Control Method for a Three-Port Interface Converter Using an Indirect Matrix Converter with an Active Snubber Circuit

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***Abstract*— This paper proposes a novel control method for an interface converter using an indirect matrix converter with three power supplies, which consist of two AC and one DC supplies. An active snubber circuit in the indirect matrix converter is used as an interface with the DC power supply. The proposed control method is based on the indirect control method with a triangular carrier wave [10]. Therefore the proposed method can be easily applied to a DC/DC converter. In addition, this paper proposes reducing the number of switching during one carrier period for the inverter stage converter. In the proposed method, the inverter stage carrier is controlled asymmetry to reduce the switching times in the inverter stage. To apply the proposed method, the switching loss of the inverter stage can be decreased to 2/3 times in comparison with a conventional method. The validity of the proposed method is confirmed by simulation and experimental results.**

***Keywords*—Matrix converter, Converter control, Power factor correction, Energy converters for HEV.**

I. INTRODUCTION

Recently, renewable energies and hybrid electric vehicle (HEV) systems are receiving significant interest, with consideration of global warming and environmental problems. There are two types of power sources for renewable energies; AC power sources such as wind power generator, and DC power sources such a photovoltaic cells, batteries, and fuel cells. Therefore, to implement these applications, interface power converters have been intensely studied. A conventional power converter system, which consists of a pulse width modulation (PWM) rectifier, a DC/DC converter and an inverter, requires a large energy buffer, such as an electrolytic capacitor. However, the electrolytic capacitor in a conventional system has disadvantages such as large size, short-life time and high costs.

On the other hand, there is an AC/AC direct converter with a DC link, which is referred to as an "indirect matrix converter" [1-5]. The indirect matrix converter is composed by the current source rectifier and voltage source inverter without energy buffer in DC link part. The utilization of an indirect matrix converter, which has no large energy buffer such as an electrolytic capacitor, can bring advantages such as size reduction, long-life time and cost reduction. We have already proposed an interface converter using an indirect matrix converter [6]. The proposed interface converter connects a DC/DC converter to DC link of the indirect matrix converter. With regard to the voltage relationship between the battery and the DC link, the proposed circuit works as a boost up converter for the battery. However, the proposed converter has the same problem due to an indirect matrix converter. That is, the voltage transfer ratio of indirect matrix converters, which defines the ratio between the output and input voltage, is well known as being constrained to 0.866. Improvement of the voltage transfer ratio for indirect matrix converters has been widely discussed [7,8]. However, it seems that the proposed methods increase the number of components, due to the insertion of voltage transfer ratio compensator, which consists of an H-bridge inverter and a capacitor, to the DC link of the indirect matrix converter.

Meanwhile, a snubber circuit is required in order to protect the indirect matrix converter from over-voltage and over-current. In Ref. [9], a snubber circuit was used in order to compensate the imbalance in the supply voltage. However there was no discussion of the DC power supply interface using a snubber circuit.

This paper proposes a novel control method for multi-power supply interface system using an indirect matrix converter with a step-down chopper. The proposed converter is constructed based on an indirect matrix converter that does not have a large energy buffer, such as an electrolytic capacitor. The active snubber circuit of the indirect matrix converter is used as a step-down chopper for a DC power supply. In addition, the voltage transfer ratio can be improved by the DC power supply. An indirect control method with a triangular carrier wave [10] is expanded into the proposed control method. In the proposed control system, a DC/DC converter can be easily added to the indirect matrix converter.

In addition, this paper also proposes a control method reducing the number of switching for the inverter stage converter. In the proposed converter which is composed by a current source rectifier, a voltage source inverter and a step-down chopper, the switching frequency of the inverter stage increases in comparison with rectifier stage. Because the zero current switching operation of the rectifier stage can be achieved when the inverter output zero voltage vectors, which are generated by every upper or lower peak of the inverter carrier. Therefore, in the proposed method, the switching frequency is reduced by using a transformed asymmetry inverter carrier in order to control the zero voltage vector timing.

The basic operation of the proposed method is confirmed by the simulation and experimental results; the total harmonic distortion (THD) of the input, output and dc output currents are 7.4%, 4.8%, 1.9%, respectively, and the input power factor is 99% and efficiency is 93.8%. In

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addition, bidirectional energy flow characteristic among the power supplies in this circuit is confirmed.

