# Battery Energy Storage System with Isolated Single-phase Matrix Converter using Center-tapped Transformer for Power Decoupling Capability

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*Abstract*—**This paper discusses a bi-directional isolated single-phase matrix converter using center-tapped transformer, which has a power decoupling capability for battery energy storage systems for renewable energy sources such as PV and wind turbine systems. The proposed converter is comprised of a full bridge inverter, a high frequency transformer and a matrix converter in order to eliminate large DC-link smoothing capacitor. The power decoupling method employs a center-tapped transformer and a small capacitor without any additional switches, which aims to achieve high efficiency. In this paper, by harmonic analysis, the effectiveness of power decoupling capability is verified in two cases: discharging/charging modes of a battery, which need to keep output power constant from battery for a single-phase grid system. As a simulation and experimental result, the validity of the power decoupling capability is confirmed in a charging/discharging mode. In addition, the proposed power decoupling method reduces the DC bus current ripple generated by a single-phase load to 85.1% in the discharging mode of experiments.**

***Keywords-component; matrix converter; power decoupling; bi-direction converter;***

## I. INTRODUCTION

Recently, photovoltaic (PV) and wind turbine systems have actively researched in terms of furtherance for renewable energy [1-4]. Energy storage systems such as using batteries are required for power leveling because renewable energy sources generate power fluctuation depending on natural conditions. The DC to AC converter needs isolation between the battery and the AC equipment for safety. Therefore, a bi-directional isolated DC to single-phase AC converter is required. Downsizing, long life-time and high efficiency are required for the isolated DC to single-phase AC converter. A conventional converter constructed by a full bridge inverter as a primary converter, a high frequency transformer, and a secondary converter composed of a diode rectifier and an inverter, has been proposed in [5]. However, a bulky electrolytic capacitor is required in the secondary converter to smooth DC-link voltage. Therefore, this circuit topology restricts downsizing and high efficiency.

On the other hand, a matrix converter has attracted a lot of attentions because of no energy buffer [6]. Thus, the matrix converter is expected to achieve higher efficiency, smaller size and longer life-time compared to the conventional rectifier-inverter system. However, a matrix converter cannot absorb power ripple which is generated by a single-phase grid because of no energy buffer in its topology. As a result, a power decoupling capability using small passive components is required to the isolated DC to single-phase AC converter in order to remove the power ripple component.

In last few years, some circuit topologies with the power decoupling capability have been proposed [7-9]. However, these papers employ not only passive components but also additional switching devices for the power decoupling. On the other hand, in order to achieve high efficiency, a power decoupling method using a center-tapped transformer and a small capacitor has been presented [10]. This method does not use additional switches and suppresses the ripple component in the input current significantly. However, this circuit still restricts downsizing, long life-time and high efficiency because [10] deals with the isolated DC to single-phase AC converter by using a diode bridge rectifier and a PWM inverter as described previously.

The authors have already proposed the power decoupling method for the isolated single-phase matrix converter with a center-tapped transformer in [11]. The proposed system consists of a full bridge inverter, a center-tapped transformer, a small capacitor a matrix converter. The proposed converter does not require extra switching devices for the power decoupling, owing to the center-tapped transformer. In contrast, a Pulse Density Modulation (PDM) which is appropriated to convert a high frequency voltage to a sinusoidal voltage at 50 Hz is applied to the matrix converter. In order to suppress fluctuation of an output power, this proposed circuit needs a bi-direction operation to charge an energy flow between a single-phase grid system and a battery for PV system. However, the bi-directional operation of the proposed circuit is not discuss in past works.

This paper demonstrates the bi-directional operation of the proposed power decoupling method for the isolated single-phase matrix converter with a center-tapped transformer. In addition, this paper clarifies the validity of the proposed power decoupling method at mode transition of an energy flow between a single-phase grid system by simulations and experiments.

This paper is organized as follows; first, the circuit configuration of the proposed DC to single-phase AC converter and the modulation method of the matrix converter at secondary side are described. Second, the principle of the power decoupling is described. Finally, the fundamental operation waveforms of the proposed system with discharging/charging operation modes are considered by simulations and experiments.

