

Proposal of Electric Disconnection Method with Boost Converter in Dynamic Wireless Power Transfer

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Abstract—The technology that not only transmits power from a road to an electric vehicle is called *Dynamic wireless power transfer (DWPT)*. In this system, a power supply battery is installed in the vehicle. Voltage control is necessary to maintain the desired voltage of this battery. Furthermore, from a safety perspective, there is a risk that battery cells may be damaged due to overcharging. Therefore, in this study, we propose a power disconnection method using a boost chopper capable of voltage control. Simulation results confirmed that increasing the time required for disconnection can mitigate the adverse effects of disconnection on the system. We also demonstrated that this is independent of the circuit configuration (single or multiple).

Keywords— *Dynamic Wireless Power Transfer, DWPT, MIMO, Power Control, Boost Converter*

I. INTRODUCTION

Electric vehicles (EVs) are attracting attention as part of policies aimed at realizing a carbon-neutral society, one of the SDGs [1]. Currently available technologies include charging via a plug while the vehicle is stationary, as well as methods for wireless power transmission. This is referred to as Wireless Power Transfer (WPT). Since power transmission is limited to when the vehicle is stationary, there are challenges such as short driving ranges and long charging times [2]. The focus here is on (DWPT). Since this method allows power transmission while the vehicle is in motion, it is expected to help resolve the aforementioned issues. In fact, research on DWPT for passenger cars is already well underway [3]. Additionally, experiments using large vehicles have already been conducted [4][5]. For DWPT in large vehicles, sharing

the same power supply lines as passenger cars—which have relatively lower power requirements—is both compatible with existing research and economically rational. Therefore, there is a need to develop a power reception system for large commercial vehicles that utilizes multiple power reception coils designed for passenger cars [6]. There is extensive research on Multiple-Input Multiple-Output (MIMO) WPT systems, and their power characteristics have been well-established [7].

In addition, the transmitted power can be used to charge the battery. In this case, it is assumed that the transmitted power is supplied to the battery on the receiving side [8]. Considering safety, if the battery is overcharged, there is a risk that the battery will generate heat due to the excess power and experience thermal runaway [9]. To avoid this risk, the power supply must be interrupted. Furthermore, given the potential for communication delays, independent interruption control must be performed on the receiving side. One method for this is control via a short-circuit mode tailored to the impedance characteristics of the WPT circuit.

Short mode refers to a state in which, as shown in Fig. 1(b), the circuit around the battery is isolated from other circuits, thereby halting the power supply to the battery. At this time, the voltage at the power receiving section (V_{out}) and the current flowing through the power receiving section (I_{out}) take the following values [10].

$$V_{out} = 0, I_{out} = 0 \quad (1)$$

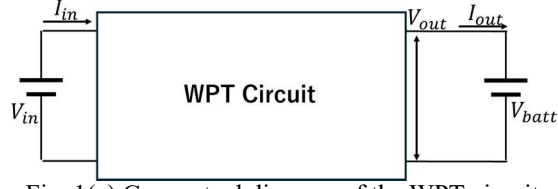


Fig. 1(a) Conceptual diagram of the WPT circuit
(Normal Condition)

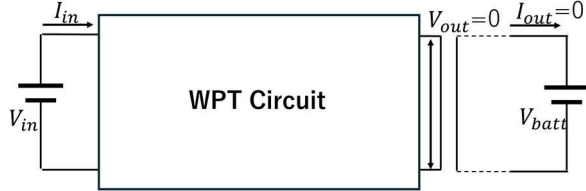


Fig. 1(b) Conceptual diagram of the WPT circuit
(Power Disconnection)

In this paper, we propose a control method that minimizes the number of additional components required for conventional circuits to achieve short-circuit mode. In particular, considering the risk of communication delays, control is performed independently on the receiving side rather than the transmitting side. The proposed method applies power control based on the duty cycle of a boost chopper to regulate the desired power and executes power disconnection using a chopper circuit that leverages the flexibility of the duty cycle.

In this paper, Section 2 describes the circuit configuration, and Section 3 explains the proposed method. Subsequently, Section 4 presents the simulation results, Section 5 presents actual experiment and Section 6 presents the conclusions.

