A Novel Control Method for Direct Interface Converters used for DC and AC Power Supplies

Koji Kato, Jun-ichi Itoh
Nagaoka University of Technology
1603-1 Kamitomioka-cho
Nagaoka city Niigata, Japan
Tel./FAX: +81/ (258) . 47.9533
E-Mail: itoh@vos.nagaokaut.ac.jp
URL: http://pelab.nagaokaut.ac.jp/itohlab/

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Abstract

This paper proposes a novel control method for a direct interface converter for management of the energy flow in either an AC or DC supply. The proposed converter is constructed based on an indirect matrix converter. Therefore a proposed control strategy is based on an indirect control method with a triangular carrier wave. This paper proposes two control methods, using a boost up and a step down type DC/DC converter. The basic operation of the proposed control method is confirmed by simulation and experimental results.

In addition, this paper also proposes a commutation error compensation method for an output voltage error and an input current error for an indirect matrix converter. In the proposed method, the output voltage and input current error by the commutation can be compensated at the same time, because the PWM pulse of each switch is directly compensated. The validity of the proposed method is confirmed by experimental results. Those results prove that the proposed compensation method can decrease total harmonic distortion (THD) of the input and output current.

I. Introduction

Recently, interface power converters for renewable energy and hybrid electric vehicle (EV) systems have been studied intensely. Power sources can different types; AC power sources such as wind power, and DC power sources such a photovoltaic cells, a batteries, and fuel cells. Therefore, a conventional power converter system composed of AC/DC, DC/DC and DC/AC converters requires a large energy buffer, such as an electrolytic capacitor. However, the electrolytic capacitor in a conventional system interferes with down sizing, long-life time and low costs.

On the other hand, there is an AC/AC direct converter with a DC link, known as an indirect matrix converter [1-10]. The indirect matrix converter, which does not have a large energy buffer such as an electrolytic capacitor, can solve these problems. This converter is suitable to realize direct interface converters with multi-port for several power supplies. However, it is difficult to be added a DC/DC converter, because the conventional control method for the indirect matrix converter uses the space vector modulation [1], which is expressed by three dimensions.

This paper proposes tri-port converters using a simple control method based on the indirect control method with a triangular carrier wave [11]. By using a triangular carrier, the PWM pulse can be generated without relationship to the number of phases. As a result, the proposed control system can be easy added to a DC/DC converter. In addition, this paper proposes the commutation error compensation method for the output voltage error and the input current error of the indirect matrix converter. The commutation causes the output voltage error and the input current error, such as the dead-time in a conventional inverter. In the proposed method, the output voltage and input current error are compensated at the same time, because the PWM pulse of each switch is directly compensated. As a result, the influence of the commutation for the input and output current can be decreased by the proposed commutation method.

Experimental results with an AC power grid, a motor, and a battery are also provide. The basic operation and validation of the proposed method are confirmed by simulation and experimental results. As a result, input, output and DC output current total harmonics distortion (THD) are 1.4, 1.8%, 2.3%, were confirmed. In addition, an input power factor of over 99% and an efficiency of 95.4% were obtained.

II. Circuit topology

Figure 1 shows the proposed direct interface converters for the energy management system. This system consists of two AC power sources or loads and the DC power source without a large energy buffer, such as an electrolytic capacitor. In case of a hybrid EV system, the energy flow of the interface converter must be maintained in three directions, as shown Fig. 1.

Figure 2 shows the main circuits of the proposed system. There are two operation methods in this system. The first operation method is to operate the inverter side converter as a four-phase voltage source inverter, including the DC/DC converter. For this operation, the DC link voltage becomes higher than the DC power supply. Therefore, it is referred to as a "boost type AC/DC/AC direct converter". The second operation method is to operate the rectifier side converter as the four-phase current source rectifier, including the DC/DC converter. In this case, DC link voltage becomes lower than DC power supply, and thus, is referred to as a "step down type AC/DC/AC direct converter" in this paper.

The proposed control strategy, which is based on an indirect control method with the triangular carrier wave, easily realizes the addition of a DC/DC converter. The conventional indirect control