## II. CIRCUIT TOPOLOGY AND MODULATION METHOD

### *A. Circuit Toporogy*

#### *1) Conventional circuit*

Fig. 1 shows the conventional isolated DC to single-phase AC converter. The conventional circuit comprises of a full bridge inverter, a high frequency transformer and a rectifier-inverter system. The full bridge inverter outputs a square voltage at high frequency in order to reduce the volume of the transformer. The secondary rectifier converts the high frequency voltage to a DC voltage and the PWM inverter control the load current with a feedback control. When the load current is sinusoidal waveform and achieves the unity power factor, an instantaneous output power $p_{out}$ is expressed by (1).

$$\begin{aligned} p_{out} &= \sqrt{2}V_{grid}\sin(\omega_o t)\cdot\sqrt{2}I_{grid}\sin(\omega_o t) \\ &= V_{grid}I_{grid}\{1-\cos(2\omega_o t)\} = P_{out}\{1-\cos(2\omega_o t)\} \end{aligned} \tag{1}$$

where, $V_{load}$ is the load voltage (RMS), $I_{load}$ is the load current (RMS), $P_{out}$ is the output average power and $\omega_o$ is the output angular frequency. A ripple component shown in the second term of (1) should be bypassed in order to obtain a constant DC current in the DC bus. Hence, this system has to adopt a balky electrolytic capacitor $C_{dc}$ to absorb the power ripple.

#### *2) Proposed circuit*

Fig. 2 shows the isolated single-phase matrix converter using a small LC buffer. The DC bus voltage $V_{bus}$ is expressed the battery. The matrix converter is employed as a secondary converter in order to eliminate the DC-link capacitor which is used in conventional circuit. In addition, a center-tapped transformer, whose role is to link the full bridge inverter not only to the matrix converter for isolation, but also to the power decoupling which is used to reduce the DC bus current ripple, is employed. A buffer circuit including a buffer capacitor $C_{buf}$ and a buffer inductor $L_{buf}$ is used to absorb the power ripple. It should be noted that the charge and discharge to compensate the power ripple is implemented at the buffer capacitor $C_{buf}$. In order to yield a DC bus current without the ripple, the relationship between the instantaneous output power $p_{out}$ and the charged power $p_{buf}$ is defined as (1), assuming that the load current is sinusoidal waveform and achieves the unity power factor.

### *B. Modulation Method of Matrix Converter at Secondary Side*

Fig. 3 shows the control block diagram of the proposed converter. These current and voltage controls in the proposed method are implemented by PI controllers. The full bridge inverter independently provides a differential mode voltage to excite the transformer and a common mode voltage to compensate the power ripple [7]. The buffer current control is for the power decoupling. As shown in Fig. 3, the buffer current control is applied to vary the voltage of the buffer capacitor $v_{Cbuf}$ which is used to absorb the power ripple caused by the single-phase grid. Moreover, the buffer current reference $i_{buf}*$ and the output current reference $i_{grid}*$ are decided by the direction of the power flow in order to achieve the bidirectional power flow operation. Besides, the modulation of the matrix converter is discussed in the next chapter.

The matrix converter used as a secondary converter in the proposed system applies the PDM (Pulse Density Modulation) of [11-13]. The PDM is suitable to the direct AC to AC converter which provides a sinusoidal voltage at a commercial frequency from a high frequency voltage, such as the proposed system. The PDM treats the input voltage waveform at high frequency as a pulse and synthesize a grid voltage with a density of the input voltage pulses. A half cycle of the input voltage pulses are used as the minimum unit of the grid voltage waveform. Then, the matrix converter switches in zero voltage period of the input voltage waveform. In consequence, the matrix converter achieves Zero Voltage Switching (ZVS) which results in decreasing a switching loss. Thus, the PDM is applied to the matrix converter in this paper.

## III. POWER DECOUPLING METHOD

When the DC bus as battery energy storage systems is connected to power grid distribution systems, DC bus current includes a ripple component at twice of the grid frequency. In this chapter, the principle of the power decoupling for power flow where the battery is charged/discharged mode is explained.

