon Chemi-Con Co, DDLE2R5LGN701KAA5S) is designed in 12.1 kJ [10]. In addition, the specification of the charging time is 1 minute. The wireless power transfer system is adopted the primary and secondary series resonant capacitors (SS topology) [15].

Fig. 10 shows the comparison of the charging time for charging the 12.1 kJ of the proposed system and conventional system. The charging energy of the conventional system is calculated from specification of the product. From Fig. 10, the proposed system can shorten to 1/4 the charging time of the conventional system.

Fig. 11 shows the equivalent circuit diagram of the SS topology. The transmitting antenna is connected to the RF power supply. The receiving antenna is connected to the rectifier.

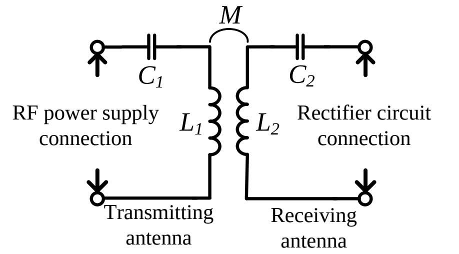


Fig. 11. Equivalent circuit diagram of the SS topology.
The capacitor is connected to an external antenna.

Table I. Specification of antenna.

Items	Values	
Outline (Length)	250	mm
Outline (Side)	200	mm
Number of turns (surface)	5	turn
Number of turns (reverse face)	5	turn
Space between copper trace	5	mm
Width of copper trace	3	mm
Thickness of PCB (FR-4)	2	mm
Thickness of copper trace	70	μm
Self-inductance L_1	8.6	μH
Self-inductance L_2	8.6	μH
Mutual inductance M	1.4	μH
Designed coupling factor k_0	0.16	
Primary capacitance C_1	2.9	nF
Secondary capacitance C_2	2.9	nF

Table I shows the specification of antenna for wireless power transmission. The designed coupling factor and the self-inductance are measured by a LCR meter. The capacity C_1 and C_2 of the series capacitor is given by (4).

$$C_1 = \frac{1}{L_1\omega_0^2} = C_2 = \frac{1}{L_2\omega_0^2} \quad (4)$$

where L_1 is the self-inductance of receiving antenna, ω_0 is the resonance angular frequency, L_2 is the self-inductance of transmitting antenna.

Fig. 12 shows the control block diagram of wireless charging. In the SS topology, if the voltage of transmitting antenna is not controlled, the voltage of the receiving antenna

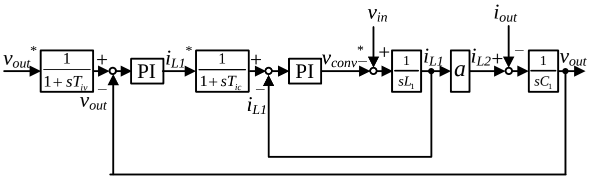


Fig. 12. Control block diagram.
The output voltage of bi-directional DC-DC converter is controlled to a constant 24V.

Table II. Conditions of the experiment.

Items	Values	
Frequency of the FG	1	MHz
Resonant frequency	1	MHz
Voltage of the FG	380	mVrms
Gain of the RF power source	100	
Transmission distance	50	mm

is varied by variation of the coupling factor and load [2]. In this problem, the breakdown voltage of the switching device must be designed by taking into account the variation of the coupling factor and the load. Therefore, charging control by the combination of two points as below is proposed.

1) The output voltage of the bi-directional DC-DC converter is controlled to be constant.

2) The voltage of the receiving antenna is set higher than the output voltage of the bi-directional DC-DC converter.

Thus, the design of the breakdown voltage of the switching device can be simplified. The charging experiment is based on the experimental conditions shown in Table II.

B. Experimental Results of Wireless charging

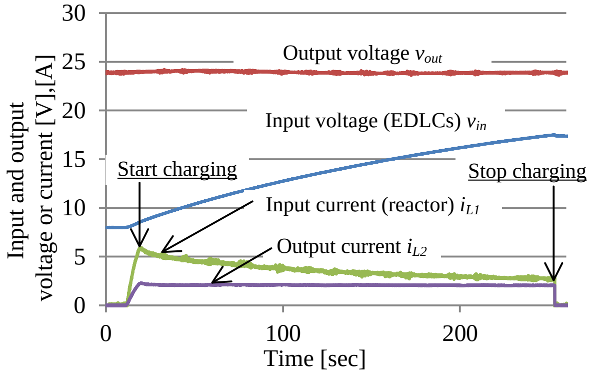
Fig. 13 shows the experimental results of the wireless charging to the EDLCs.

Fig. 13(a) shows the voltage and current waveform of the input and output for the bi-directional DC-DC converter. From Fig. 13(a), the output voltage of the bi-directional DC-DC converter is controlled to be constant, and the EDLCs are charged.