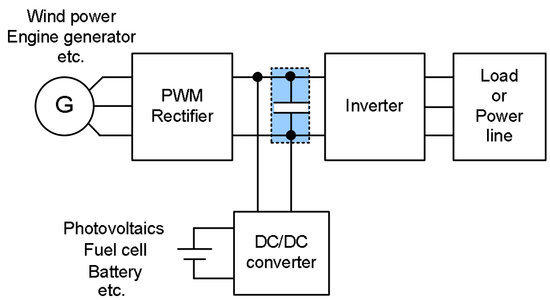
II. Circuit Topology

Figure1 shows AC and DC power supply interface systems. A conventional interface system consists of a PWM rectifier, a DC/DC converter and an inverter, as shown in Fig. 1(a). This system requires a large electrolytic capacitor in DC link part in order to smooth DC link voltage. This system is very flexible in term of voltage condition among the AC input AC output side and DC power source because of using voltage type converters. However, the problem for an electrolytic capacitor in DC link part is large volume, short lifetime in high temperature and high cost.

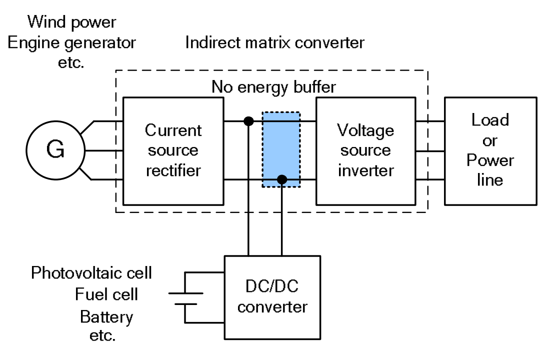
Figure 1(b) shows the proposed AC and DC power supply direct interface converters for the energy management system. The proposed interface converter is constructed based on an indirect matrix converter without a large energy buffer such as an electrolytic capacitor. The DC/DC converter connects to DC link of the indirect matrix converter.

Figure 2 shows the specific main circuit of the proposed interface converter. The DC/DC converter is built as an active snubber circuit in the indirect matrix converter. An IGBT is connected anti-parallel to the snubber circuit diode. This snubber circuit with the IGBT is used as a step-down chopper of the DC power supply. In this case, the DC power supply voltage of the snubber circuit is higher than the peak of the AC input line voltage, because a rush current occurs between the AC and the DC input power supplies when the peak of the AC input line voltage is higher than the DC power supply voltage. Therefore, this converter is referred to as a "step-down type AC/DC/AC direct converter".

Figure 3 shows the equivalent circuits of the proposed converter. The rectifier stage converter is similar to a four phase current source rectifier including the DC/DC converter. Thus, the switches in the three-phase PWM rectifier and DC/DC converter must be separately turned on in order to avoid a short circuit of the AC and DC power supplies. When the DC/DC converter switch S_{bp} is turned off, the proposed converter operates as a conventional indirect matrix converter. In this case, the DC/DC converter becomes a conventional snubber circuit, as shown in Fig. 3(a). On the other hand, the proposed converter operates as a conventional inverter when the DC/DC converter switch S_{bp} is turned on, when all switches in the rectifier are turned off. In this case, the DC/DC converter is similar to a DC power supply, as shown in Fig. 3(b). That is, the proposed circuit operates as an indirect matrix converter or inverter alternately. In



(a) Conventional system.



(b) Proposed system.

Fig. 1. Block diagrams of AC and DC power supply interface system.

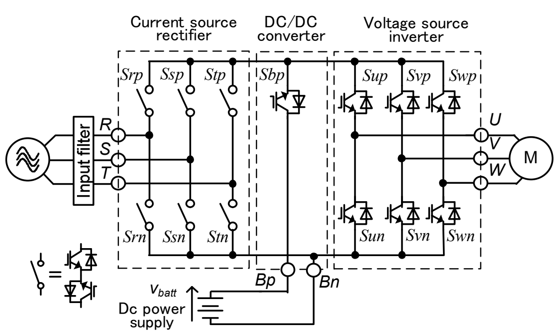
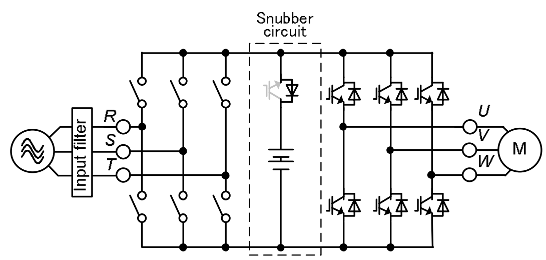
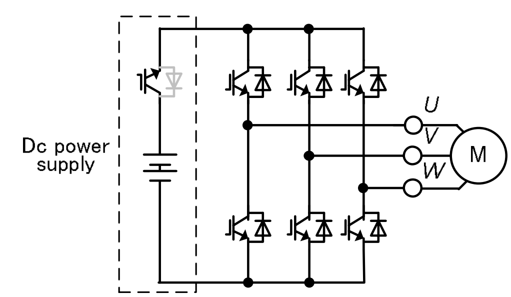


Fig. 2. Proposed circuit configuration.