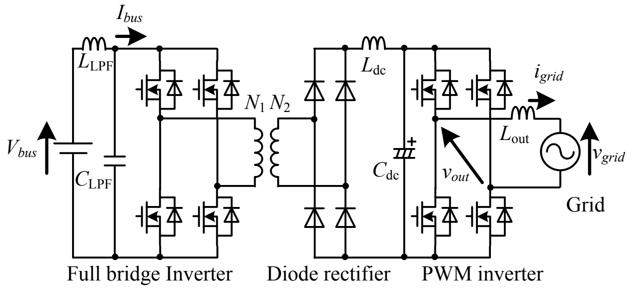


Figure 1. Conventional isolated DC to single-phase AC converter. Conventional converter uses bulky electrolytic capacitor $C_{dc}$ to absorb power ripple caused by single-phase load.

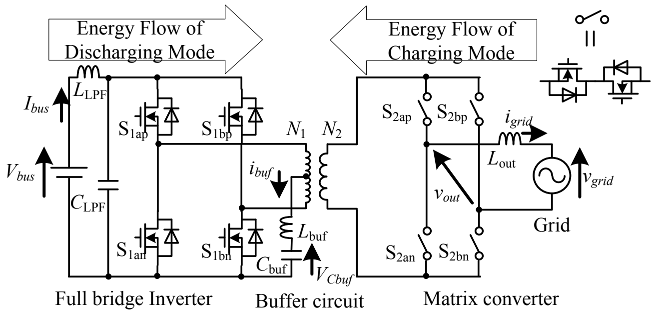


Figure 2. Proposed isolated DC to single-phase AC converter. Secondary converter consists of matrix converter in order to eliminate DC-link smoothing capacitor.

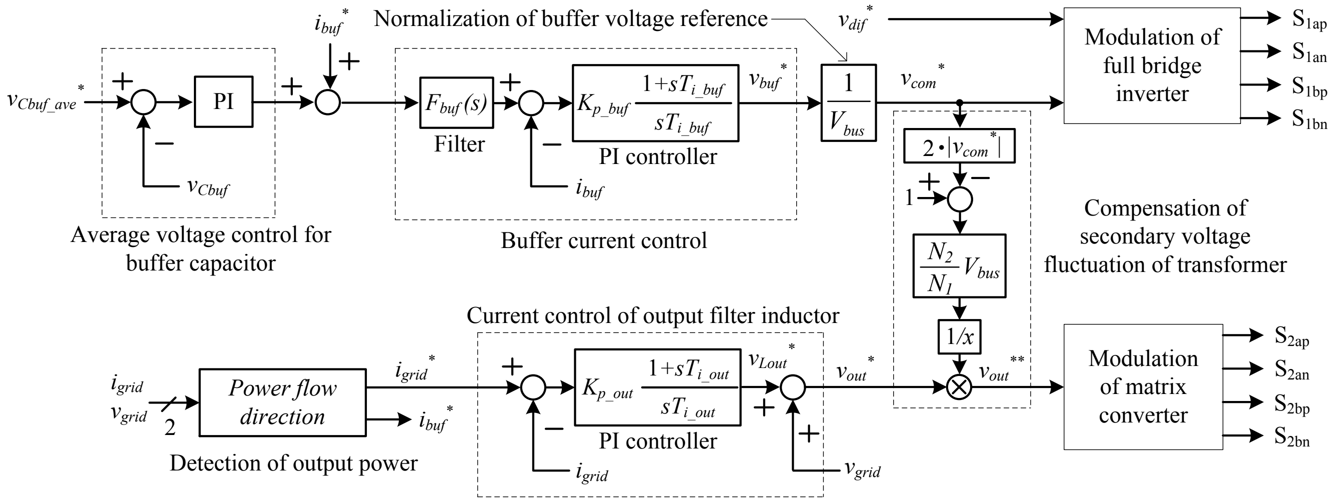


Figure.3. Control block diagram of proposed converter. Buffer current control is for power decoupling. Output filter current control is applied as minor loop of output filter capacitor voltage control that is originally required. By PLL, direction of power flow decides amplitude and phase which is assigned to output current reference and buffer current reference.

### A. *Discharging Mode of Battery*

In this section, the principle of the power decoupling when the battery is discharged is explained as shown in Fig. 2.