II. THEORY

A. Boost Converter

In this paper, we propose a boost converter as a circuit to realize short-circuit mode. Voltage control is necessary to maintain the desired battery voltage, which requires a DC/DC converter. The circuit diagram shown in Fig. 2 illustrates the power receiving-side circuit configuration assumed in this paper in a single-output form. Since the output of the resonant circuit exhibits a constant-current characteristic, the receiving current I_{DC_in} becomes constant. As a result, a constant current flows continuously through the smoothing capacitor located downstream of the rectifier, thereby fulfilling the step-down function. Furthermore, since the power reception voltage V_{DC_in} must be controlled to meet the desired battery voltage, a boost chopper is adopted as the DC/DC converter. Since the output voltage of the boost chopper is fixed at the battery voltage V_{batt} , the power reception voltage V_{DC_in} is determined by the duty cycle value according to Equation (2). The on-duty ratio of the high-side MOSFET, d , can be controlled within the range of $0 \leq d \leq 1$, and due to this high degree of freedom, it is possible to set the lower limit of the input voltage, V_{DC_in} , to 0. In Fig. 1, when $V_{out} \equiv V_{DC_in}$,

Equation (2) satisfies the condition of Equation (1). In contrast, in the case of a buck chopper, Equation (3) shows that the condition of Equation (1), $V_{DC_in} \equiv V_{out} = 0$, cannot be satisfied.

Therefore, this paper adopts a boost chopper as the power cutoff circuit.

$$V_{DC_in} = (1 - d)V_{batt} \quad (0 \leq d \leq 1) \quad (2)$$

$$V_{DC_in} = \frac{V_{batt}}{d} \quad (0 < d \leq 1) \quad (3)$$

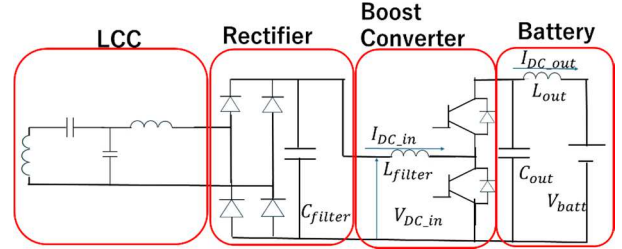


Fig. 2. Configuration of the receiver-side circuit with a boost converter

B. Double-LCC Topology

This section discusses the advantages of the Double-LCC circuit and the feasibility of achieving short-circuit mode.[11] Fig. 3 shows the circuit diagram, and Fig. 4 shows the exploded view of Fig. 3. As shown in Fig. 4, when the Double-LCC circuit diagram is decomposed, the gyrator circuits composed of L_{T0} and C_{Tp} , as well as L_{R0} and C_{Rp} , have the characteristic of swapping the constant-voltage and constant-current characteristics of the two terminal pairs. As a result, the transmission and reception coils in a Double-LCC circuit connecting a constant-voltage power source and a constant-voltage load exhibit constant-current characteristics, providing robustness against resonance shifts. Similarly, since constant-current characteristics also appear on the output side, when using a constant-voltage load such as a battery, controlling the reception voltage with a DC/DC converter simultaneously controls the received power.

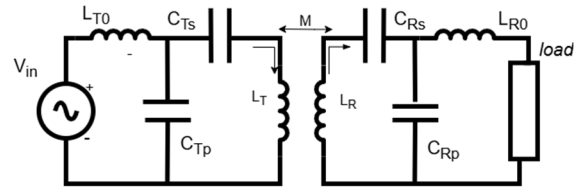


Fig. 3. Double-LCC Circuit

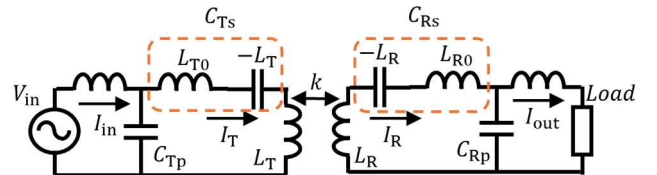


Fig. 4. Double-LCC Circuit (explicitly representing a gyrator)

Furthermore, research indicates that the output power characteristics of a Double-LCC circuit are less susceptible to

the effects of the cross-coupling (CC) phenomenon compared to an S-S circuit [12]. We evaluate whether the short-circuit mode can be achieved. Following Equation (1), we calculate and evaluate the impedance of the Double-LCC circuit when the input voltage V_2 is set to $V_2 = 0$. The circuit showing each impedance is shown in Fig. 5, and the calculation results are shown in Table 1.