(a) S_{bp} is turned off



(b) S_{bp} is turned on

Fig. 3. Equivalent circuits of the proposed converter.

addition, the input power ratio between the AC and DC power supplies and the voltage transfer ratio between the input and the output voltage are controlled by the duty ratio of the DC/DC converter.

III. Control Strategy

The proposed control strategy, which is based on an indirect control method with a triangular carrier wave, can easily realize the addition of the DC/DC converter. The conventional indirect control strategy, which uses space vector modulation, must calculate the pulse width for each switch, including the DC/DC converter. In addition, it is difficult to define the input current command vector, because it is four-phase, consisting of the three-phase AC power supply and the DC power supply. Therefore, the control in this paper can be achieved by using an independent command for the DC/DC converter based on carrier comparison modulation.

A. Control method for the rectifier stage and DC/DC converter

Figure 4 shows a block diagram of the step-down type AC/DC/AC direct converter. The rectifier stage converter in the proposed interface converter functions as a four-phase current source rectifier including the DC/DC converter. The relation between the input voltage $[v_r\ v_s\ v_t\ v_b']^t$ and the output voltage $[v_u\ v_v\ v_w]^t$ can be expressed as

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} s_{up} & s_{un} \\ s_{vp} & s_{vn} \\ s_{wp} & s_{wn} \end{bmatrix} \begin{bmatrix} s_{rp} & s_{sp} & s_{tp} & s_{bp} \\ s_{rn} & s_{sn} & s_{tn} & 0 \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \\ v_b' \end{bmatrix} \quad (1),$$

where the input voltage v_b' is the DC power supply voltage v_{batt} based on the neutral point of the input voltage. To avoid a short circuit of the AC and DC power supplies, the switches in the rectifier stage converter and the DC/DC converter are not turned on at the same time. As a result, the current command for each phase is decreased by the working time of the DC chopper. Therefore, the input current command i_{rec}^{**} for one phase is converted by

$$i_{rec}^{**} = i_{rec}^{*} \cdot (1 - i_b^{*}) \quad (2),$$

where i_{rec}^{*} is rectifier stage current command, and i_b^{*} is the DC/DC converter input current command.

Figure 5 shows the relationship between the DC link voltage and the DC/DC converter duty ratio for the proposed converter. The DC link voltage is decided by the average value of the output voltage between the rectifier stage and the DC/DC converter. Therefore the average value of the DC link voltage E_{dc} in the proposed circuit can be expressed as

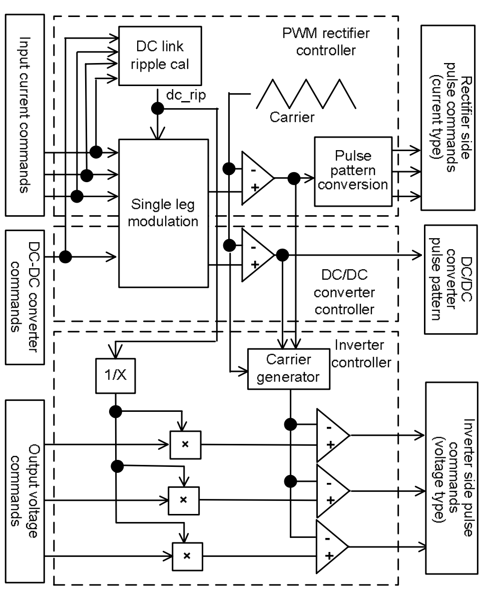


Fig. 4. Control block diagram of step-down mode.

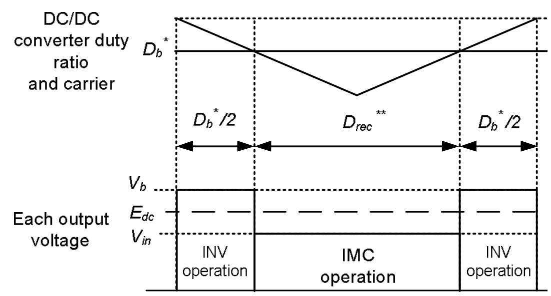


Fig. 5. The relationship between the DC link voltage and the DC/DC converter duty ratio.

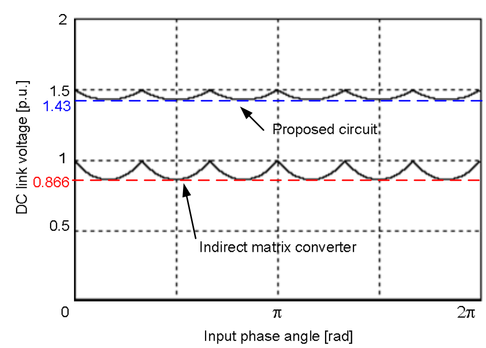


Fig. 6. DC link voltage waveform.