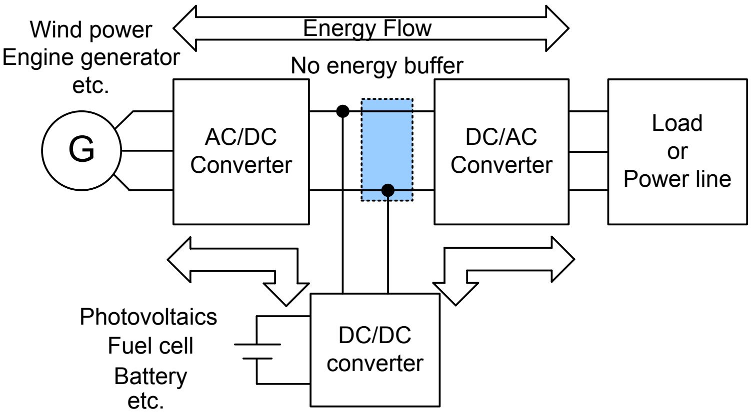
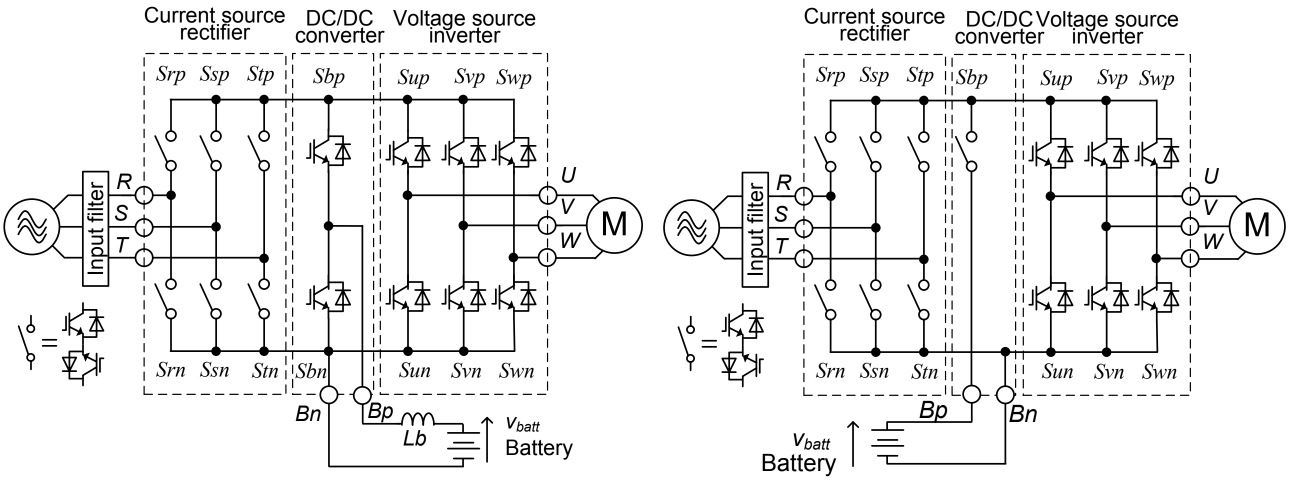


Fig. 1. Block diagram of AC and DC power supply interface system.



(a)Boost type AC/DC/AC direct converter. (b) Step down type AC/DC/AC direct converter.

Fig. 2. Proposed circuits.

strategy, which uses space vector control, must calculate the PWM pulse width to include a DC/DC converter. In addition, it is difficult to define the output voltage command vector to include a DC output. However, the proposed control system can include a DC/DC converter by using a command for the comparison of the carrier wave and the voltage. This chapter describes two types of control method for the DC/DC converter.

A. Boost type AC/DC/AC direct converter

Figure 3 shows a block diagram of the boost type DC/DC converter with the indirect matrix converter. This converter operates the inverter side converter as a four-phase voltage source inverter including the DC/DC converter. The relation between the input voltage $[v_r\ v_s\ v_t]^t$ and the output voltage $[v_u\ v_v\ v_w\ v_b{}']^t$ can be expressed as

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

where S_{xy} is the switching function of the switch S_{xy} in Fig. 2. $S_{xy} = 1$ when S_{xy} is turned on, and $S_{xy} = 0$ when S_{xy} is turned off. The output voltage $v_b{}'$ is the battery voltage v_{batt} based on that the motor neutral point.

The rectifier side converter uses single-phase modulation, as shown in Ref. [11]. Thus, the DC link voltage contains the ripple, which contains sixth order component of a power supply frequency. The output voltage commands of the inverter side converter including the DC/DC converter must compensate for this ripple. Moreover, the output voltage commands of the four-phase voltage source inverter are based on the neutral point of the motor. In contrast, the DC/DC converter output voltage commands are based on the point B_n, as shown in Fig. 2. Therefore, the DC/DC converter voltage command $v_{bout}{}^{**}$ is converted by the following equation:

$$\boldsymbol{v_{batt}}^{***} = 2\boldsymbol{v_{batt}}^{**} - 1 \quad (2).$$

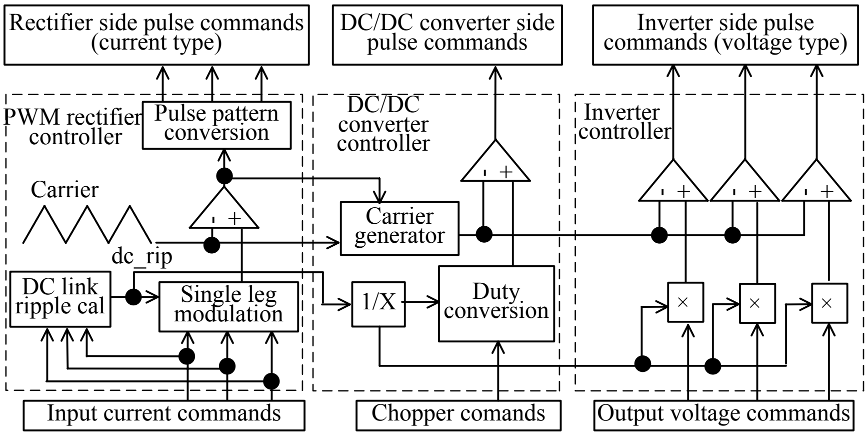


Fig. 3. Control block diagram of boost type AC/DC/AC direct converter.