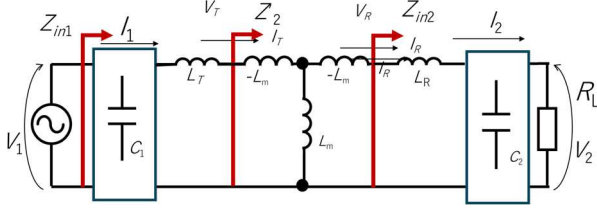


Fig. 5. Extended Circuit

Table 1. Circuit Selection

Topology	R_L	Z_{in1}	Z'_2	Z_{in2}
Double-LCC	$R_L \neq 0$	$\frac{1}{\omega^6 C_{p1}^2 C_{p2}^2 L_m^2 R_L}$	$\omega^4 C_{p2}^2 L_m^2 R_L$	$\frac{1}{\omega^2 C_{p2}^2 R_L}$
	$R_L = 0$	∞	0	∞

Table 2 shows that when the load at the power receiving end is $R_L = 0$ ($V_2 = 0$), Z_{in1} , Z_{in2} diverges. From this, since both the input current I_1 and the output current I_2 converge during a power interruption, we evaluate that the short-circuit mode is feasible, assuming the safety of the components is ensured. Based on the advantages in power receiving control and the feasibility of the short-circuit mode, this paper adopts the Double-LCC circuit.

III. METHOD

A. System Goal

When the two MOSFETs in the boost chopper used for this disconnection operate in a complementary manner, the two operating states are designated as Mode 1 and Mode 2. This section explains the circuit states at these times and describes the objectives of the proposed disconnection method. The respective operating states are shown in Fig. 6(a) and (b).

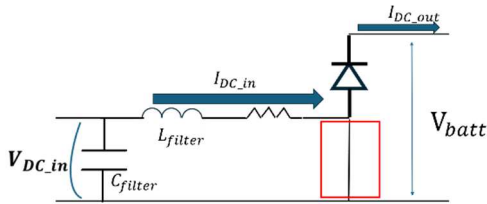


Fig. 6(a). Boost converter Mode 1

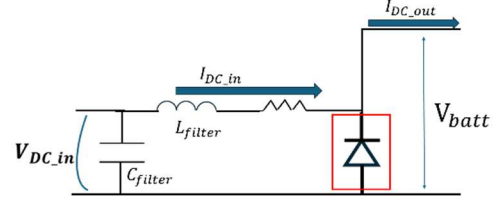


Fig. 6(b). Boost converter Mode 2

The values of $V_{DC,in}$, $I_{DC,out}$ in each mode are expressed using V_{batt} , and $I_{DC,in}$ as shown in Equations (4) and (5). The time spent in each operating state is denoted as t .

$$V_{DC,in} = 0, \quad I_{DC,out} = 0 \quad \text{Mode1} \quad (0 \leq t < dT) \quad (4)$$

$$V_{DC,in} = V_{batt}, \quad I_{DC,out} = I_{DC,in} \quad \text{Mode2} \quad (dT \leq t < T) \quad (5)$$

From Equations (4) and (5), $I_{DC,out}$, $V_{DC,in}$ can be expressed in terms of the duty ratio as

$$V_{DC,in} = (1 - d)V_{batt}, \quad I_{DC,out} = (1 - d)I_{DC,in} \quad (6)$$

. From Equations (2) and (6), when $d = 1$ —that is, when the system is permanently in Mode 1—the condition in Equation (1) is satisfied.

To maintain Mode 1, the target power is limited. When the number of power circuits is N , the current supplied to the battery from the i th and $(1 \leq i \leq N)$ th circuits is $I_{DC,out,i}$, and the total power $P_{receive}$ is proportional to the sum of the $I_{DC,out}$ values for each phase, as shown in Equation (7).

$$P_{receive} = \sum_{i=1}^N P_i = \sum_{i=1}^N V_{in,i} I_{DC,in,i} \quad (7)$$

When the target power consumption P_{target} is set, $P_{receive}$ is controlled to track P_{target} , so using Equations (6) and (7), this can be expressed as Equation (8).

$$P_{receive} \approx P_{target} = \sum_{i=1}^N (1 - d_i) V_{batt} I_{DC,in,i} \quad (8)$$

Here, if we set $P_{target} = 0$, then based on $V_{batt} \approx \text{const} \neq 0$ and $I_{DC,in,i} \neq 0$ (assuming a power supply state), the relationship in Equation (9) holds uniformly regardless of the value of i .

$$(P_{target}, I_{DC,out,i}, d_i, V_{DC,in}) = (0, 0, 1, 0) \quad (9)$$

Therefore, by performing target power control, the cut-off criteria in Equation (1) can be satisfied.

