Control Strategy for a Buck-boost Type Direct Interface Converter Using an Indirect Matrix Converter with an Active Snubber

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Abstract— **This paper proposes a novel control method for an interface converter that is using an indirect matrix converter (IMC) with a DC power supply. The proposed converter is constructed based on an indirect matrix converter and a converter that combined the function of a boost type converter and a step-down type converter. The proposed converter connects an active snubber to the DC link part of IMC along with a boost type converter. The voltage transfer ratio from the AC power sources to the load can be improved by this active snubber. In addition, the proposed control method able to control the power distribution ratio and the output voltage at a same time. The basic operation of the proposed method has confirmed by simulation and experimental results.**

I. INTRODUCTION

Recently, renewable energies and hybrid electric vehicle (HEV) systems are receiving significant interest, with considerations of global warming and environmental problems. There are two types of power sources for renewable energies; AC power sources such as a wind turbine and DC power sources such as batteries, and fuel cells. In these systems, 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 an electrolytic capacitor. However, this electrolytic capacitor in the conventional system is facing with several subjects, such as size, life time and costs. Particularly this large electrolytic capacitor has a problem in HEV applications because a power converter is installed at a high temperature area. Therefore, it is difficult to use electrolytic capacitors for HEV applications in terms of the lifetime that is affecting by the high temperature.

On the other hand, there is an AC/AC direct converter without a large energy buffer such as a matrix converter, which uses nine bidirectional switches, and an IMC, which consists of a current source rectifier and a voltage source inverter without a capacitor in the DC link part[1]-[8]. The utilization of these AC/AC direct converter in renewable energy systems can achieve the following advantages; downsizing, long-life cycle and low costs.

There are some studies about how to interface the matrix converter with a DC power supply as mentioned in [9]-[10]. A voltage source inverter is connected to the input or output side of the matrix converter. In this system, the matrix converter operates in parallel with the inverter. However, the drawback is size will be extended because of constituting many components. The inverter is used to interconnect with a DC power source because the matrix converter has no DC component. However, this turns out to be a high cost structure for the matrix converter.

On the other hands, there are two types of interface converters using an IMC have been proposed, which are classified as the boost type converter[11] and step-down type converter[12]. Since the IMC contains of a DC link part, it is easy to interconnect with a DC power supply from that connection. The boost type converter connects a DC/DC converter using a chopper to the DC link part of the IMC. The control strategy of the voltage source converter, which consists of the inverter and the added DC/DC converter, is implemented as a four-phase voltage source inverter. With regard to the voltage relationship between the DC power supply voltage and the DC link voltage, the proposed circuit provides a boost-up operation for the DC power supply. However, the proposed boost type converter does not improve the voltage transfer ratio of the IMC. That is, the voltage transfer ratio of IMCs, which defines the ratio between the output voltage and the input voltage, is well known as being constrained to 0.866.

The step-down type converter interfaces the DC power supply using an active snubber circuit in the IMC. The active snubber circuit is composed by a capacitor connected to a switching device in series. This snubber circuit pairs with a switching device to work as a step-down chopper for the DC power supply. In addition, the voltage transfer ratio can be improved by using the DC power supply because the DC power supply should be higher than the DC link voltage to avoid short circuit. However, when the battery is used for the DC power supply in this system, a lot of batteries have to be connected in series. In this case, the battery volumes and costs will increase.

This paper proposes a converter which is combined by a boost type converter and a step-down type converter. The proposed converter connects an active snubber to the DC link part in the boost type converter. The voltage transfer ratio from the AC power source to the load can be improved by the active snubber. Besides, the high voltage battery is not required because the DC voltage source is boosted by the boost type DC/DC converter. That is, the proposed system covers the disadvantage of the boost type converter and step-down type converter from one to each other. The PWM generator is implemented based on the space vector modulation (SVM). The proposed control method controls the DC/DC converters and the inverter independently. The fundamental operation of the proposed method has confirmed by experimental results and loss analysis results.

II. PROPOSED SYSTEM CONFIGURATION

A. Back to Back converter system

Figure 1 shows the AC and DC power supply interface systems using the back to back converter. A conventional interface system consists of a PWM rectifier, a DC/DC converter and an inverter, as shown in Fig. 1. This system requires a large electrolytic capacitor in the DC link part in order to smooth the DC link voltage. This system is very flexible in term of voltage condition among the input and output side because of using voltage type converters in both sides. However, the electrolytic capacitor in DC link part gives problem such as large volume, short lifetime in high temperature ambience and high cost. Particularly, the large electrolytic capacitor has a problem for the HEV application because the power converter is installed at a high temperature area. Therefore, the electrolytic capacitor is not suitable for the HEV applications.