Fig. 4 shows the relationship among the DC bus power, an instantaneous output power $p_{out}$ and the power decoupling with $C_{buf}$. The feature of Fig. 2 is that the buffer current control to fluctuate the voltage of buffer capacitor $v_{Cbuf}$ absorbs the power ripple which is caused by the single-phase load. First, the buffer capacitor energy $W_{Cbuf}$ is presented by using (1) and a voltage–current equation of a capacitor.

$$\begin{aligned} W_{Cbuf} &= \int_{t_0}^{t} v_{Cbuf} i_{buf}\, d\tau = \int_{t_0}^{t} v_{Cbuf}\left(C_{buf}\frac{dv_{Cbuf}}{d\tau}\right)d\tau \\ &= \int_{t_0}^{t} P_{out}\cos(2\omega_o\tau)\,d\tau \end{aligned} \tag{2}$$

where, $t_0$ is a start time of operation. The buffer capacitor voltage $v_{Cbuf}$ which needs to absorb the power ripple is derived from (2).

$$v_{Cbuf}{}^* = \sqrt{\frac{V_{bus}{}^2}{4} + \frac{P_{out}}{\omega_o C_{buf}}\sin(2\omega_o t)} \tag{3}$$

where, $V_{bus}$ is an average DC bus voltage, $V_{bus}/2$ is an initial voltage of $C_{buf}$. Finally, $i_{buf}{}^*$ is derived by using an output power reference $P_{out}{}^*$.

$$i_{buf}{}^* = C_{buf}\frac{dv_{Cbuf}{}^*}{dt} = \frac{P_{out}{}^*\cos(2\omega_0 t)}{\sqrt{\frac{V_{bus}{}^2}{4} + \frac{P_{out}{}^*}{\omega_o C_{buf}}\sin(2\omega_o t)}} \tag{4}$$

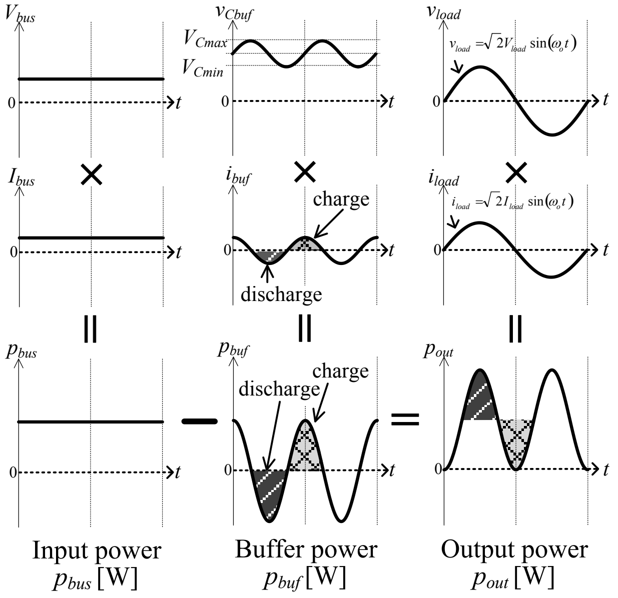


Figure.4. Principle of power decoupling with buffer capacitor in discharging mode. Buffer power to compensate power ripple is charged or discharged at $C_{buf}$. As a result, DC bus current without ripple component is obtained.

The power ripple in discharging mode is compensated by using the buffer current control with the current reference $i_{buf}{}^*$ as shown (4).

### B. *Charging Mode of Battery*

In this section, the principle of the power decoupling when battery is charged in order to build up the power from a single-phase grid system is explained. The power flow in this mode is reverse from that in the above session as shown in Fig. 2.