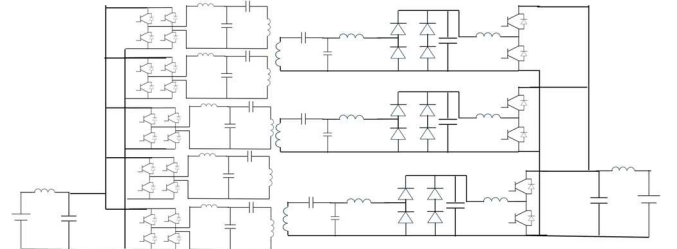


Fig. 7. Entire DWPT circuit in this paper

IV. SIMULATION OF CIRCUIT

A. Circuit Simulation Conditions

Simulations were performed using MATLAB/Simulink. The purpose of the simulation was to verify the feasibility of the proposed method. The simulation utilized a circuit system consisting of five transmission coils and three reception coils, as shown in Fig. 7. As shown in Figure 7, the three power receiving units are used to perform simultaneous disconnection. Note that a system with no current coupling (CC) between the reception coils was adopted. The proposed method involves changing the desired power during operation and controlling the duty cycles (d_1, d_2, d_3) of the three boost converters individually to meet the desired power. In this study, the target power was set to 6000 W under normal conditions and changed to 0 W during disconnection. Disconnection was determined by incrementally increasing the battery voltage in proportion to the simulation time (Time) and setting it to a threshold voltage (V_{th}); disconnection occurred when the voltage reached $V_{batt} = V_{th}(Time = 0.5)$. The simulation parameters are shown in Table 2.

Table 2. Simulation parameters.

Vehicle velocity	v	100 km/h
DC input voltage	V_{in}	600 [V]
Battery voltage	V_{batt}	600 + 0.04Time V
Threshold voltage	V_{th}	600.002 V
Operating frequency	f	85 kHz
Primary compensated inductance	L_{T0}	49.3 μ H
Primary compensated capacitor	C_{Tp}	71.1 nF
Primary resonant capacitor	C_{Ts}	22.4 nF
Primary transmitter inductance	L_T	205.8 μ H
Primary transmitter resistance	r_T	150 m Ω
Secondary compensated inductance	L_{R0}	26.4 μ H
Secondary compensated capacitor	C_{Rp}	132.6 nF
Secondary resonant capacitor	C_{Rs}	139.8 nF
Secondary receiver inductance	L_R	51.52 μ H
Secondary receiver resistance	r_R	65 m Ω
Target power	P_{target}	6000W
DC/DC carrier frequency	$f_{DC/DC}$	20 [kHz]
Transmission coil length	l_{Tx}	500 mm
Power transmission coil spacing	G_{Tx}	200 mm
Receiving coil length	l_{Rx}	200 mm
Receiving coil spacing	G_{Rx}	50 mm
DC/DC input inductor	L_{filter}	900 μ H
DC/DC input capacitor	C_{filter}	30 μ F
Inductor in front of the battery	L_{out}	100 μ H
Inductor upstream of the battery	C_{out}	300 μ F

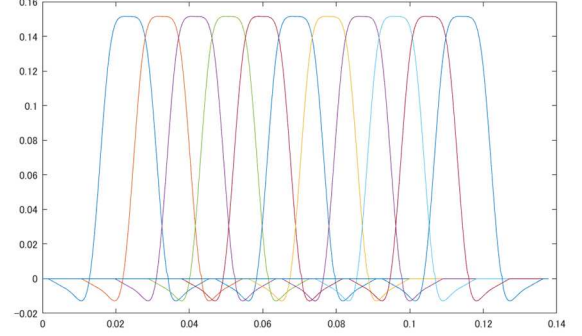


Fig. 8 5to3 coupling coefficient data

B. Simulation results of the disconnection method

($P_{target}, I_{DC_in_i}, I_{DC_out_i}$)($1 \leq i \leq 3$) The simulation results are shown in Figs. 9 and 10. The results for the case where the circuit was not disconnected are also shown. Note that " $I_{DC_in_i}$ " represents the total " I_{L_total} " for each circuit.