B. Matrix converter system

Figure 2 shows a AC and DC power supply interface system using the matrix converter[9] [10]. In Ref.[9], the inverter is connected to the input side of the matrix converter. The characteristic of this system is that an input filter can be replaced by the inverter. In addition, the voltage transfer ratio of the matrix converter is improved by using the inverter. However, the efficiency between the battery and the load is not high because this system requires twice power conversion between a battery and load.

Figure 2(b) shows the interconnection system, which has been proposed in Ref. [10]. This system is a kind of delta configuration system which is connected by the rectifier, the inverter and the matrix converter. Furthermore, the power can be converted directly among the three sources; the generator, the battery and the motor. Therefore, the efficiency of this proposed system becomes higher than the BTB system. Moreover the proposed system does not require the interconnection transformers or reactors at the connection point between the matrix converter and the inverter because

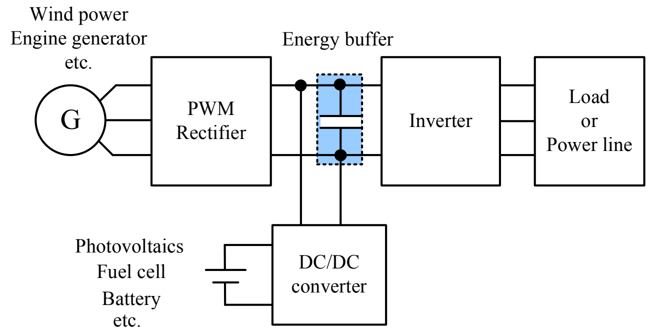
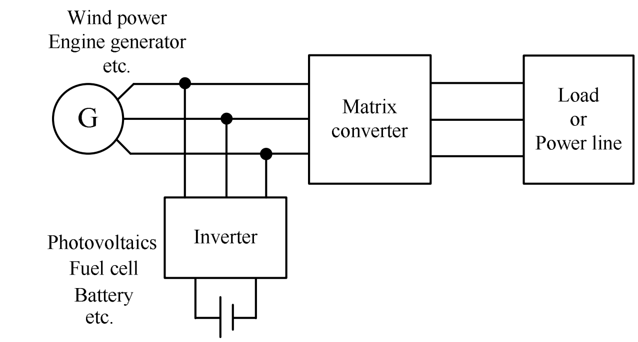
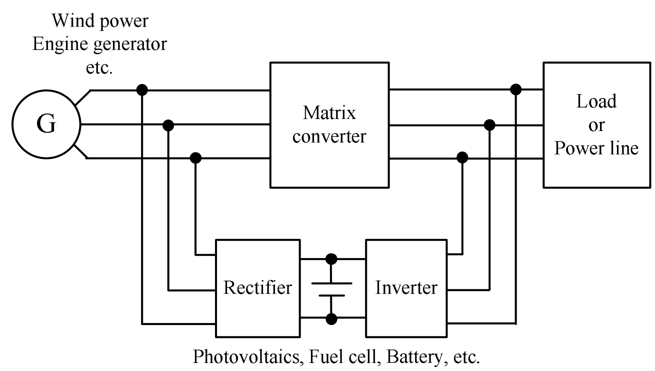


Fig. 1. Block diagram of the conventional AC and DC power supply interface system.



(a) System configuration of Ref. [9].



(b) System configuration of Ref. [10].

Fig. 2. Block diagram of the AC and DC power supply interface system using matrix converter.

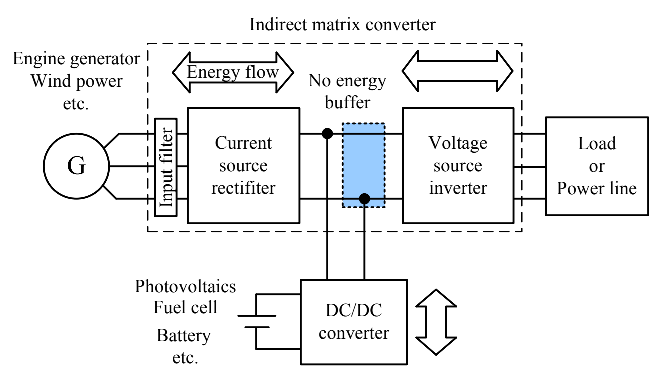


Fig. 3. Block diagram of the proposed system.

the operation of these two converters share the same time in one carrier cycle. However, it seems that the Ref. [9]-[10] system requires many components due to the insertion of the inverter and rectifier.

C. Proposed system

Figure 3 shows the block diagram of the proposed direct interface converters for the energy management system. The proposed interface converter is constructed based on an indirect matrix converter without the electrolytic capacitor as a large energy buffer. The DC/DC converter connects to the DC link of the indirect matrix converter. The proposed system can achieve higher efficiency than the conventional BTB system. In addition, the cost structure for the indirect control is lower than the matrix converter system because the number of components for the proposed system is less than the matrix converter system. Therefore, in this proposed circuit, since the size is smaller, the cost is lower as well and yet long life time.

