Power Decoupling Method Comparison of Isolated Single-phase Matrix Converters using Center-tapped Transformer with PDM

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***Abstract*— This paper presents an isolated type of single-phase matrix converter topology for PHV/EV on-board battery chargers. The proposed converter is comprised of a full bridge inverter, a high frequency transformer and a matrix converter. Due to the lack of DC link bus in matrix converter, in order to suppress the power fluctuation, a power decoupling method which only employs a center-tapped high frequency transformer and a small LC buffer where requires no additional switches is applied. On the other hand, the matrix converter applies PDM (Pulse Density Modulation) which achieve ZVS (zero voltage switching) in order to generate a 50Hz/60Hz sinusoidal waveform at the grid side. As a result, this converter shows promising features small size and high efficiency. In this paper, by harmonic analysis, the effectiveness of power decoupling method is evaluated in two cases: the PDM based on the PWM as a conventional method and the PDM based on the delta-sigma conversion. In the experimental results, the power decoupling method with the PDM based on the delta-sigma conversion reduces the DC bus current ripple by 84.8% comparing to the case where the power decoupling method is not applied, while the output voltage distortion is reduced by 64.1% compared with that of the PDM based on the PWM is applied.**

Keywords*— *matrix converter; isolated single-phase AC converter; power decoupling; pulse density modulation

I. Introduction

An increasing focus on the reduction of CO_2 has lead a rapid expanding in the growth of PHV/EV. In order to sustain such growth, a small size, high efficiency and bidirectional energy controlled on-board vehicle battery charger is actively being researched [1]. An isolated type of DC to single-phase AC converter is compulsory in order to achieve the safety requirement in a PHV/EV. A conventional converter that is 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 [2]. In order to reduce the power ripple component in the DC bus current which is caused by the single-phase load in this system, a high volume of bulky electrolytic capacitors is required in the secondary converter, which causes difficulty in downsizing the on-board vehicle battery charger.

In order to reduce the power ripple component, circuit topologies with power decoupling capability have been studied. In [3], this method adds a current loop control which reduces a ripple current into the existing voltage loop control system without additional converters or energy storage components for power decoupling. However, this system restricts downsizing because a large capacitor or reactor which is consisted as a component of DC to DC converter is required as an energy buffer. In other approaches, DC active filters have been proposed, where these methods usually consist of a small buffer capacitor as an energy buffer, a reactor to reduce the switching ripple, and a DC chopper [4-8]. As a result, volume reduction of the buffer capacitor is possible. However, these circuits restrict the high efficiency because in the tradeoff for passive components, more switching devices are used for the power decoupling.

On the other hand, a power decoupling method that utilizes the center-tapped transformer with a small LC buffer in an inverter has been presented [9]. This topology can compensate the power ripple without any additional switching devices however but then needs a DC-link smoothing capacitor in DC link bus at the secondary side. Since this circuit needs to deal with the isolated DC to single-phase AC converter by using a diode bridge rectifier and a PWM (Pulse Width Modulation) inverter, where the smoothing capacitors are required in the DC bus link, light weight design is difficult in the AC/AC conversion in the secondary side of the transformer.

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The diode bridge rectifier and the PWM inverter system of the secondary side raises large size, heavy in weight and shorter life-time because this system needs the smoothing capacitors in the DC bus link. Many studies have shown that the topology of matrix converters promises to achieve higher efficiency, smaller size and longer life-time [10-11]. The topology of a matrix converter is employed between the isolated transformer and single-phase grid instead of the conventional diode bridge rectifier and inverter [12]. From the above combination, the proposed on-board battery charger can achieve light weight by using small volume of LC buffer circuit to achieve power decoupling, and also achieve higher efficiency by applying ZVS (Zero Voltage Switching) in the switching devices of the matrix converter.

This paper proposes an isolated single-phase matrix converter with a PDM based on a delta-sigma conversion in order to improve the effectiveness of the proposed power decoupling method. The modulation method of a matrix converter used in [12] is a PDM (Pulse Density Modulation) based on a PWM [13-14]. This method can suppress a conversion loss because of enabling ZVS by synchronizing the gate pulses of the matrix converter with zero voltage term of the secondary voltage of transformer. However, when the carrier frequency ratio between the full bridge inverter and the matrix converter is not large enough or the modulation index of the matrix converter becomes relatively low, the output voltage distortion caused by the quantization error increases. The output voltage distortion influences the power ripple component in the DC bus current, and this decreases the effectiveness of the power decoupling because the proposed power decupling method cannot compensate the power fluctuation of an effect on the output voltage distortion.

In the PDM based on the delta-sigma conversion, the resolution becomes independent on the carrier frequency ratio and the modulation index of the matrix converter. Thus, this proposed PDM method not only decreases the output voltage distortion but also further reduce the power ripple by using the proposed power decoupling method.

II. CIRCUIT TOPOLOGY

A. Conventional Converters

Fig. 1 shows a conventional isolated DC to single-phase AC converter. The conventional circuit is comprised of a full bridge inverter, a high frequency transformer and a rectifier-inverter system. The full bridge inverter outputs a square voltage at a high frequency in order to reduce volume of the transformer. The secondary rectifier converts the high frequency voltage to a DC voltage and the PWM inverter controls an output filter capacitor voltage 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).