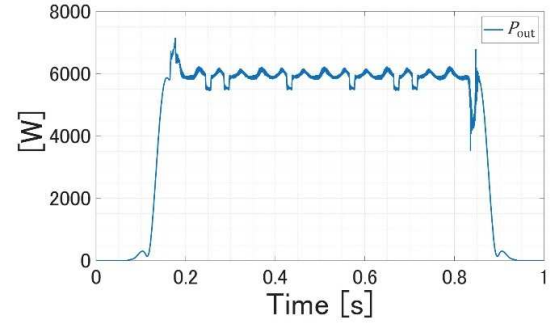


Fig. 9(a). Received Power (Normal Condition)

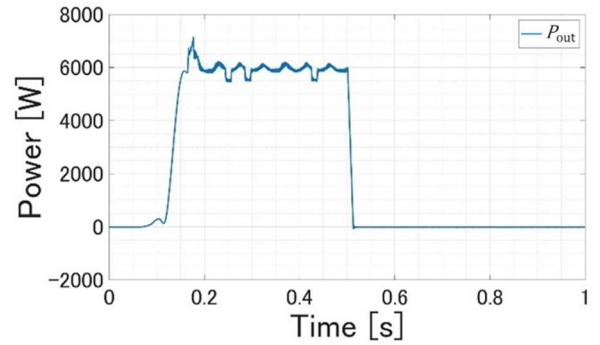


Fig. 9(b). Received Power (Power Disconnection)

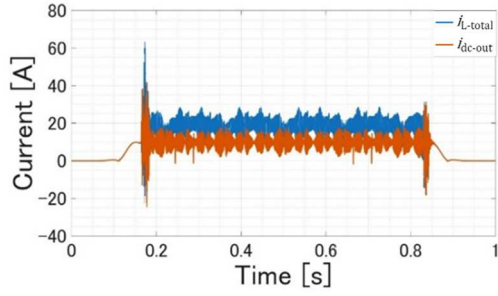


Fig. 10(a). Rectifier output current and current to battery
(Normal Condition)

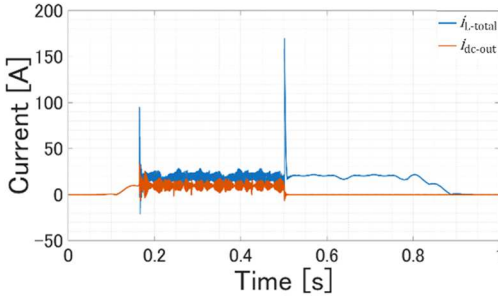


Fig. 10(b). Rectifier output current and current to battery
(Power Disconnection)

Comparing Figs. 10(a) and 10(b), we confirmed that the disconnection conditions in Equations (1) and (9) are satisfied at Time = 0.5 s. From Figs. 9(a) and (b), we observed a surge current of approximately 170 A in the " i_{L_total} " at Time = 0.5 s. Therefore, we perform power control to suppress this surge current.

From Time = 0.5 s onward, the target power is gradually reduced as shown in Equation (11) and this process continues until Equation (9) is satisfied. The duration of this continuous operation is defined as the disconnection time γ .

$$P_{target} = 6000 - \frac{6000}{\gamma} (Time - 0.5) \geq 0 (Time \geq 0.5) \quad (11)$$

γ We attempt to suppress the inrush current by varying this parameter. As examples, Fig. 11 and Fig. 12(a) show the waveforms for $P_{receive}$ and i_{L_total} when $\gamma = 0.05$ s, respectively, and Fig. 12(b) shows an enlarged view of Fig. 12(a). As shown in Fig. 12(b), we measured the maximum value I_{L_max} of i_{L_total} during the disconnection operation between $0.5 \leq Time \leq 0.5 + \gamma$, and Fig. 12 illustrates the relationship between this value and γ .

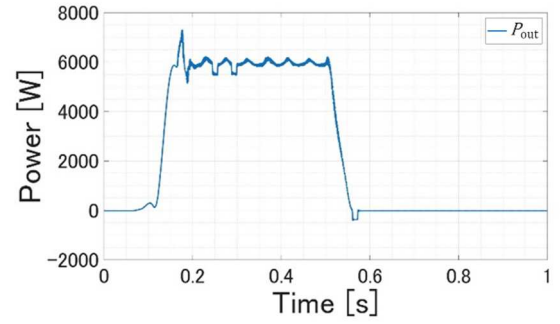


Fig. 11. Received Power (Power Disconnection) $\gamma = 0.05$
s

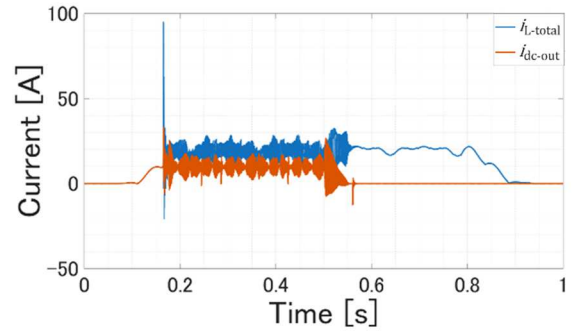


Fig. 12(a). The rectifier output current and current to the battery
(Power Disconnection) $\gamma = 0.05$ s