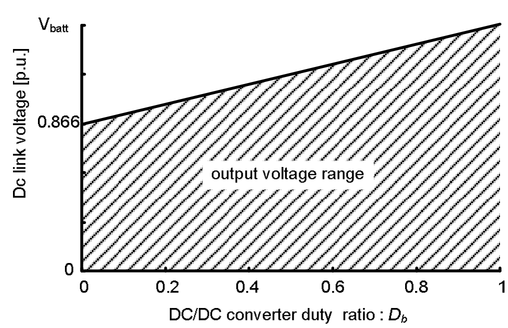


Fig. 7. Output voltage range for proposed converter.

$$E_{dc} = D_{rec}^{**} v_{in} + D_b^{*} v_b \quad (3),$$

where D_{rec}^{**} is the rectifier stage converter duty ratio based on input current command converted by equation (2), and D_b^* is the DC/DC converter duty ratio, and v_{in} is input voltage for maximum value, and v_b is DC power supply voltage.

Figure 6 shows a comparison between the DC link voltage of the proposed circuit and the indirect matrix converter, where the maximum value of the indirect matrix converter is defined as 1 [p.u.]. The DC link voltage contains a ripple, which is constrained by the sixth order component of the AC power supply frequency. Therefore, the output voltage is limited to 0.866 times that of the maximum DC link voltage. On the other hand, the proposed circuit can operate alternately between the indirect matrix converter and inverter as discussed and shown early in Fig. 3. The DC link voltage waveform of the proposed circuit is shown in Fig. 6 when D_b^* is set to 0.5 and the DC power supply voltage v_b is assumed to be 2 times that of the indirect matrix converter. In this case, the DC link voltage of the proposed circuit obtains 1.43 times that of the indirect matrix converter. Thus, the proposed circuit can improve the voltage transfer ratio from the AC input side to the AC output side by using the DC power supply voltage.

Figure 7 shows the DC link voltage range for the proposed converter. In the proposed converter, the DC power supply voltage of the snubber circuit has to keep higher than the peak of the AC input line voltage in order to prevent a rush current. Thus, the range of the DC link voltage is defined from the output voltage of rectifier stage to battery voltage, as expressed by equation (3). Therefore, the range of the output voltage is defined from zero volts to battery voltage as show in Fig. 7.

It should be noted that the ratio between the rectifier duty D_{rec}^* and the DC/DC converter duty D_b^* is the same as the input power ratio between the AC and DC power supplies.

B. Basic control method of the inverter stage

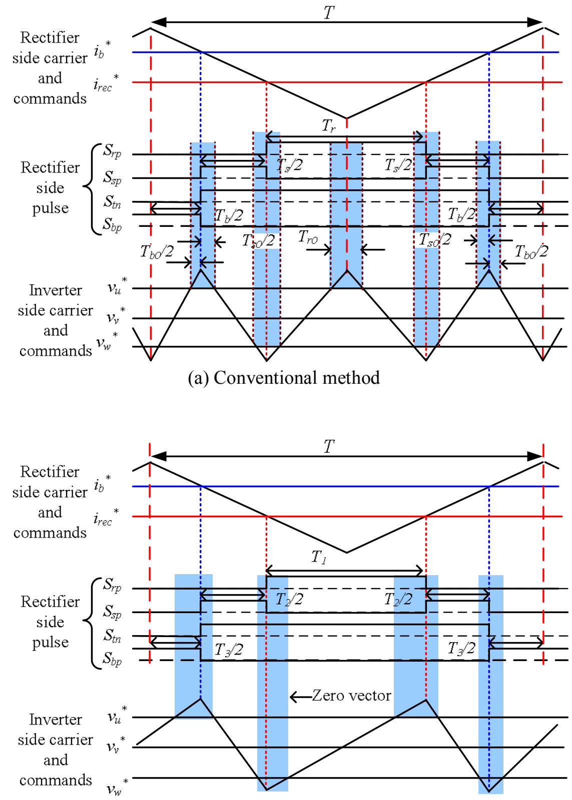
Figure 8(a) shows the relation of carrier signals between the inverter and the rectifier stages. The rectifier stage is controlled under the condition of constant DC link current. However, the actual DC link current must be zero when the inverter stage controller selects the zero voltage vectors. In the proposed method, this is achieved by controlling the slope of the inverter carrier signal, as shown in Fig. 6. By adopting this method, the zero current period of the DC link is distributed to each input current by the same ratio, as expressed by equation (4).

$$\frac{T_{r0}}{T_r} = \frac{T_{s0}}{T_s} = \frac{T_{b0}}{T_b} = \frac{T_{r0}+T_{s0}+T_{b0}}{T_r+T_s+T_b} \quad (4),$$

where T_r is turn on period in S_{rp}, T_s is tern on period in S_{sp},, T_b is tern on period in S_{bp},, T_{r0} is zero current period in T_r, T_{s0} is zero current period in T_s, T_{b0} is zero current period in T_b.