Fig. 5 shows the relationship among the DC bus power, an instantaneous output power $p_{out}$ and power decoupling in a

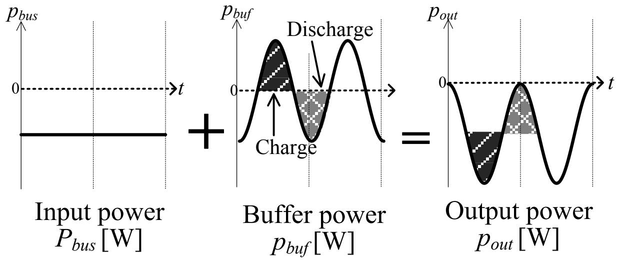


Figure 5. Principle of power decoupling with buffer capacitor in charging mode to battery at DC bus side.

charging mode. A buffer current control to fluctuate the voltage of buffer capacitor $v_{Cbuf}$ absorbs the power ripple caused by the single-phase load which is reverse compared to the discharging mode as described previously. Therefore, the buffer power $p_{buf}$ which needs to absorb the power ripple of the charging mode is expressed by (5) using the power flow direction as shown in Fig. 2.

$$p_{buf} = P_{bus} - p_{out} = -P_{out}\cos(2\omega_o t) \tag{5}$$

where the buffer capacitor voltage $v_{Cbuf}$ is derived from (6).

$$v_{Cbuf}^{*} = \sqrt{\frac{V_{bus}^{2}}{4} - \frac{P_{out}}{\omega_o C_{buf}}\sin(2\omega_o t)} \tag{6}$$

In this way, the buffer capacitor voltage $v_{Cbuf}$ which absorbs the power ripple of the charging mode is decided by the power ripple and the power flow. The buffer capacitor voltage can be changed to each power flow in detecting the polar of output power as shown in Fig. 4 and Fig. 5.

## IV. SIMULATION AND EXPERIMENTAL RESULTS

Table 1 shows the simulation condition to verify the fundamental operation of the proposed converter with the decoupling method as drawn in (3) and (6). In should be noted that, in simulation was done an ideal condition without an input filter and a dead-time.

### A. Simulation Results in Discharging Mode

Fig. 6 shows the input and the output waveforms in the discharging mode of a steady state. Fig. 6 (a) and (b) show results without/with the power decoupling method. The DC bus current is filtered by a LPF with a cut-off frequency of 1 kHz in order to remove a switching ripple. As shown in Fig. 6 (a), the DC bus current has a ripple component at 100 Hz caused by the single-phase load. The current ripple component at 100 Hz is 101% with reference to the average current. In contrast, the current ripple component is reduced in (b), owing to the power decoupling method. As a result, the ripple of the DC bus current is suppressed by 4.37%.

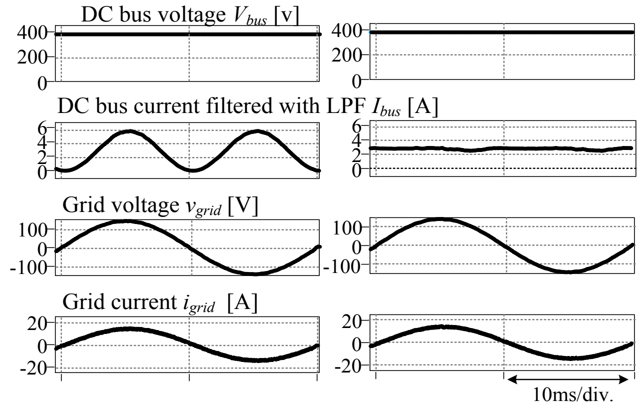
### B. Simulation Results in Charging Mode

#### 1) Steady state

Fig. 7 shows the input and the output waveforms in the charging mode at steady state. Fig. 7 (a) and (b) show results without/with the proposed power decoupling method. As shown in Fig. 7 (a), in the charging mode, the DC bus current has a ripple component at 100 Hz caused by the single-phase load in an opposite direction compared with the discharging mode as shown in Fig. 6(a). As a result, without the power decoupling method in the charging mode, current ripple component at 100