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

where, V_{load} is the load voltage (RMS), I_{load} is the load current (RMS), P_{out} is an output mean power and ω_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 of the DC bus. Hence, this system has to adopt a bulky electrolytic capacitor C_{dc} and a inductor L_{dc} to absorb the power ripple.

Fig. 2 shows an isolated DC to single-phase AC converter with a DC active buffer circuit in [9]. This circuit comprises a full bridge inverter, a high frequency center-tapped transformer, a DC active filter and a rectifier-inverter system. The converter combines a full bridge inverter at primary side and a small LC buffer circuit as a function of a DC active filter by using the center-tapped transformer. Therefore, the primary side of this system has two capabilities of the full bridge inverter and the buffer circuit and absorbs the power ripple. This system reduces a volume of a DC-link smoothing capacitor C_{dc}. In addition, this circuit does not require additional switching devices in comparison to the conventional circuit. However, this circuit still needs a large DC-link smoothing capacitor C_{dc} and transforms the power in twice at secondary side of the transformer because this system deals with the isolated DC to single-phase AC converter by using a diode bridge rectifier and a PWM inverter as described previously. Thus, this circuit restricts a downsizing and high efficiency.

B. Proposed Converter

Fig. 3 shows the isolated DC to single-phase AC converter

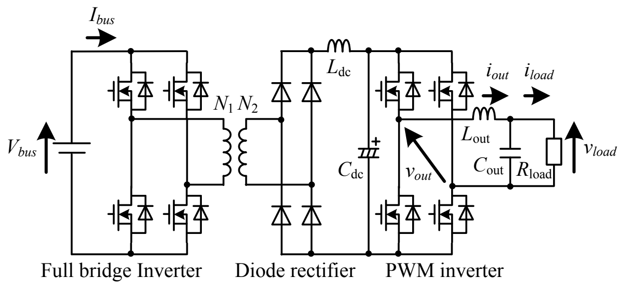


Fig.1 A conventional isolated DC to single-phase AC converter. The conventional converter uses a bulky electrolytic capacitor C_{dc} and an inductor L_{dc} to absorb the power ripple caused by a single-phase load.

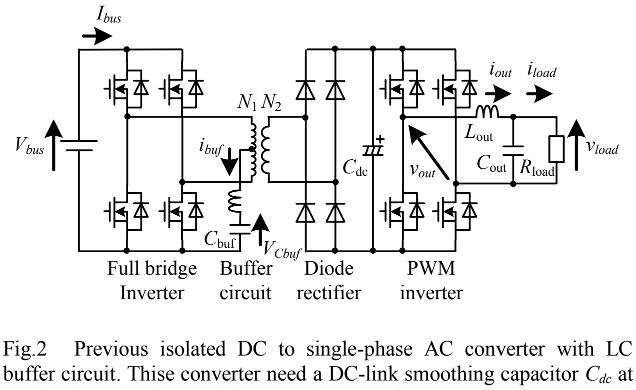


Fig.2 Previous isolated DC to single-phase AC converter with LC buffer circuit. Thise converter need a DC-link smoothing capacitor C_{dc} at DC bus in secondary side because the secondary converter is comprised of diode rectifier and PWM inverter.

using a matrix converter and a small *LC* buffer which is proposed in this paper. The matrix converter is employed as a secondary converter in order to eliminate the DC-link smoothing capacitor, which is used in Fig. 2. When the matrix converter applies in a secondary converter, this system can suppress a conversion loss because of enabling ZVS by synchronizing the gate pulses of the matrix converter with zero voltage term of the secondary voltage of transformer. In addition, a center-tapped transformer links the full bridge inverter to the matrix converter for isolation and the power decoupling which results in reducing the DC bus current ripple. A buffer circuit including a buffer capacitor C_{buf} and a buffer inductor L_{buf} is used in order to absorb the power ripple. It should be noted that a charge and a discharge of the buffer capacitor C_{buf} to compensate the power ripple is implemented at C_{buf}. As explained above, the proposed converter achieves higher efficiency, smaller size and longer life-time compared to the conventional rectifier-inverter system.

Fig. 4 shows a principle of the power decoupling with C_{buf}. In order to yield a DC bus current without the ripple, a relationship among the output power p_{out}, a DC bus power P_{bus} and a buffer power p_{buf} is defined as (2)-(4).

$$p_{out} = P_{bus} - p_{buf} \tag{2}$$

$$p_{out} = P_{bus} \tag{3}$$

$$p_{buf} = P_{out}\cos(2\omega_o t) \tag{4}$$

where, a polarity of p_{buf} is defined as positive when C_{buf} is charged. In order to even out a DC bus current, the buffer circuit has to reduce the ripple component of a paragraph 2 in (1). Therefore, p_{buf} consists with the second term of (1). It should be noted that the used capacitor is smaller than one in the conventional converter because the power ripple is compensated by varying a buffer capacitor voltage v_{Cbuf} not a large capacitance. On the other hand, an inductor in the buffer circuit is used for the current control for the power decoupling, which is equivalent to control of p_{buf}. The buffer current control is carried out by the full bridge inverter. The full bridge inverter outputs a differential mode voltage to excite the transformer and a common mode voltage to compensate the power ripple with the LC buffer independently, owing to the center-tapped transformer [7]. Thus, the proposed converter does not require additional switching devices for the power decoupling and number of devices of the proposed converter is the same as one of the conventional circuit.