C. Proposed switching loss reduction method for inverter stage

In the Fig. 8(a), two-phase modulation is introduced in order to reduce the switching loss in the inverter stage besides the zero current period distribution. However, the



(a) Conventional method

(b) Proposed method

Fig.8. Relation between inverter carrier and rectifier pulse.

number of switching of the inverter stage increases to 3 times in compared with rectifier stage. For example, the U-phase switching devices in the inverter stage are changed in one rectifier carrier period 6 times though that of the rectifier stage is 2 times. The switch timings of the rectifier and DC/DC converter stage are only agree with the bottom of the inverter carrier in order to achieve the zero current switching. As a result, the switching loss of the inverter stage increases.

Figure 8(b) shows proposed switching loss method using the carrier signals. In the proposed method, the inverter stage carrier is controlled asymmetry to reduce the number of switching of the inverter stage, as shown in Fig. 8(b). The switch timings of the rectifier and DC/DC converter stage are agree with both bottom and top of the inverter carrier. In this case, the U-phase switching devices in the inverter stage are changed 4 times. It is should be noted that the zero current period of the DC link is also distributed to each input current by the same ratio in the proposed method, as expressed by equation (4).

As a result, the switching loss of the inverter stage can be decreased to 2/3 times in the comparison with a conventional method because the number of the switching in one carrier period is 4 times though that of the conventional method 6 times. Note that the proposed method requires the zero voltage vectors at both top and bottom of the inverter carrier. This means that the two phase modulation can not be applied to the inverter voltage command. That is, the proposed method is effective in low voltage aria such as low speed in motor drive applications because the three phase modulation is used in low speed aria.

D. Commutation method

In indirect matrix converter, the rectifier stage converter can achieve zero current switching when the inverter generates the zero voltage vectors [11]. In other words, the DC link current must be zero when the inverter controller selects the zero voltage vectors. The proposed circuit alternately operates between an indirect matrix converter and an inverter. The switching of S_{bp} in the DC/DC converter is also achieved when the inverter outputs the zero vectors. Therefore, switching losses do not occur in the rectifier stage converter and the DC/DC converter. It is should be noted that a conventional dead time is applied for the commutation of the inverter stage. The conventional dead time for the inverter stage causes output voltage error and input current error. To overcome it, the commutation error compensation method [6] is applied for proposed circuit. As a result, the influence of the commutation for the input and output current can be compensated.

IV. Simulation and Experimental Resuls

Table 1 provides the simulation and experimental circuit parameters and conditions. The operation of the proposed circuit is demonstrated by the simulation and experimental results.

A. Basic operation simulation results for the proposed converter

Figure 9 shows the simulation results of the proposed converter. In the simulation, an ideal current source load and a main circuit are used to check the proposed control strategy. Good sinusoidal waveforms are obtained for the input current and the output voltage. The THD of the input and the output current are less than 1%, respectively. In addition, a good DC waveform, without low frequency ripple, is obtained for the DC power supply current.

In the waveform of Fig. 9(a), power grid generation, battery discharge, and motoring operations are obtained. Similarly, power grid regeneration, battery charge, and generating operations are obtained for waveform of Fig. 9(b). As a result, bidirectional energy flow among the power supplies in this circuit is confirmed.

These simulation results confirm the basic operation of the proposed circuit.

B. Basic operation experimental results for the proposed converter

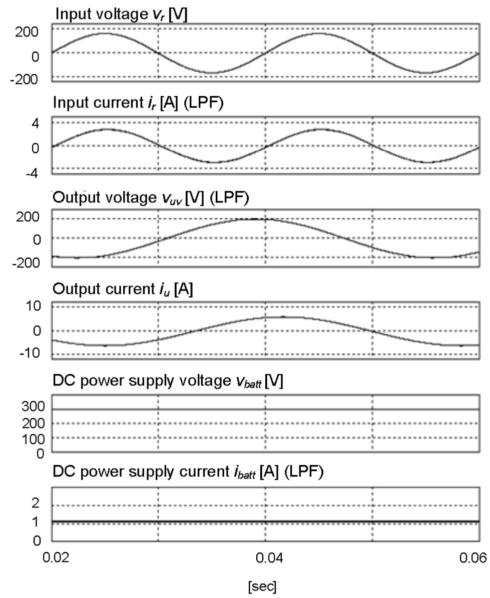
This chapter shows the basic operation of the proposed converter. The proposed switching loss reduction method is not applied in experimental results of this chapter as rated voltage range. However the validity of the proposed switching number reduction method is confirmed by next chapter.

Figure 10 shows the input current, the output current and the DC current waveforms. Good sinusoidal and dc waveform are obtained for input and output current. In the waveform of Fig. 9(a), power grid generation, battery discharge, and motoring operations are obtained.