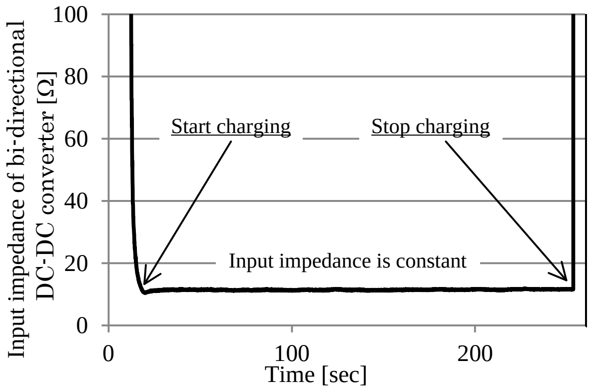
Fig. 13(b) shows the input impedance of the bi-directional DC-DC converter during the wireless charging to the EDLCs. From Fig. 13 (b), the input impedance of bi-directional DC-DC converter is controlled to be constant is confirmed. Therefore, the transmission efficiency can be kept constant.

Fig. 13(c) shows the energy storage capacity of EDLCs from the start of charging to the end of charging. From Fig. 13 (c), the energy capacity of the EDLCs are charged from 0% to 100% in about 4 minutes is confirmed. The reason that charging time is not within 1 minute is power transmission frequency of the prototype is 1 MHz. Therefore, if the power transmission frequency is adjusted within the Industry Science Medical band, the full charging of 1 minute is achieved.

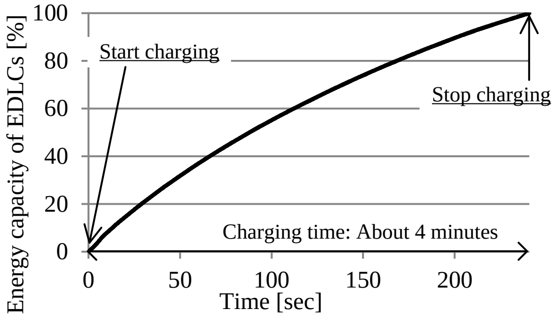
Fig. 13(d) shows the voltage and current waveforms of the output of the RF power source, the voltage and current waveforms of the output of bi-directional DC-DC converter. From Fig. 13(d), the input power factor of the high frequency power source is approximately 1 is confirmed.



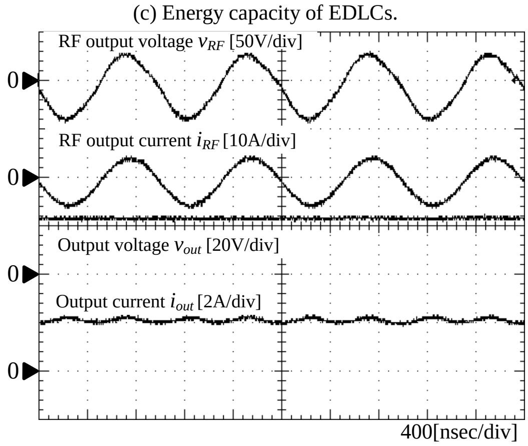
(a) Voltage and current waveform of the input and output for the bi-directional DC-DC converter.



(b) Input impedance of the bi-directional DC-DC converter.



(c) Energy capacity of EDLCs.



(d) Voltage and current waveforms of the output of the RF power source.

Fig. 13. Experimental results of the wireless charging to the EDLCs.

C. *Wireless Charging Method*

Fig. 14 shows the wireless charging method to the electric assisted bicycle. The receiving antenna is connected to the sides of the front basket of the electric assisted bicycle. The proposed system is introduced to a charging side. There are the following advantages by this method.

1) The foreign body (Dust, etc) is less likely to adhere to the power transmitting and receiving antenna, as compared to a system for power transmission from the ground (Therefore, it does not affect the transmission efficiency)

2) The variation of transmission distance and the positional deviation of between the transmitting and receiving antenna can be reduced by the front wheel is fixed using bicycle parking stand.

3) It is low cost because the antenna and wiring are not placed into the ground.

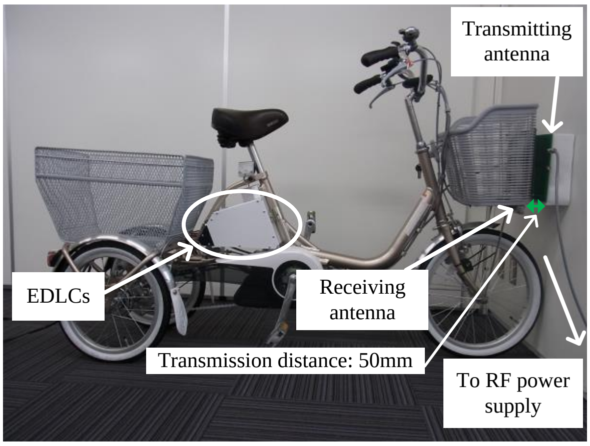


Fig. 14. Wireless charging method to the electric assisted bicycle.

VI. CONCLUSION

This paper evaluated the energy capacity of EDLCs, the antenna for wireless power transmission and the charger, the interface converter for EDLCs in proposed system configuration. The proposed system was experimentally verified as the prototype. The results showed following conclusions;

1) The results showed that the short type as the antenna for wireless power transmission is higher efficiency than the open type with the same size.

2) The results showed that such as an electric assisted bicycle for small-capacity system, boost-type is small. On the other hand, such as electric vehicles for large-capacity system, buck-type is small.

3) The results showed that the charging time of EDLCs in proposed system can be shorten by 1/4 compared to the conventional system.

Finally, effectiveness of the proposed control was confirmed experimentally.

In the future work, the running test using the proposed system in an actual road will be experimentally verified.

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