III. CONTROL STRATEGY

Fig. 5 shows a control block diagram of the proposed converter. The current and voltage control 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 [12]. In contrast, the modulation of the matrix converter is discussed in the next chapter. Fig. 5 shows the control block diagram, the buffer current control is

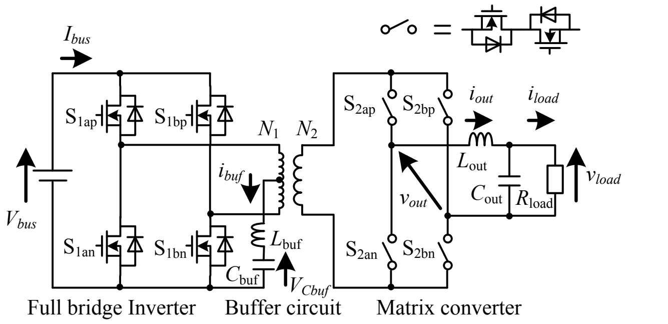


Fig.3 Proposed isolated DC to single-phase AC converter. The secondary converter is comprised of a matrix converter in order to eliminate DC-link smoothing capacitor.

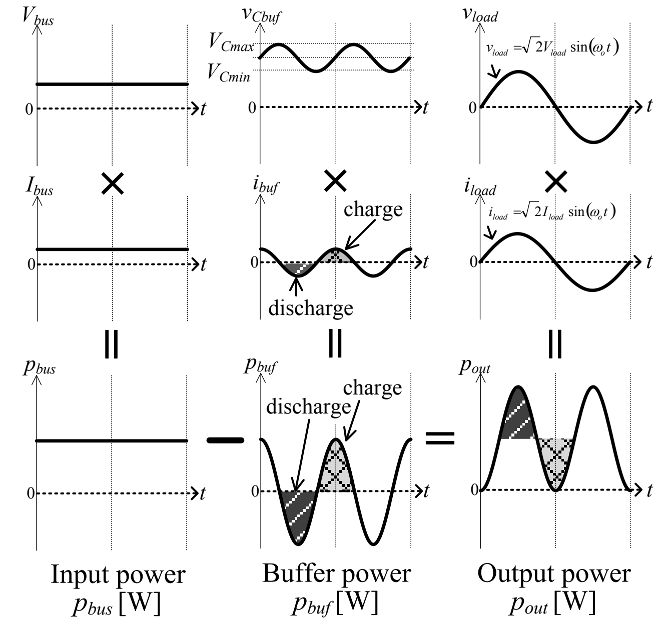


Fig.4 A principle of the power decoupling with the buffer capacitor. A buffer power to compensate the power ripple is charged or discharged at C_{buf}. As a result, a DC bus current without the ripple component is obtained.

applied to vary the voltage of buffer capacitor v_{Cbuf} which is used to absorb the power ripple caused by the single-phase load.

First, the buffer capacitor energy W_{Cbuf} is presented by using (4) and a voltage–current equation of a capacitor.

$$W_{Cbuf} = \int_{t_0}^{t} v_{Cbuf} i_{buf} d\tau = \int_{t_0}^{t} v_{Cbuf}\left(C_{buf}\frac{dv_{Cbuf}}{d\tau}\right)d\tau$$
$$= \int_{t_0}^{t} P_{ave}\cos(2\omega_o\tau)d\tau \tag{5}$$

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 (5).