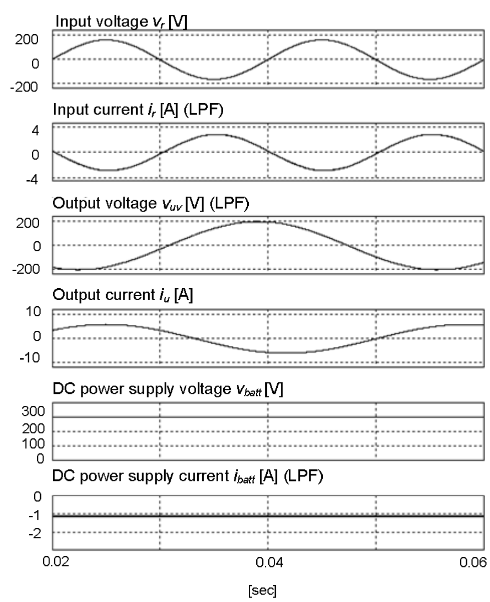
Figure 11 shows the DC link voltage waveform for the conventional indirect matrix converter and proposed converter. In consideration of the low frequency

Table 1. Experimental parameters.

Input voltage	200 [V]	LC filter	2 [mH]
Input frequency	50 [Hz]		6.6 [□F]
Carrier frequency	10 [kHz]	Cut-off frequency	1.3 [kHz]
Output frequency	30 [Hz]	load	R-L
DC power supply	300 [V]	Commutation time	2.5 [□s]
Power ratio (AC:DC)		2:1	



Waveform when power grid generation, battery discharge, and motoring operations



(b) Waveform when power grid regeneration, battery charge, and generating operations

Fig. 9. Simulation results.

components, a low pass filter was applied to the lower waveform in Fig. 10. As a result, the DC link voltage of the conventional indirect matrix converter is 245 [V]. On the other hands, the results shown in Fig.11 (b) confirm that the DC power supply voltage and the input voltage are alternated to the DC link voltage. As a result, the minimum average value of the DC link voltage is 260 [V], as shown by the upper waveform of Fig. 11(b). The DC link voltage of the conventional indirect matrix converter is 245 [V]; therefore, the proposed circuit can improve the voltage transfer ratio.

Figure 12 shows the efficiency and the input power factor of the proposed circuit. An input power factor (P.F.) over 99% and high efficiency of 93.8% were obtained. In comparison, the efficiency of a conventional multi-power supply interface converter with a large electrolytic capacitor is approximately 90%. In addition, the efficiency can be improved by the applying of reverse blocking IGBTs to the rectifier stage.

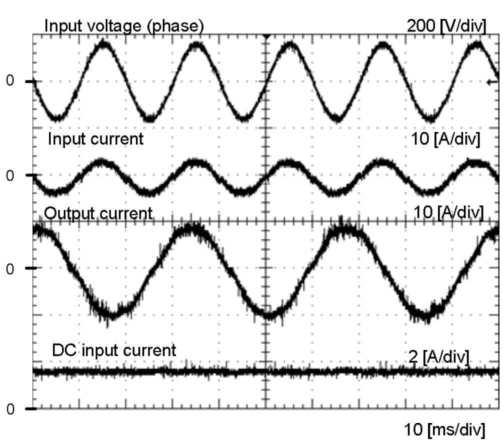
Figure 13 shows the THD of the input and output current confirming that the input, output and DC input current THD are 7.5%, 3.7% and 1.9%, respectively.

These experimental results confirm the validity and basic operation of the proposed circuit.

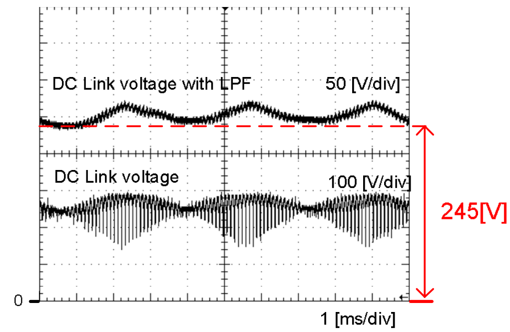
C. The proposed switching loss reduction method

This chapter shows the validity of the proposed switching loss reduction method. The validity of proposed method is confirmed by the indirect matrix converter. This means that the DC/DC converter duty ratio is just zero. The reason is that the effect of switching loss ruction is depends on the DC/DC converter duty ratio. Therefore, to clear the effect of the proposed method, the DC/DC converter stage was stopped.