B. Step down type AC/DC/AC direct converter

Figure 4 shows a block diagram of the step down type AC/DC/AC direct converter. This converter operates the rectifier side converter 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:

$$\begin{bmatrix} \boldsymbol{v_u} \\ \boldsymbol{v_v} \\ \boldsymbol{v_w} \end{bmatrix} = \begin{bmatrix} \boldsymbol{s_{up}} & \boldsymbol{s_{un}} \\ \boldsymbol{s_{vp}} & \boldsymbol{s_{vn}} \\ \boldsymbol{s_{wp}} & \boldsymbol{s_{wn}} \end{bmatrix} \begin{bmatrix} \boldsymbol{s_{rp}} & \boldsymbol{s_{sp}} & \boldsymbol{s_{tp}} & \boldsymbol{s_{bp}} \\ \boldsymbol{s_{rn}} & \boldsymbol{s_{sn}} & \boldsymbol{s_{tn}} & \boldsymbol{s_{bn}} \end{bmatrix} \begin{bmatrix} \boldsymbol{v_r} \\ \boldsymbol{v_s} \\ \boldsymbol{v_t} \\ \boldsymbol{v_b}' \end{bmatrix} \quad (3),$$

where the input voltage v_b' is the battery voltage v_{batt} based on the input voltage neutral point. To avoid short circuit of the power supply, the rectifier side converter and DC/DC converter must be switched separately.

Figure 5 shows the relation of the carrier signals between the inverter and the rectifier. Usually, a current type rectifier is controlled under the constant DC link current. However, the DC link current must be zero when the inverter controller selects zero voltage vectors. In the proposed method, this is achieved by controlling the slope of the inverter carrier signal as shown in Figure 5. By adopting this method, the zero current period of the DC link is distributed by the same ratio as each input current, as described in Eq. (4).

$$\frac{T_{r0}}{T_1}=\frac{T_{s0}}{T_2}=\frac{T_{b0}}{T_3}=\frac{T_{r0}+T_{s0}+T_{b0}}{T_1+T_2+T_3} \qquad (4).$$

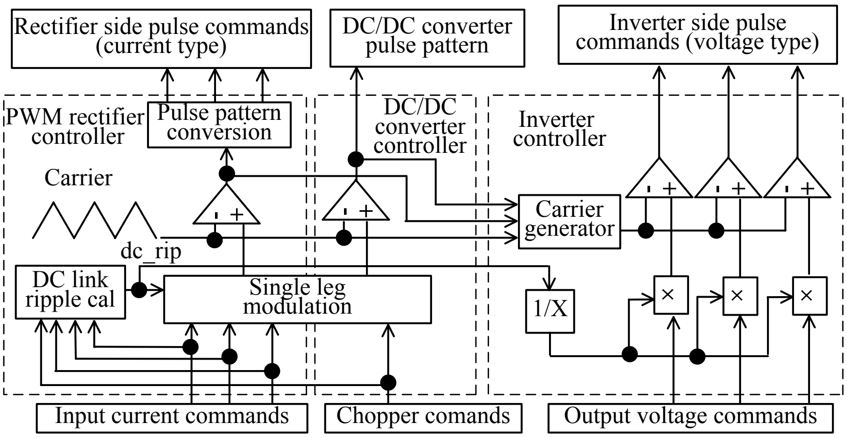


Fig. 4. Control block diagram of step down type AC/DC/AC direct converter.