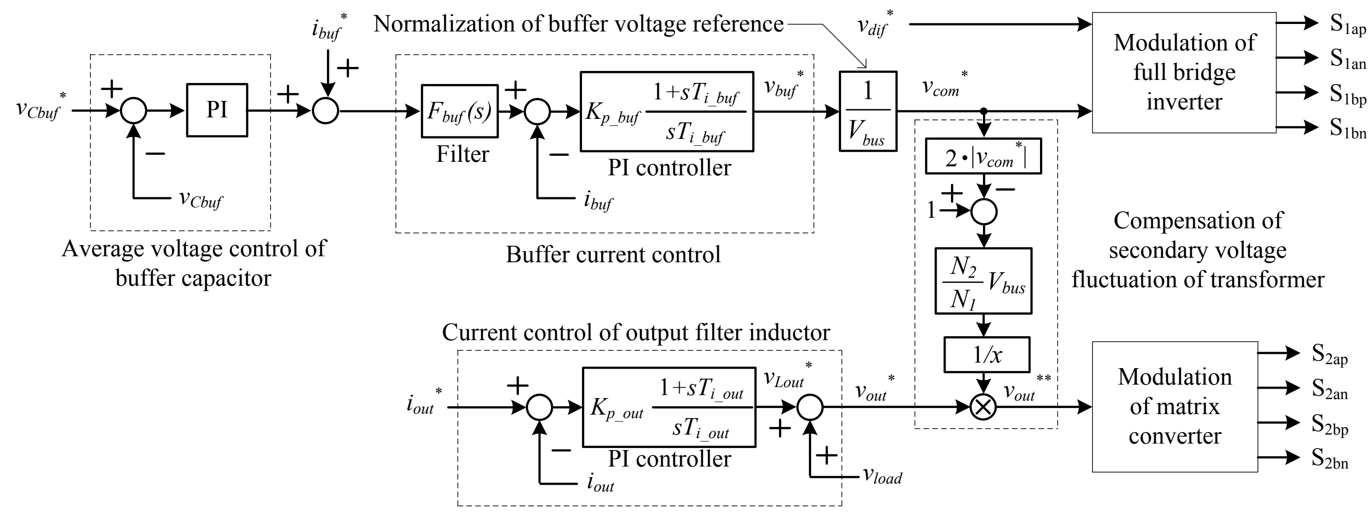


Fig.5 Control block diagram of the proposed converter. A buffer current control is for the power decoupling. An output filter current control is applied as a minor loop of the output filter capacitor voltage control that is originally required.

$$v_{Cbuf} = \sqrt{V_{C0}^{2} + \frac{P_{ave}}{\omega_o C_{buf}}\{\sin(2\omega_o t) - \sin(2\omega_o t_0)\}} \tag{6}$$

where, V_{bus} is the average DC bus voltage and P_{ave}* is calculated by load resistance.

$$i_{buf}^{*} = C_{buf}\frac{dv_{Cbuf}^{*}}{dt} = \frac{P_{ave}^{*}\cos(2\omega_0 t)}{\sqrt{\frac{V_{bus}^{2}}{4} + \frac{P_{ave}^{*}}{\omega_o C_{buf}}\sin(2\omega_o t)}} \tag{7}$$

The output filter current control is applied as a minor loop of the output filter capacitor voltage control that is originally required. The buffer capacitor voltage control is introduced in order to avoid the divergence of the average voltage due to discretization.

IV. Modulation Method of Matrix Converter

Fig. 6 shows a concept of the PDM method applied in the matrix converter as a secondary converter. The PDM treats the input voltage waveform at high frequency as a pulse and synthesize the output voltage with the density of the input voltage pulses. In Fig. 6, a half cycle of the input voltage pulses are used as the minimum unit of the output voltage waveform. The switching devices in the matrix converter switch at the zero voltage term of the input voltage waveform. As a result, the matrix converter achieves ZVS which results in decreasing switching loss.

A. PDM Based on PWM

Fig. 7 shows a block diagram of the PDM based on the PWM, which is considered as conventional method in [7]. First of all, this PDM method yields a PWM pulse, which is generated by triangle carrier comparison. In order to convert the PWM pulse to a PDM pulse, the PWM pulse forcibly synchronizes with the zero voltage term of the secondary voltage of the transformer by a D-FF (D flip flop). Then, the PWM pulse is synchronized with double edges of a primary switching signal S_{1bn} because the double edges of S_{1bn} agrees with the zero voltage term of the secondary voltage of the transformer. In addition, the gate signal of the matrix converter is controlled according to the polarity of the secondary voltage of the transformer through CLK and EXNORs.

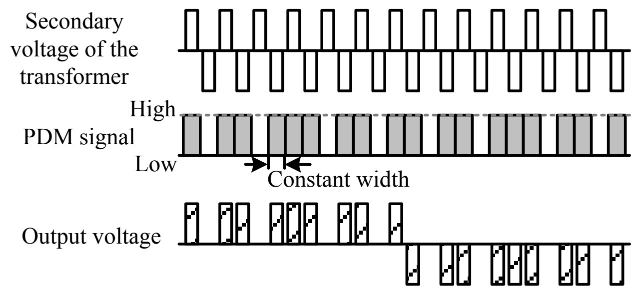


Fig.6 Concept of a PDM method applied in the matrix converter. The PDM treats a half cycle of an input voltage waveform as a pulse and synthesizes the output voltage with a density of the input voltage pulses.

When the PDM based on the PWM is applied in the matrix converter, the output voltage distortion increases because of the problem with the resolution and the output voltage ripple. As a result, the output voltage distortion which influences the power ripple component in the DC bus current interferes in the power decoupling. In the next paragraph the cause of the output voltage distortion is explained.

Fig. 8 shows the relationship between the output voltage reference v_{out}* and the output voltage waveform with the PDM in conventional method. Fig. 8 shows results when changing v_{out}* from 0.20 to 0.25, and 0.30 p.u.. The output voltage ripple is high because the conventional PDM method outputs concentrated pulses instead of distributed pulses in one carrier period. Furthermore, when v_{out}* =0.20 p.u., the pulse number of the output voltage n in a half of the carrier period is 2. In contrast, when v_{out}* =0.25 and 0.30 p.u., n in a half of the carrier period is 3. As a result, n in a half of the carrier period wave is expressed by (8).