**TABLE Simulation Condition**

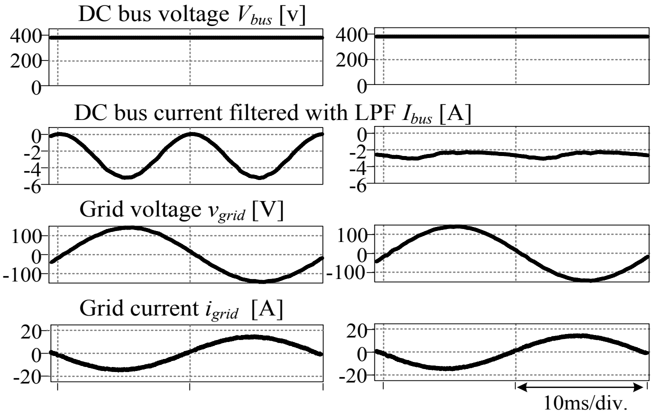
| DC bus voltage | 380 $V_{dc}$ | Grid voltage | 100 $V_{rms}$ |
|---|---|---|---|
| Rated power | 1kW | Grid frequency | 50 Hz |
| Buffer L ($L_{buf}$) | 2.0 mH | Buffer C ($C_{buf}$) | 200 μF |
| Grid connected inductor ($L_{out}$) | 2.0 mH (6.3%) | Turn ratio of transformer $N_2/N_1$ | 0.5 |
| Carrier frequency of full bridge inverter | 100 kHz | Carrier frequency of matrix converter | 10 kHz |
| Natural angular frequency of buffer current control | 4000 rad/s | Natural angular frequency of grid current control | 4000 rad/s |



(a)Without power decoupling method.

(b) With power decoupling method.

Figure 6. Input and output waveforms in discharging mode at steady state. Proposed power decoupling method reduces DC bus current ripple by 95.7% in discharging mode.



(a)Without power decoupling method.

(b) With power decoupling method.

Figure 7. Input and output waveforms in charging mode at steady state. Proposed power decoupling method reduces DC bus current ripple by 82.3% in charging mode.

Hz is 102% in reference to the average current. In contrast, the proposed power decoupling method reduces the DC bus current ripple by 13.0%. The reason, which the effectiveness of power decoupling is difference between the discharging/charging modes is an effect with the phase of the grid current by PDM.

### 2) *Mode transition*

Fig. 8 shows the input and the output waveforms in the mode transition which is changed in charging/discharging mode with the proposed power decoupling method. As a simulation result, the proposed power decoupling method can achieve to compensate the DC current ripple at constant, when the proposed system is changed in discharging/charging mode. Besides, surge current which is generated by point of changing power flow is compensated by an input LC filter because the surge current is enough low. Moreover, between a battery and proposed circuit is isolated. Hence, the effect on surge current to a battery is almost nothing.

## C. *Experimental Results in Discharging Mode*

An experimental setup is demonstrated in order to validate the proposed system. It should be noted that a LC filter is inserted in the DC bus side.

Fig. 9 shows the experimental waveforms of the proposed converter with $V_{bus}$ of 350 V, $v_{grid}$ of 100 Vrms and an R-L load of 500 W. Fig. 9 (a) shows a result without the power decoupling method and (b) shows a result with the method. As shown in Fig. 9(a), the buffer capacitor voltage does not vary because the full bridge inverter does not output the common mode AC voltage. As a result, the DC bus current has ripple component at 100 Hz. In contrast, the proposed power decoupling method provides the common mode AC voltage to fluctuate the buffer capacitor voltage. In consequence, the power ripple component in the DC bus current is decreased. Besides, the grid voltage THD in (b) is 2.17%.

Fig. 10 shows the harmonic analysis of the DC bus current. It should be noted that the harmonic number is based on the output frequency of 50 Hz. From the result, it is understood that without the power decoupling method, the ripple component at 100 Hz is 62.6% with reference to an average current, whereas the proposed power decoupling reduces the DC bus current ripple by 85.1%. As a result, these experimental results verified the effectiveness of the proposed power decoupling in the discharging mode.