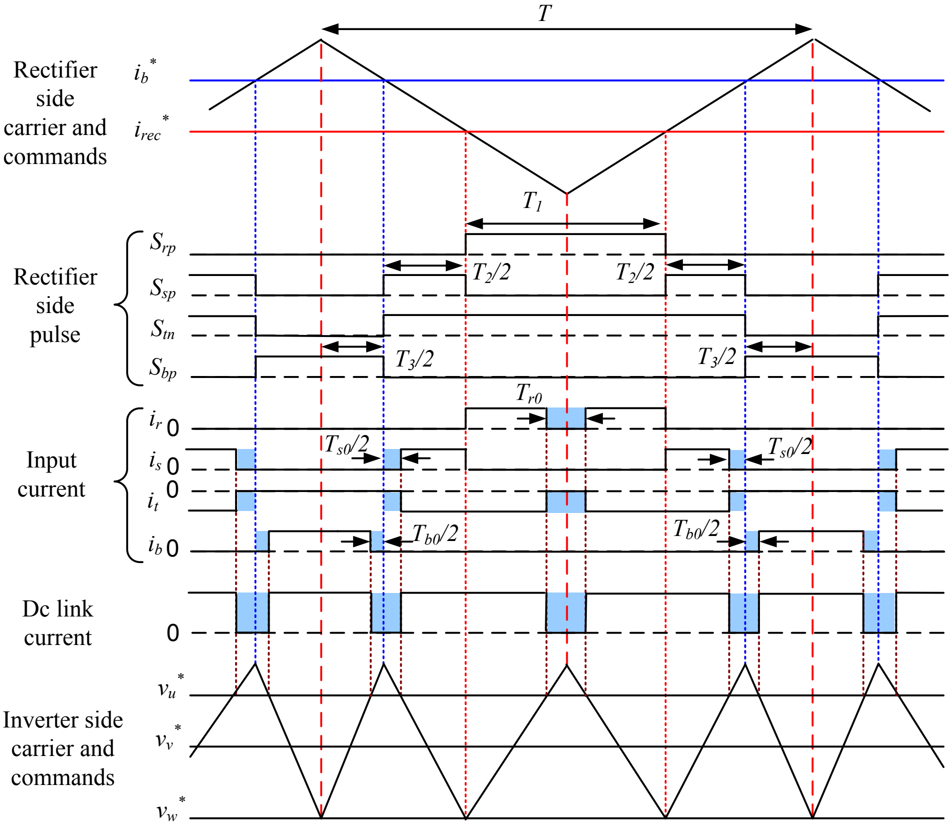


Fig. 5. Relation between inverter carrier and rectifier pulse.

III. Improvement of waveform for boost type AC/DC/AC direct converter

Figure 6 shows a part of the pulse pattern and behavior of the voltage error for the proposed indirect converter. In an indirect matrix converter, the rectifier side converter can achieve the zero current switching when the inverter generates the zero voltage vectors [4]. In other words, the dc-link current must be zero when the inverter controller selects the zero voltage vectors. However, the dc-link current flows in the proposed circuit when the inverter generates the zero voltage vectors of the upper (P) arms. Therefore, the proposed circuit has to choose only lower (N) arms zero voltage vectors. It is should be note that the conventional dead-time is applied for the commutation of the inverter side.

A. Analysis of the commutation error

In order to realize the low harmonics input and output current, the voltage error by the commutation is important as a conventional inverter. At first, this paper analyzes the commutation error of the indirect matrix converter. The relation between input voltage and output voltage of the indirect matrix converter can be expressed as Eq. (5) using "D_{mn}",which is duty ratio for switch S_{mn}.

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} D_{up} & D_{un} \\ D_{vp} & D_{vn} \\ D_{wp} & D_{wn} \end{bmatrix} \begin{bmatrix} D_{rp} & D_{sp} & D_{tp} \\ D_{rn} & D_{sn} & D_{tn} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \qquad (5).$$

As shown in Figure 4, the error by the dead time occurs to the inverter side and rectifier side duty ratio. In this case, the duty ratio considering the dead time error can be expressed by Eq. (6).

$$\begin{aligned}\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} &= \begin{bmatrix} D_u^* + \Delta D_u & 1 - D_u^* - \Delta D_u \\ D_v^* + \Delta D_v & 1 - D_v^* - \Delta D_v \\ D_w^* + \Delta D_w & 1 - D_w^* - \Delta D_w \end{bmatrix} \begin{bmatrix} D_{rp}^* + \Delta D_{rp} & D_{sp}^* + \Delta D_{sp} & 0 \\ 0 & 0 & D_{tn}^* + \Delta D_{tn} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \\ &= \begin{bmatrix} (D_u^* + \Delta D_u)(D_{rp}^* + \Delta D_{rp}) & (D_u^* + \Delta D_u)(D_s^* + \Delta D_{sp}) & (1 - D_u^* - \Delta D_u)(D_{tn}^* + \Delta D_{tn}) \\ (D_v^* + \Delta D_v)(D_{rp}^* + \Delta D_{rp}) & (D_v^* + \Delta D_v)(D_s^* + \Delta D_{sp}) & (1 - D_v^* - \Delta D_v)(D_{tn}^* + \Delta D_{tn}) \\ (D_w^* + \Delta D_w)(D_{rp}^* + \Delta D_{rp}) & (D_w^* + \Delta D_w)(D_s^* + \Delta D_{sp}) & (1 - D_w^* - \Delta D_w)(D_{tn}^* + \Delta D_{tn}) \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \qquad (6),\end{aligned}$$

where ΔD_{mn} represents the duty error by the dead time, and the suffix '*' represents the command.

From Eq. (6), the output voltage v_u can be determined by Eq. (7).

$$\begin{aligned} v_u = v_u^* &+ \Delta D_u (D_{rp}^* v_r + D_{sp}^* v_s - D_{tn}^* v_t) + \Delta D_u (\Delta D_{rp} v_r + \Delta D_{sp} v_s - \Delta D_{tn} v_t) \\ &+ \left\{ D_u^* (\Delta D_{rp} v_r + \Delta D_{sp} v_s) + (1 - D_u^*) \Delta D_{tn} v_t \right\} \end{aligned} \qquad (7).$$