$$n = \frac{f_{trans}}{f_{sw}} v_{out}^* \tag{8}$$

where f_{trans} is the frequency of secondary voltage of the transformer and f_{sw} is the carrier frequency of the matrix converter. It should be noted that n is rounded to an integer because the PDM pulse exist only in the integer. In Fig. 8, for simplicity f_{trans} and f_{sw} are set as 10 kHz and 1 kHz respectively. This makes the carrier frequency ratio become 10. Thus, n becomes 2 while v_{out}*=0.20 in a half of the carrier period. In contrast, n which should be 2.5 becomes 3 while v_{out}*=0.25 in a half of the carrier period because the conventional PDM method do not consider number of digits after the decimal point. This error is called as the quantization error, which increases the output voltage distortion and it is influenced by the resolution N_{res} of the PDM. Consequently, n is proportional to N_{res} which is expressed by (9) in this paper. Besides, v_{out}* is proportional to a modulation index α of a matrix converter.

$$N_{res} = \frac{f_{trans}}{f_{sw}} \alpha \tag{9}$$

If the output voltage reference is sinusoidal waveform, the level of pulse density of the output voltage is changed stepwise by quantization. Then, N_{res} agrees with levels expressing the positive output voltage and is proportional to the carrier frequency ratio and α. In addition, N_{res} invariably is an integer because N_{res} expresses the levels of the pulse density. From (9), if the carrier frequency ratio or α is lower, N_{res} of an output voltage waveform is lower. As a result, the distortion against the fundamental component of the output voltage is increased with the quantization error. Especially, if α is lower, the term in the generation of the quantization error becomes longer by decreasing of dv/dt of v_{out}*. Moreover, if the carrier frequency ratio is small, the quantization error becomes higher by a decrease of the levels of the pulse density. Thus, if the resolution N_{res} is lower, the quantization error becomes higher and the output voltage distortion is increased. Furthermore, due to the PWM comparison method, high frequency transformer pulse voltage is converted in a form of low frequency concentrated pulse voltage in the output voltage of the matrix converter, which results the output voltage ripple becomes higher. The quantization error and the output voltage ripple have a huge effect on the power ripple at primary side. On the basis of these results, it is needed to apply a PDM method

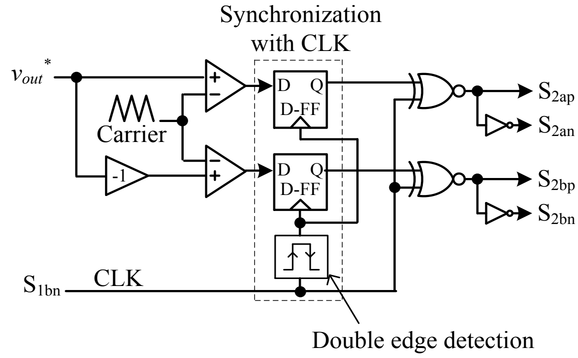


Fig.7 Block diagram of the PDM based on the PWM.

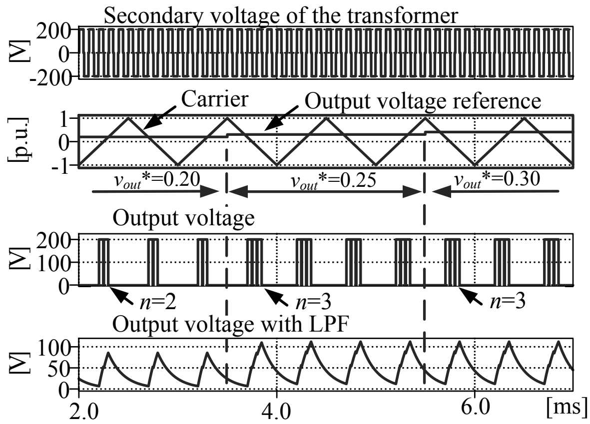


Fig.8 Waveform of matrix converter with the PDM based on the PWM. The output voltage ripple is high because the concentrated bunchy pulse is output in one carrier period in conventional PDM method. In addition, the quantization error,which is generated by having no the pluse for vout* after the decimal, is high.

which reduces the quantization error and output voltage ripple in order to improve the effect of the proposed power decoupling method.

B. PDM Based on Delta-sigma Conversion

As a solution for the output voltage distortion, this paper improves the distortion with applying a PDM based on a delta-sigma conversion in the matrix converter.

Fig. 9 shows a block diagram of the PDM based on the delta-sigma conversion, which is considered as the proposed method [12]. A delta-sigma conversion is kind of Analog-digital conversions, which convert an analog signal into a digital signal of 1 bit. First of all, the proposed PDM method integrates the quantization error by comparing the quantized output voltage reference v_{out}* by ZOH (Zero Order Hold), which is synchronized with carrier peak of the matrix converter, and the quantizer outputs at 1 clock before. The output signal of the quantizer is changed when this integrated quantization error exceeds a threshold. Due to the reason of switching signals do not depend on the carrier frequency of the matrix converter, the pulse density of the output voltage changes continuously, which results in distributed pulses. Therefore, the PDM based on the delta-sigma conversion reduces the quantization error and improves the output voltage distortion because this PDM method has no resolution limits.