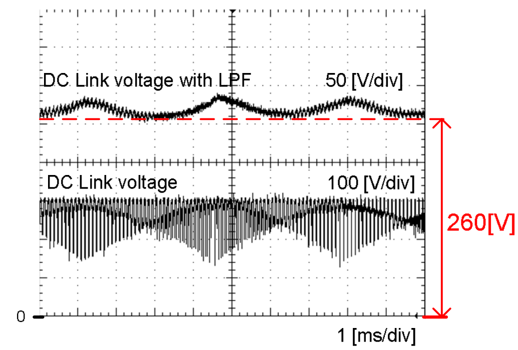
Figure 14 shows the input current and the output current waveforms of the proposed method. Good sinusoidal waveform are obtained for input and output current. In addition, it is confirmed in Figure 15 that the input and output current THD are 1.8% and 1.3% respectively. In the input and output waveform, almost a similar waveform is obtained in comparison with the conventional method. Thus, the good experimental waveforms are confirmed, in case of the reducing of switching number for inverter stage.



(a) Waveform when power grid regeneration, battery charge, and generating operations.
Fig. 10. Experimental waveform.



(a) Conventional indirect matrix converter.



(b) Proposed converter.
Fig. 11. DC link voltage waveform.

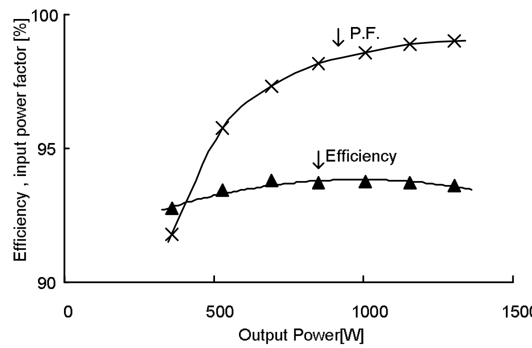
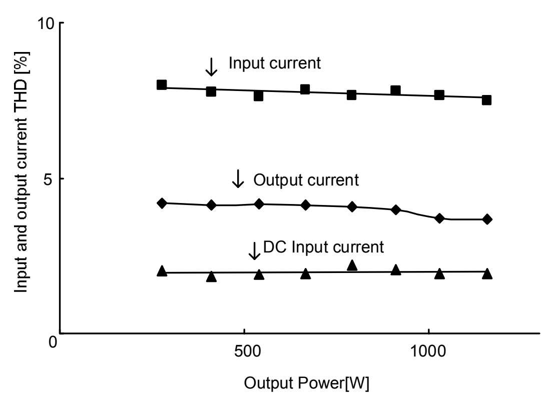


Fig. 12. Efficiency and input power factor. (IMC=indirect matrix converter; INV=inverter.)



Fi
g. 13. THD of input and output current.

Figure 16 shows the efficiency and the input power factor of the proposed circuit. In the conventional method, the input power factor over 99% and high efficiency of 93.8% were obtained. On the other hand, the efficiency is improved by about 0.5 point by applying the proposed method. In addition, the input power factor over 99% is obtained.

Figure 17 shows the loss analysis for the proposed circuit using circuit simulator (PSIM, Powersim Technologis Inc) and DLL file (Dynamic Link Library)[12]. The three phase modulation, two phase modulation, and proposed switching loss reduction method are applied for the inverter stage control. The two phase modulation decreases the switching loss of inverter stage by about 2/3 in compared with a three phase modulation. On the other hands, the switching loss of the inverter stage is improved by about 1/2 by applying of the proposed switching loss reduction method. In the view of loss on rectifier stage, there is no difference in each method, since the switching losses do not occur in the rectifier stage during zero current switching. In case of the heavy load, the conduction loss is dominant to the switching loss. In contrast, the switching loss is dominant to conduction loss when the light load is used. Therefore, proposed method is valid in the low speed and light load area, because the two-phase modulation can not apply in the low speed area to avoid the output current bias to one switching device and to keep the output voltage accuracy.

These experimental results confirm the validity of the proposed circuit and proposed switching loss reduction method.

V. Conclusions

This paper proposes a novel control method for a multi-power supply interface converter using an indirect matrix converter. An active snubber circuit in the indirect matrix converter is used as the interface of the DC power supply. The proposed control method can be easily applied to multi-port systems, due to the use of carrier comparison modulation. Therefore the proposed method can be applied easily to a DC/DC converter. In addition, this paper proposes a control method of switching loss reduction for the inverter stage converter. Applying the proposed method, the switching loss of the inverter stage can be decreased to 2/3 times in the comparison with conventional method. The validity of the proposed method was confirmed by the simulation and experimental results.

The experimental results of the proposed system using 1kW class prototype circuit are obtained as follows,

i) The bidirectional energy flow among the power supplies in this circuit is confirmed.

ii) The input, output and dc output current THD are 7.5%, 3.7%, 1.9%, the input power factor is 99%, and the efficiency is 93.8%.

iii) The efficiency is improved by about 0.5 point by application of the proposed method.

iv) The proposed switching number reduction method is valid in the low speed and light load area.