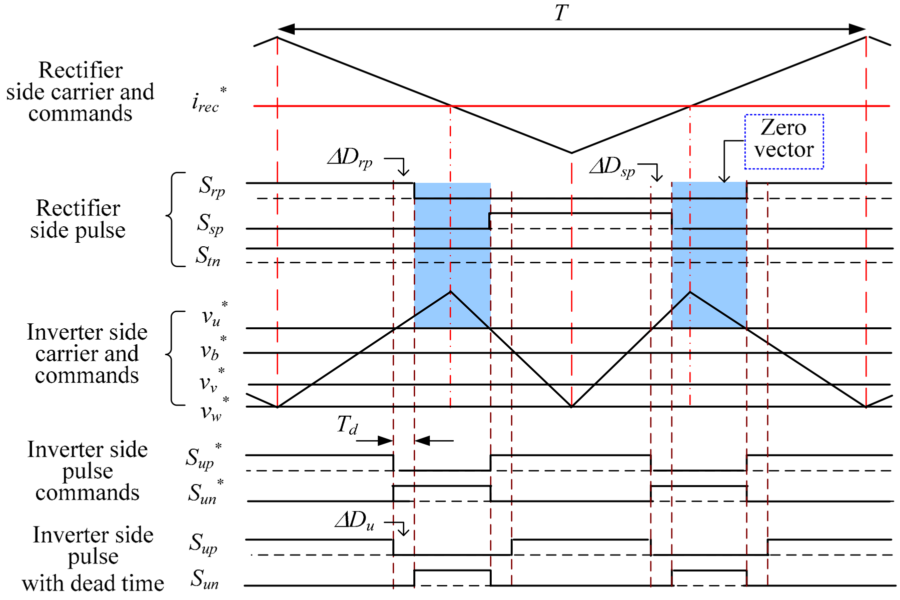


Fig. 6. Commutation example.

The second term in the right side of Eq. (7) means the voltage error directly affected by the inverter dead time, the third term means the influence of the input side, and the fourth term means mixed error between the input and output side.

On the other hand, the relation between the input and output current of the indirect matrix converter can be expressed as Eq. (8). It should be noted that Eq. (8) is the transposed matrix of Eq. (6).

$$\begin{bmatrix} i_r \\ r_s \\ i_t \end{bmatrix} = \begin{bmatrix} (D_u^* + \Delta D_u)(D_{rp}^* + \Delta D_{rp}) & (D_v^* + \Delta D_v)(D_{rp}^* + \Delta D_{rp}) & (D_w^* + \Delta D_w)(D_{rp}^* + \Delta D_{rp}) \\ (D_u^* + \Delta D_u)(D_s^* + \Delta D_{sp}) & (D_v^* + \Delta D_v)(D_s^* + \Delta D_{sp}) & (D_w^* + \Delta D_w)(D_s^* + \Delta D_{sp}) \\ (1 - D_u^* - \Delta D_u)(D_{tn}^* + \Delta D_{tn}) & (1 - D_v^* - \Delta D_v)(D_{tn}^* + \Delta D_{tn}) & (1 - D_w^* - \Delta D_w)(D_{tn}^* + \Delta D_{tn}) \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \quad (8).$$

From Eq. (8), for example, the input current i_r can be determined by Eq. (9).

$$i_r = i_r^* + \Delta D_{rp}(D_u^* i_u + D_v^* i_v + D_w^* i_w) + \Delta D_{rp}(\Delta D_u^* i_u + \Delta D_v^* i_v + \Delta D_v^* i_w) + \Delta D_u(D_{rp}^* i_u + D_{rp}^* i_v + D_{rp}^* i_w) \quad (9).$$

In the conventional compensation methods, the output voltage error is compensated by Eq. (7). That is, the voltage error adds to the voltage commands of the inverter. From Eq. (7), the compensation duty ratio D_{ucomp} can be determined by Eq. (10) because duty factor is obtained by dividing the duty ratio by the DC-link voltage. In the indirect matrix converter, the compensation values contain not only the inverter voltage error ΔD_u but also the influence error ΔD_{rucomp} of the input side. Similarly, other compensation duty ratio can be calculated.

$$\begin{aligned} D_{ucomp} &= \Delta D_u + \left\{ D_u(\Delta D_{rp} v_r + \Delta D_u \Delta D_{sp} v_s) + (1 - D_u^*)\Delta D_{tn} v \right\} / e_{dc} \\ &= \Delta D_u + \Delta D_{rucomp} \end{aligned} \quad (10).$$

This method can compensate the output voltage, however, the input current can not compensate because the compensation values is decided without consideration for the input current. In this case, the input current i_r can be expressed by Eq. (11).

$$\begin{aligned} i_r = i_r^* &+ \Delta D_{rp} \left\{ D_u^* i_u + D_v^* i_v + D_w^* i_w \right\} \\ &- \Delta D_{rucomp}(D_{rp}^* i_u - \Delta D_{rp} i_u) - \Delta D_{rvcomp}(D_{rp}^* i_v - \Delta D_{rp} i_v) - \Delta D_{rwcomp}(D_{rp}^* i_w - \Delta D_{rp} i_w) \end{aligned} \quad (11).$$