Fig. 10 shows a relationship among v_{out}*, the output voltage v_{out} and f_{sw} with the PDM based on the delta-sigma conversion. The carrier frequency ratio and v_{out}* are the same as Fig. 8. From Fig. 10, the output voltage pulse is continuously generated independently on the carrier frequency of the matrix converter. Especially, in the term of v_{out}* =0.25 p.u., n in one carrier period is 5 with the PDM based on the delta-sigma conversion whereas n is 6 for the conventional PDM method. In addition, the output voltage ripple is lower because the output voltage pulse is distributed in one carrier period. Therefore, the PDM based on the delta-sigma conversion reduces the quantization error as against the conventional PDM method in this term. Moreover, comparing to the conventional PDM method that outputs concentrated pulses, the output voltage ripple becomes lower by the pulse is output continuously in one carrier period in the proposed PDM method. Thus, the PDM based on the delta-sigma conversion reduces the quantization error and the ripple of the output voltage. Moreover, the voltage error compensation improves the DC bus current ripple with the proposed power decoupling method because the proposed PDM method reduces the effects on the power ripple at primary side by the output voltage error.

V. Experimental Results

Table 1 shows an experimental condition for the isolated single-phase matrix converter with the PDM of conventional and proposed method as drawn in Fig. 7 and 9. It should be noted that the carrier frequency ratio is 10:1 and the output side is R-L load without LC filter.

A. Power Decoupling with PDM Based on PWM

Fig. 11 shows the extended each waveform in experimental result with the PDM based on the PWM. In the conventional PDM method, the output voltage ripple is high by the output voltage pulse is output continuously because the conventional PDM method bases the PWM, which switch gate of the secondary converter at once in a carrier period as shown in Fig.11. Then, the voltage error is increased because the output voltage ripple is high as described previously.

Fig. 12 shows experimental waveforms of the proposed converter with the PDM based on the PWM. Fig. 12(a) shows a result without the power decoupling method and (b) shows a result with the power decoupling method. From 12 (a), it is understood that the buffer capacitor voltage does not vary because the full bridge inverter does not output the common

TABLE I. EXPERIMWNRAL CONDITION

DC bus voltage	350 V_{dc}	Load voltage	100 V_{peak}
Rated power	410W	Load frequency	50 Hz
Buffer L (L_{buf})	2.0 mH	Buffer C (C_{buf})	200 μF
Grid connected inductor L (L_{out})	2.0 mH	Turn ratio of transformer N_2/N_1	1.0
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 filter current control	4000 rad/s
Damping factor of buffer current control	0.7	Damping factor of filter current control	0.7

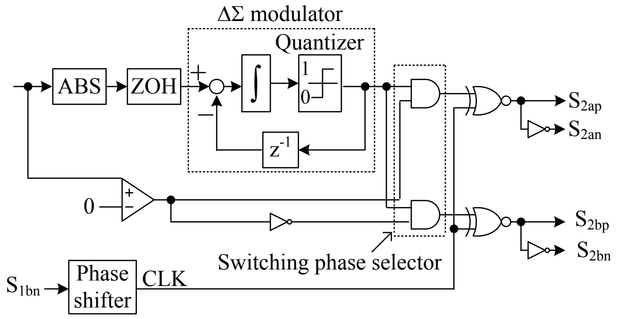


Fig.9 Block diagram of the PDM based on the delta-sigma conversion. This PDM method reduces the quantization error and improves the output voltage distortion.

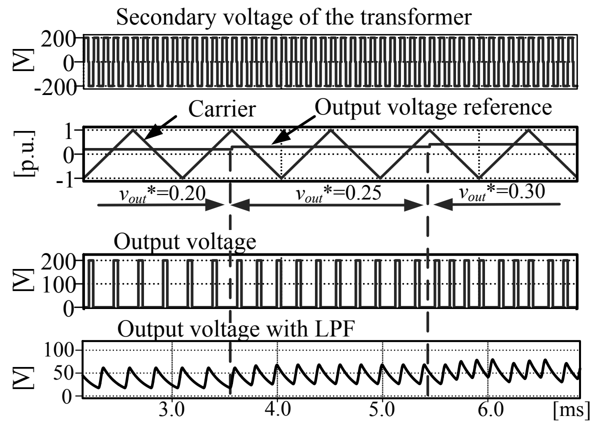


Fig.10 Waveform of matrix converter with the PDM based on the delta-sigma conversion. The quantization error and the ripple of the output voltage to apply the PDM based on the delta-sigma conversion.