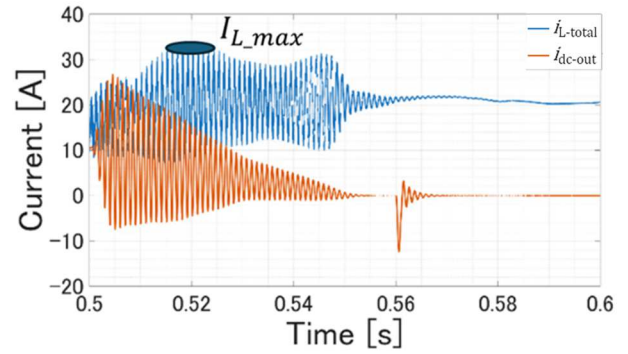


Fig. 12(b). Rectifier output current and current to battery
(Power Disconnection) $\gamma = 0.05$ s (expanded view)

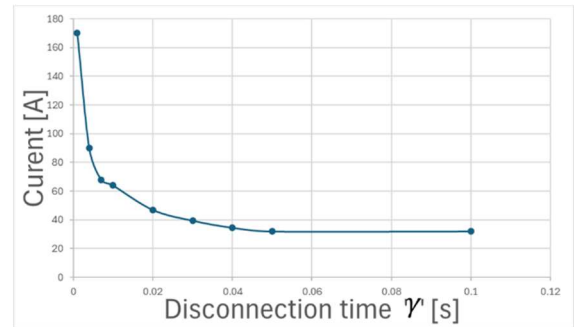


Fig. 13. Relationship between I_{L_max} and Disconnection time γ

From Fig. 13, it was confirmed that the $I_{L,max}$ changes transiently with respect to the disconnection time γ and converges to 32 A. We consider that this change with respect to the disconnection time is due to the characteristic of the inductor L_{filter} within the boost chopper to retain magnetic flux.

V. ACTUAL EXPERIMENT

I conducted experiment using a bench-top apparatus that simulates DWPT. The travel speed of this device can be freely adjusted, and it uses a bidirectional power supply. The parameters are shown in Table 2. And, just as in the simulation, we performed a power disconnection operation while the vehicle model was in motion. At this point, verify that the current flowing to the battery $I_{DC,out}$ is zero.

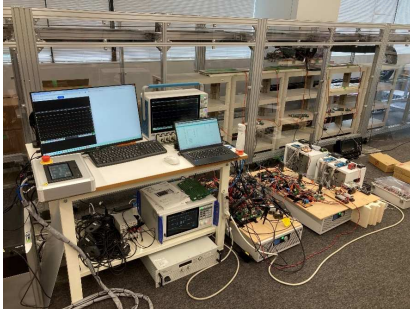


Fig 14, Bench device

Table2. Experimental parameter (Excerpt)

Vehicle velocity	v	2 m/s (7.2km/h)
DC input voltage	V_{in}	50 [V]
Battery voltage	V_{batt}	50 V

The experimental results for the input current are shown in Figure 15. As shown in Figure 15, it can be confirmed that the current to the battery $I_{DC,out}$ drops to zero when the power is cut off.

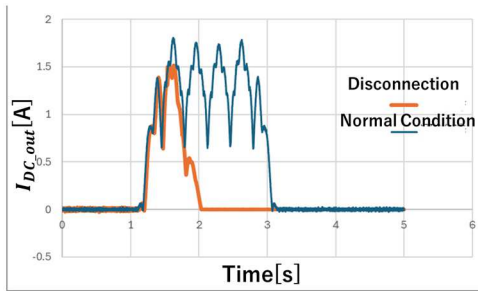


Fig15. Current to Battery

VI. CONCLUSION

In this paper, we performed power disconnection using multiple boost choppers for a multi-to-multi DWPT. The disconnection method was verified using a DWPT simulation bench. Based on the simulation results, considering safety during disconnection, we recommend minimizing the rate of change in the duty cycle or gradually reducing the desired power during disconnection, as this process typically takes at least tens to hundreds of milliseconds. We believe it is necessary to allow a margin in the SoC at which the cut-off command is issued to prevent battery overcharging.

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