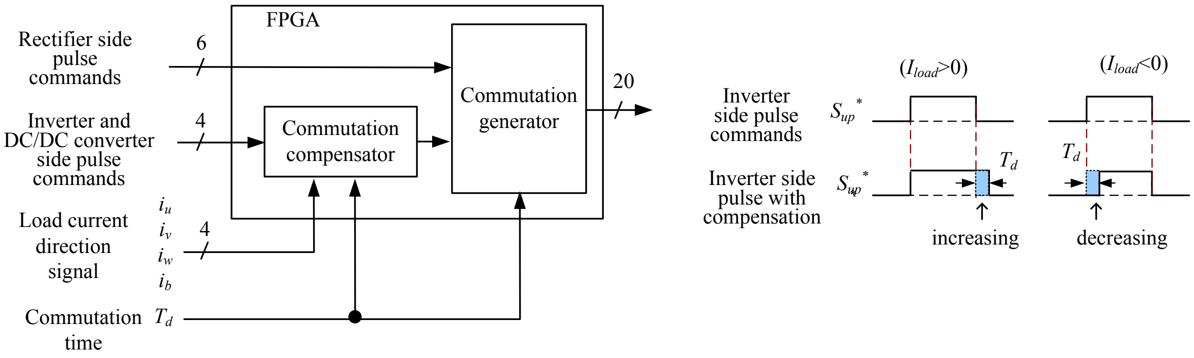
The additional input current error occurs to Eq. (11) since the output voltage is compensated by Eq. (10). Moreover, the commutation error of the rectifier side can not compensate because the commutation error of the rectifier side does not depend on the inverter side duty ratio. Therefore, the input current error remains as shown in Eq. (11).

B. Proposed compensation method

In this paper, the voltage error is directly compensated by the PWM pulse. The input current and output voltage error can compensate at the same time because the PWM pulse of each switch is directly compensated.

Figure 7 shows the proposed commutation error compensation method. The inverter side and DC/DC converter side pulse commands are compensated directly based on the load current direction in Commutation compensator as shown Fig. 7(a).

Figure 7(b) shows behavior of the commutation compensator. In case of load current direction is



(a) Configuration of proposed commutation error compensation.

(b) Behavior of compensator

Fig. 7. Proposed commutation error compensation method.

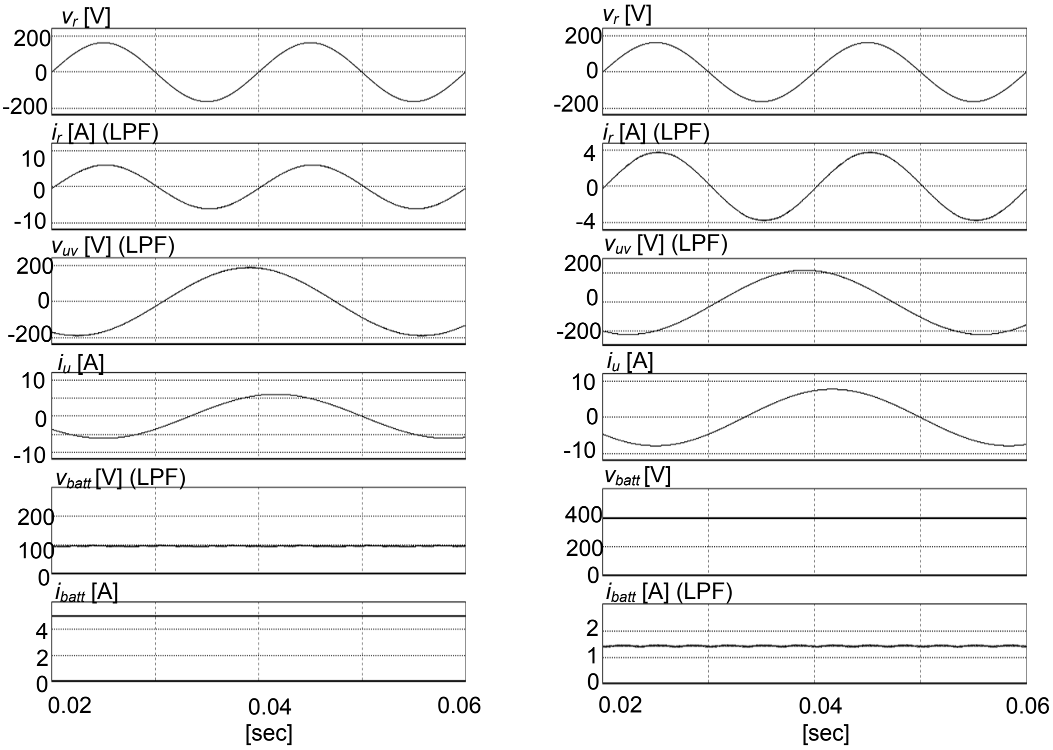
plus, the compensator adds the dead-time period to the pulse command, because actual pulse is decreased by the dead-time period. In case of load current direction is minus, the compensator subtracts the dead-time period to the pulse command, because actual pulse is increased by the dead-time period.

IV. Simulation and experimental results

Figure 8 shows the simulation results of the proposed control strategy. In the simulation, an ideal current source load and a main circuit are used to check the proposed 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 output voltage.