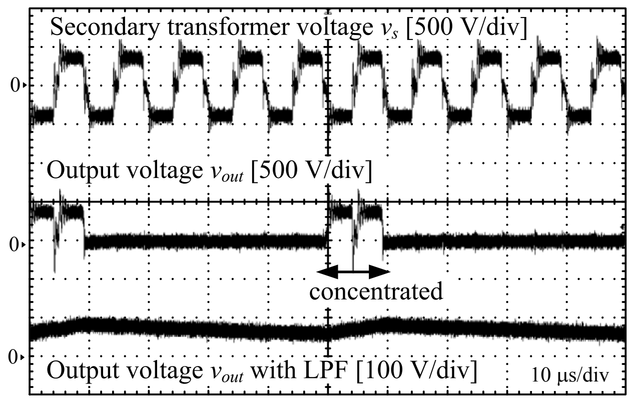


Fig.11 Experimental waveforms of the PDM based on PWM as a conventional method. The output voltage ripple is high by the pulse is output continuously because the conventional PDM method bases the PWM, which switch gate of the secondary converter at once in a carrier period.

mode AC voltage. As a result, without the power decoupling method in the conventional PDM method, power ripple component at 100 Hz is 57.4% in reference to the average DC bus current. In contrast, the proposed power decoupling method provides the common mode AC voltage to fluctuate the buffer capacitor voltage. Therefore, the proposed method reduces the 100 Hz component to 13.1%. However, the high-order distortion in the DC bus current persists by the effect, which the output voltage THD is 4.33% in (b). The reason of the output voltage THD is higher, which has the effect of the quantization error and the output voltage distortion cause of the PDM based on PWM as described previously. Especially, the eighth-order harmonic distortion in the output voltage is higher in Fig. 12(b). Therefore, a compensation reference shown (1) does not agree on the actual power ripple, which has the effect of the output voltage because the proposed power decoupling method is based on the premise that the power ripple is sinusoidal waveform without a distortion.

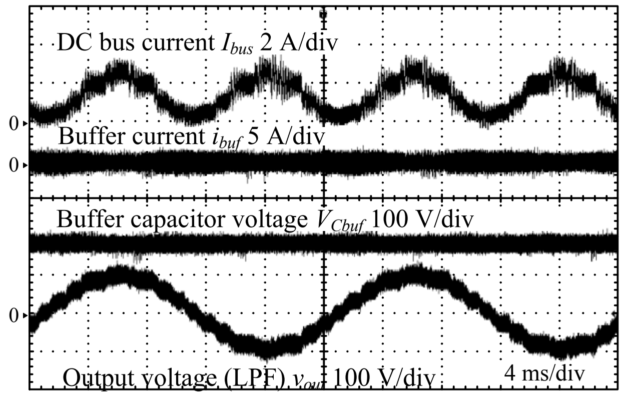
B. Power Decoupling with PDM Based on Delta-sigma Conversion

Fig. 13 shows the extended each waveform in experimental result with the PDM based on the delta-sigma conversion. The pulse is output continuously with applying a PDM based on a delta-sigma conversion in the matrix converter in Fig. 13. Therefore, the output voltage ripple is low. In additional, the voltage error is reduced because the PDM based on the delta-sigma conversion depends on the carrier frequency ratio between the full bridge inverter and the matrix converter and the modulation index of the matrix converter compared to the conventional PDM method as shown in Fig. 11.

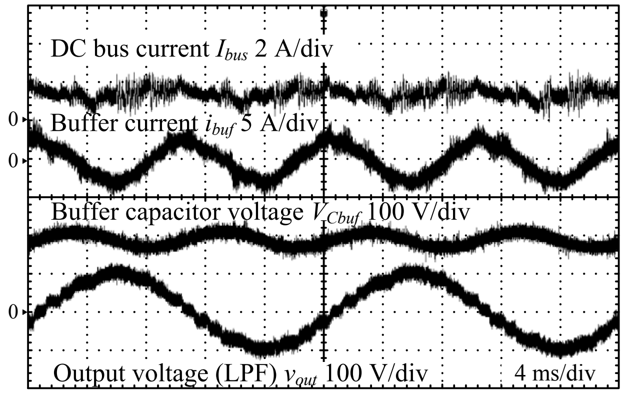
Fig. 14 shows the experimental waveforms of the proposed converter with the PDM based on the delta-sigma conversion. Fig. 14(a) shows a result without the power decoupling method and (b) shows a result with the power decoupling method. From Fig. 14, it is understood that the output voltage THD is reduced to 1.65% with the PDM based on the delta-sigma conversion. Therefore, this PDM method can improve the output voltage distortion compared with the conventional PDM method. Moreover, the proposed method can control I_{bus} almost constant because this PDM method reduces the effect on the power ripple by the output voltage distortion. Thus, the PDM based on the delta-sigma conversion can further suppress the power ripple compared with the conventional PDM method.

C. Comparison of Harmonic Analysis by two PDM Methods

Fig. 15 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 without the power decoupling method, the power ripple component at 100 Hz is 57.4% with reference to an average current. The proposed power decoupling method with the PDM based on the PWM reduces the 100 Hz component to 13.1% because the buffer capacitor voltage fluctuation absorbs the power ripple at 100 Hz. However, the 100 Hz component of the power ripple on the DC bus current remains because the quantization error and the output voltage ripple have a huge effect on the power ripple at primary side when the PDM based on the PWM is applied in the matrix comverter. Thus, when the quantization error of the output voltage waveform is reduced, the ripple for the harmonic component of the DC bus current can be reduced as shown in Fig. 12. In contrast, in the power decoupling method with the PDM based on the delta-sigma conversion, the 100 Hz component is reduced to 8.75% because the PDM based on the delta-sigma conversion reduces the effects on the power ripple at primary side by the output voltage error. Then, the PDM based on the delta-sigma conversion with the proposed power decoupling method reduces the 100 Hz component of the DC



(a)Without the power decoupling method.