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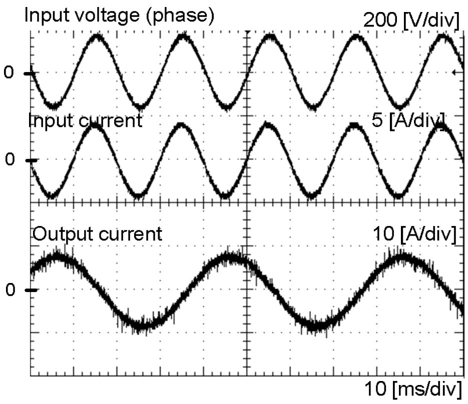
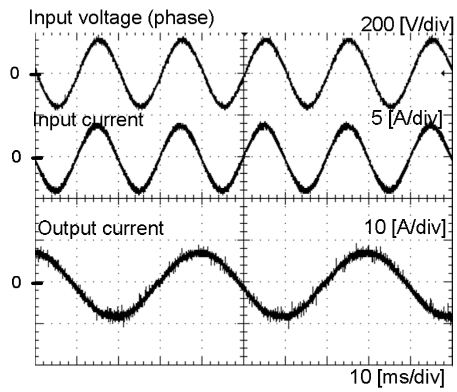
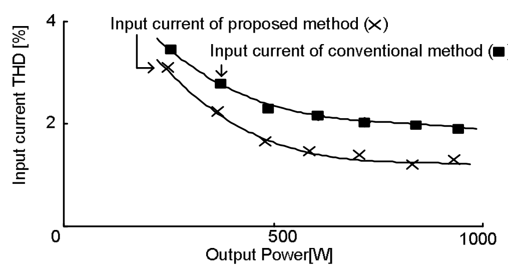


(a) Conventional method.

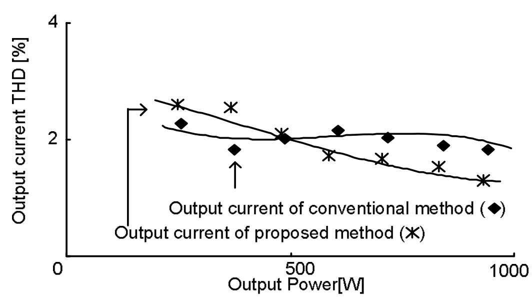


(b) Proposed method.

Fig. 14. Experimental waveform.



(a) Input current THD.



(a)

Output current THD.

Fig.15. THD of input and output current.

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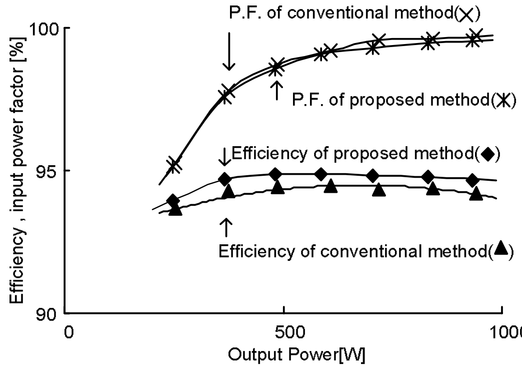
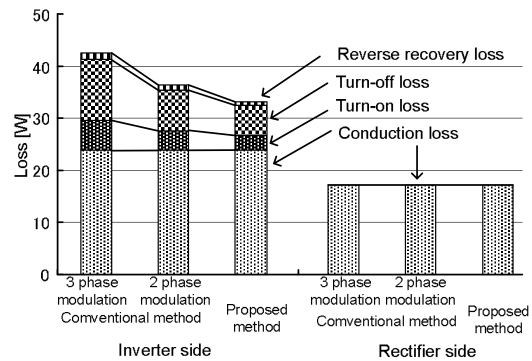
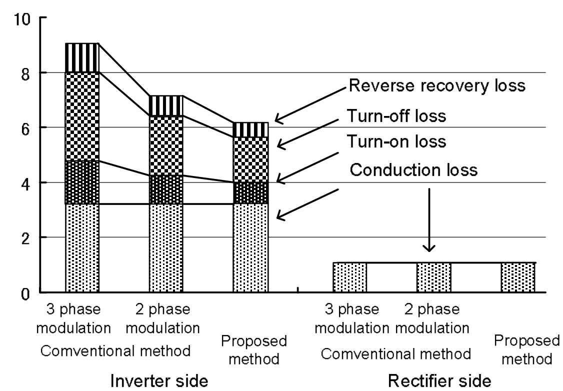


Fig. 16. Efficiency and input power factor.



(a) Loss analysis of heavy load.



(b) Loss analysis of light load.

Fig. 17. Loss analysis.