Table 1 provides the experimental parameters. The operation of a boost type DC/DC converter with indirect matrix is shown by the experimental results. This converter has six operation modes as follows. (P: power grid, B: battery, M: motor)

I:	P: generation,	B: charge,	M: motoring
II:	P: generation,	B: charge,	M: generating
III:	P: generation,	B: discharge,	M: motoring
IV:	P: regeneration,	B: charge,	M: generating
V:	P: regeneration,	B: discharge,	M: motoring
VI:	P: regeneration,	B: discharge,	M: generating



(a) boost mode (b) step down mode

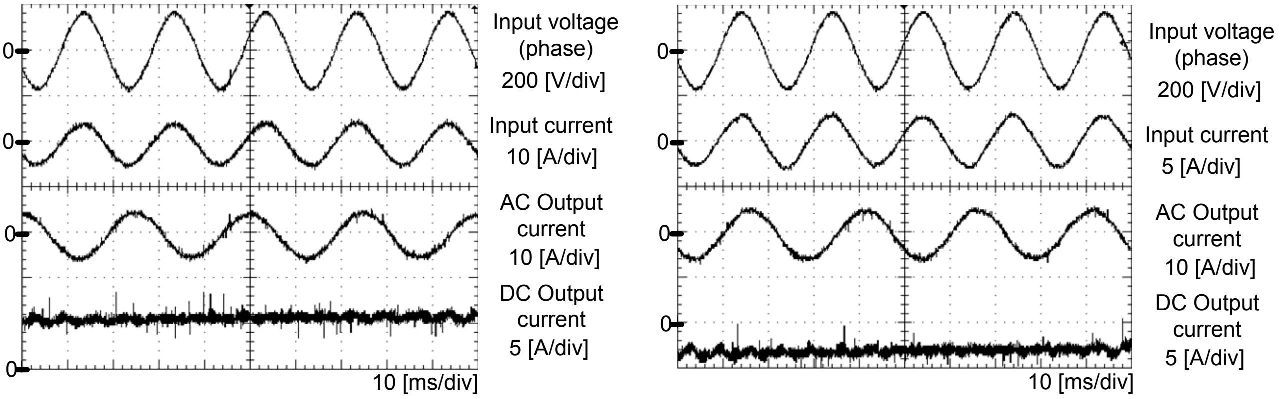
Fig. 8. Simulation results.

Table1 Experimental parameter.

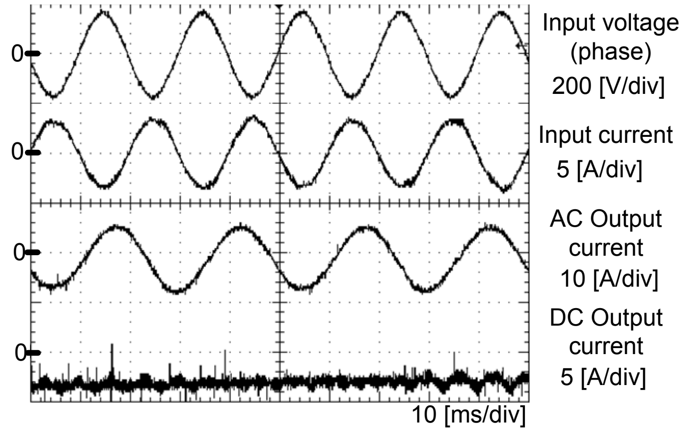
Input voltage	200[V]	LC filter	2 [mH]
Input frequency	50[Hz]		6.6 [μF]
Carrier frequency	10[kHz]	Cut-off frequency	1.3[kHz]
Output frequency	40[Hz]	DC load	R-L
AC load	1.5[kW]motor	DC source	DC power supply
Commutation time		2.5[μs]	

Figure 9 shows the waveforms for operation modes I, II, and VI, as typical modes. Good sinusoidal and dc waveforms were obtained for the input and output current. The other operation modes were also confirmed. As a result, generation and regeneration of a power grid, the charge and discharge of a battery, and motoring and generating operations are obtained for each operation waveform.

Figure 10 shows the efficiency and the input power factor when the dc/dc converter leg is stopped in the proposed converter. The input power factor of over 99% and the high efficiency of 95.4% were obtained. It should be noted that the efficiency of a conventional AC/DC/AC interface converter with a large electrolytic capacitor is approximately 90%. Therefore, the proposed converter can decrease the converter loss of 1/2.



(a) Mode I (b) Mode III



(c) Mode VI

Fig. 9. Experimental results.

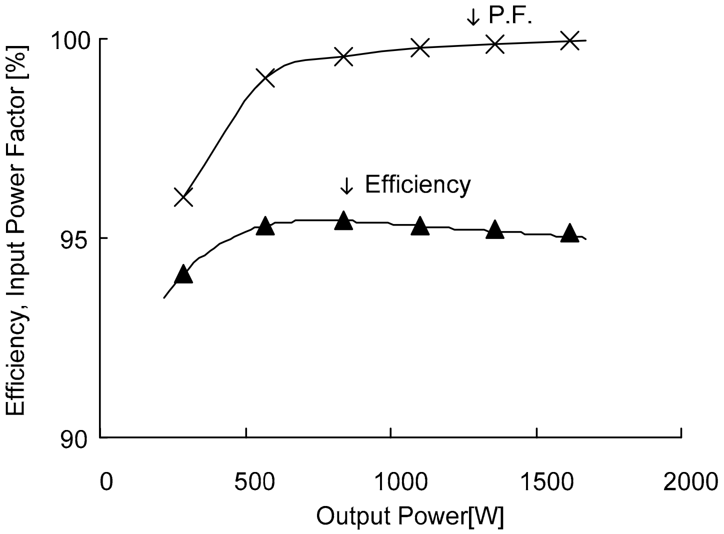
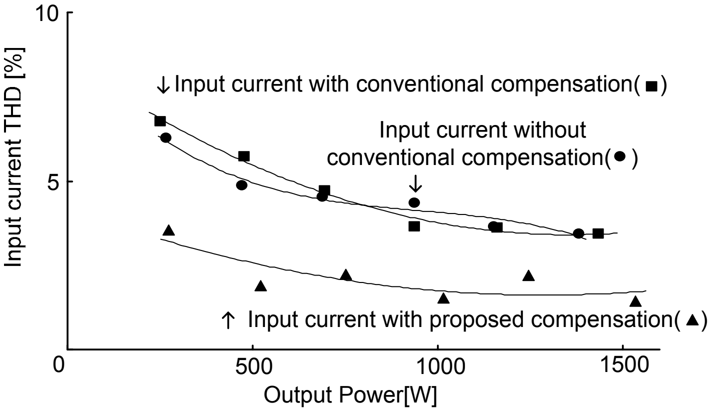