(b) With the power decoupling method.

Fig.12 Experimental waveforms with the PDM based on the PWM. The proposed power decoupling method provides the common mode AC voltage to fluctuate the buffer capacitor voltage.

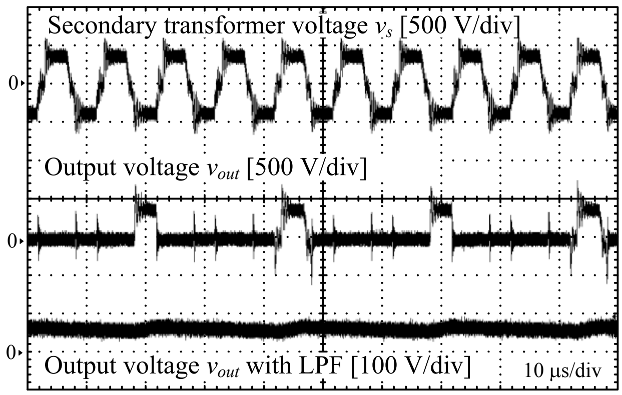
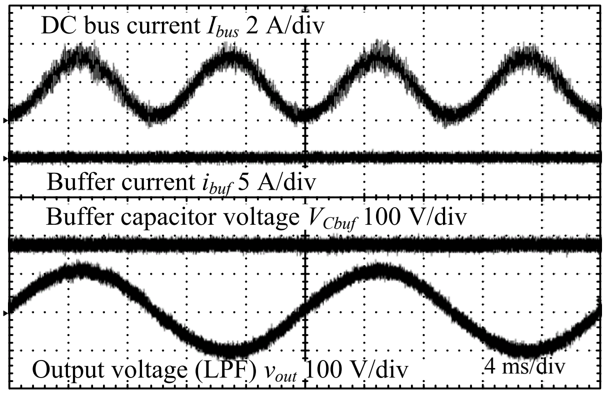


Fig.13 Experimental waveforms of the PDM based on the delta-sigma conversion as a proposed method. The pulse is output continuously with applying a PDM based on a delta-sigma conversion in the matrix converter.

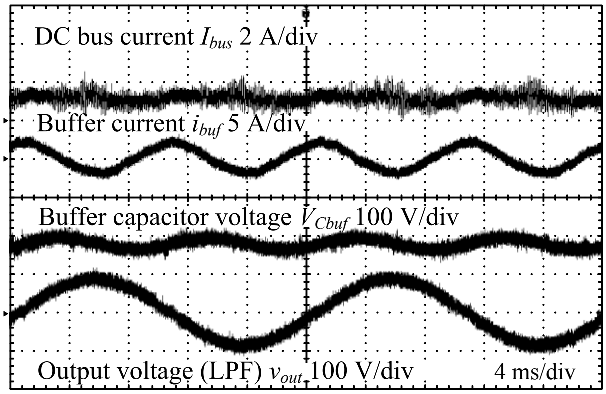
bus current by 33.5% compare to the PDM based on the PWM with power decoupling method. As a result, these experimental results verified the effectiveness of the proposed power decoupling with PDM based on the delta-sigma conversion.

VI. CONCLUSION

This paper proposed an isolated single-phase matrix converter with the PDM based on the delta-sigma conversion in order to futher improve the effectiveness of the power decoupling method. The proposed system is expected to achieve smaller size compared to the conventional rectifier-inverter system because in the proposed system the bulky electrolytic capacitor is not required. In addition, this paper clarified the cause of the output voltage distortion when the PDM based on the PWM is applied. As a solution for the output voltage distortion, this paper decreases the output voltage distortion by applied the PDM based on the delta-sigma conversion. From the experimental results, the proposed power decoupling method reduces the DC bus current ripple by 84.8%. In addition, the proposed system reduces the output voltage distortion by 64.1%. Thus, the validity of the proposed voltage error compensation method is confirmed.



(a)Without the power decoupling method.



(b) With the power decoupling method.

Fig.14 Experimental waveforms with the PDM based on the delta-sigma conversion in a steady state. The DC bus current do not have little harmonic component.

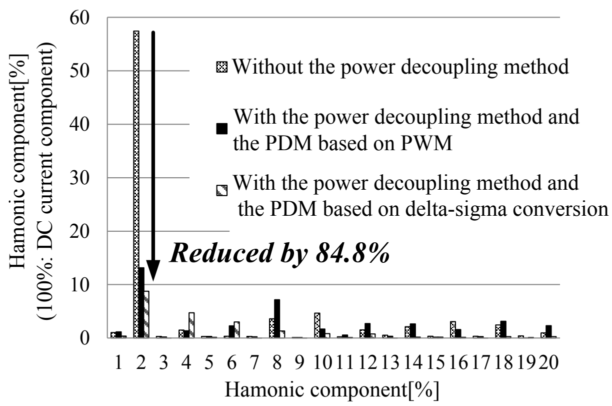


Fig.15 Harmonic analysis of the DC bus current. The power decoupling method reduces the DC bus current ripple by 84.7% with proposed voltage error compensation method.

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