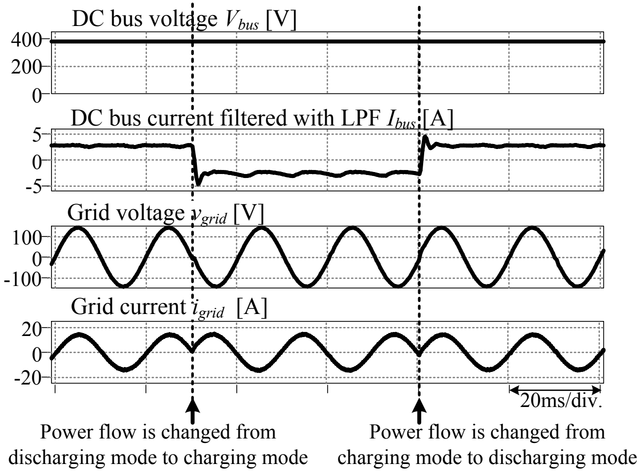
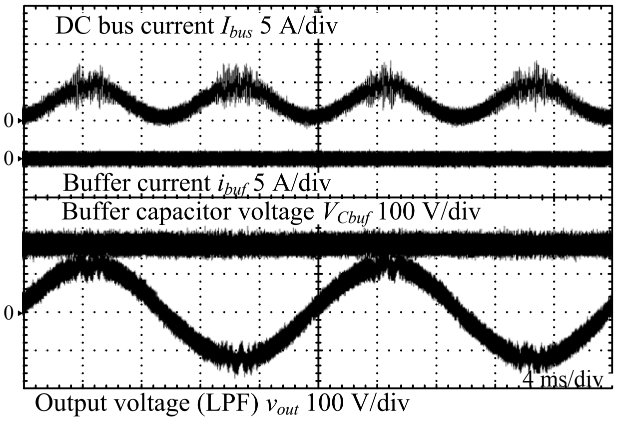
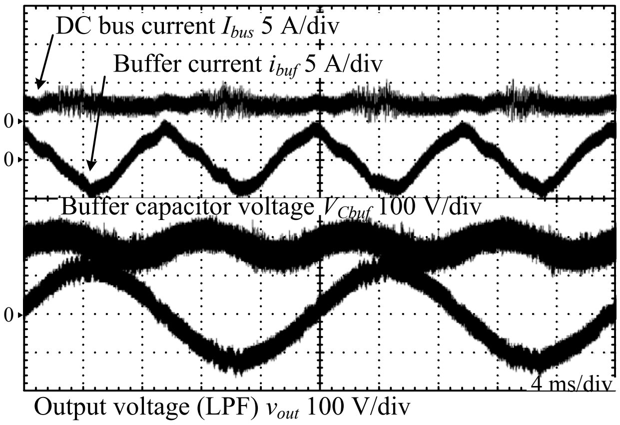


Figure 8. Input and output waveforms in discharging mode during mode



(a) Without power decoupling method.



(b) Without power decoupling method.

Figure 9. Experimental waveforms in steady state. DC bus current with proposed power decoupling method do not have little harmonic

## V. CONCLUSION

This paper discusses a bi-directional isolated single-phase matrix converter using center-tapped transformer, which has the power decoupling capability for battery energy storage systems. The proposed converter eliminates a bulky electrolytic capacitor because a matrix converter is employed as a secondary converter. The power decoupling method employs a center-tapped transformer and a small capacitor without any additional switches. In this paper, the effectiveness of the power decoupling capability is also confirmed in discharging/charging modes of a battery by simulations as first step. In simulation results, the proposed power decoupling method reduces the DC bus current ripple by 82.3% in the charging mode. In addition, in experiments, the power decoupling method reduces the DC bus current ripple generated by a single-phase load to 85.1% during the discharging mode.

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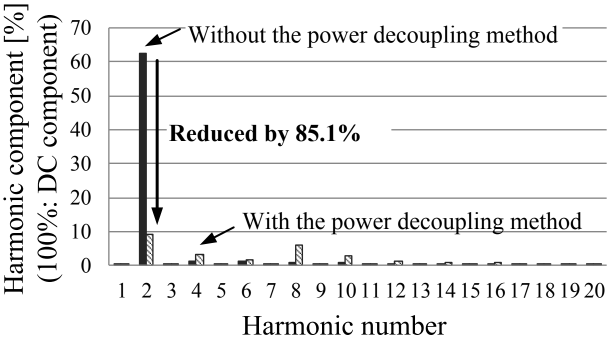

Figure 10. Experimental harmonic analysis of DC bus current. It should be noted that harmonic number is based on output frequency of 50 Hz. Power decoupling method reduces DC bus current ripple by 85.1%.

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