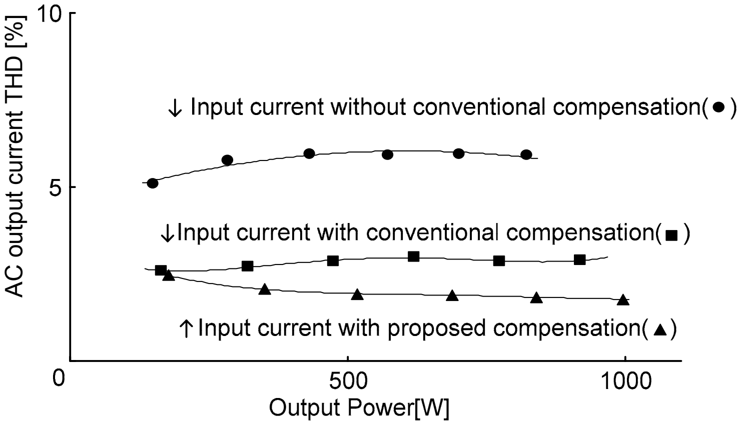
Fig. 10. Efficiency and input power factor.

Figure 11 shows the comparison among the THD of the proposed circuit without voltage and current error compensation, with the conventional compensation, which only add the voltage error to the output voltage command, and proposed compensation methods, as described in chapter III. In the input current THD, the conventional compensation methods is not effective, because the conventional compensation method only compensates the output voltage without consideration for the input current. In contrast, the THD for the input current is improved by approximate 50%, using the proposed compensation method. On the other hand, the conventional compensation method decreases the output current THD by approximate 50%. In addition, the proposed compensation method also decrease the input current THD by approximate 60%. However, almost same THD are obtained in the DC output current. This causes that an auto current regulator is used in the DC/DC converter control. In the proposed compensation, low THD is obtained for the input and output currents.

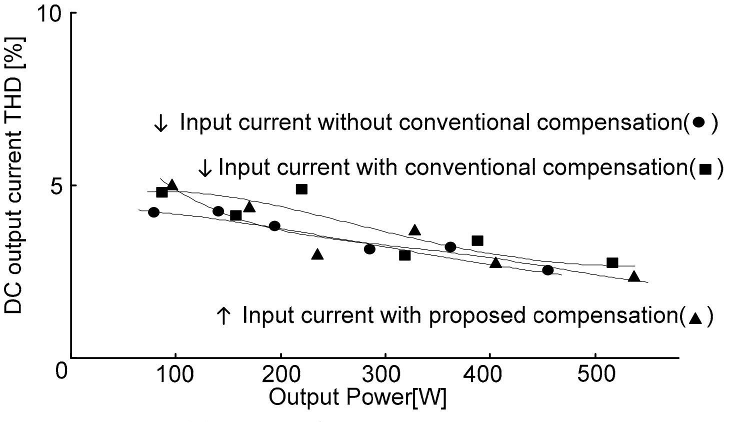
These experimental results confirm that the validity of the proposed circuit and commutation error compensation method.



(a) THD of input current.



(b) THD of AC output current.



(c) THD of DC output current.

Fig. 11. THD of input and output current using a R-L load.

V. Conclusion

This paper proposes a novel control strategy for the energy management of an AC and DC power supply direct interface converters. The proposed control strategy, which is based on an indirect control method with a triangular carrier wave, is easy to expand to the multi-phase system. This paper proposes the two control methods using a boost up and step down type DC/DC converters. Moreover the compensation method for the output voltage and the input current error by the commutation were also proposed. The proposed compensation method can be used in the indirect matrix converter. The proposed compensation methods compensate directly the PWM pulse of each switch. The validity of the proposed strategy was confirmed by both the simulation and experimental results. As a result, it is confirmed that the AC input, output current, and the DC output current THD are 1.4%, 1.8%, 2.3%, respectively, and the input power factor is over 99% and the maximum efficiency is 95.4%. Moreover, the influence of the commutation for the input and output current can be decreased by the proposed commutation method. In addition, three directions of energy flow in this circuit are confirmed.

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