III. CIRCUIT TOPOLOGY USING IMC

A. Boost type configureation

Figure 4 shows a boost type interface converter proposed in ref. [11]. A chopper is connected to the DC link part in the IMC. In this system, 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" in this paper. The chopper leg is controlled as a fourth leg of the voltage source inverter. Therefore, the control is implemented in a way that the voltage command of the chopper compares with the inverter carrier to obtain the desired PWM pattern.

However, the proposed converter has a problem which is the voltage transfer ratio between the power grid to the motor is constrained to 0.866 because the current source rectifier does not have a boost function. As a consequence, the output current of the IMC is higher than the BTB converter under the same output power rating. As a result, the motor loss and the converter loss are increased. Besides, the low voltage transfer ratio limits the applications of an IMC.

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

Figure 5 shows a step-down type interface converter proposed in ref. [12]. A DC/DC converter is constructed with an active snubber circuit in the IMC. 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 should be 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". The DC/DC converter is controlled as the fourth leg of the rectifier side converter. Time sharing is applied to the control of the snubber circuit.

Figure 6 shows the relationship between the DC link voltage and the active snubber duty ratio for the step-down type converter. For example, when the D_b becomes zero, the step-down type converter operates as a conventional IMC. The

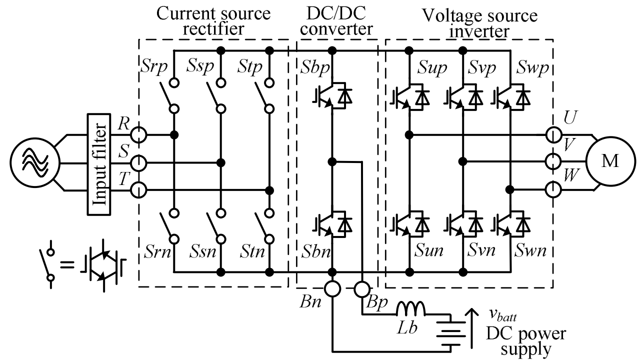


Fig. 4. Boost type AC/DC/AC direct converter.

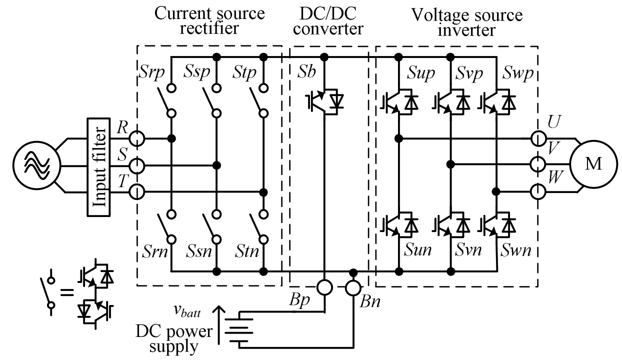


Fig. 5. Step down type AC/DC/AC direct converter.

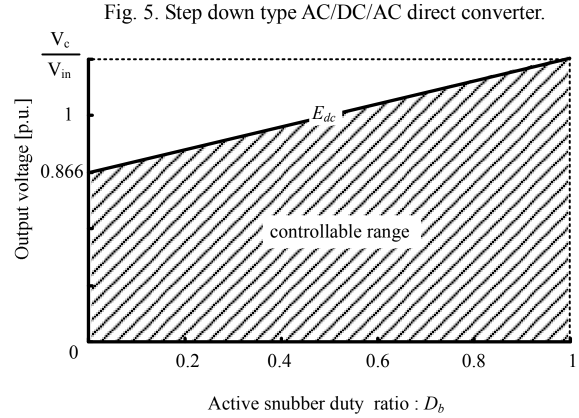


Fig. 6. Control range for each converter.

output voltage is limited to $0.866v_{in}$. On the other hand the step-down type converter operates as a conventional inverter when the D_b reaches "1". That is, the proposed circuit operates as a conventional IMC or a conventional inverter alternately in a sequence to interface the AC and the DC power supply. Therefore the DC link voltage is decided by the average value of the output voltage between the rectifier stage and the DC/DC converter. The average value of the DC link voltage E_{dc} in the proposed circuit can be expressed as,

$$E_{dc} = D_{rec}^{*} v_{in} + D^{*} v_{b} \qquad (1),$$

where D_{rec}^{*} is the rectifier stage converter duty ratio, and $D_b^{*}$is the DC/DC converter duty ratio.

In the step-down type converter, DC power supply voltage becomes higher than the DC link voltage. Therefore, a lot of batteries need to be connected in series to provide high voltage to DC power supply. In this case, the volume of the battery will increase.

C. Buck-boost type AC/DC/AC direct converter.

Figure 7 shows the proposed circuit configuration. As previously discussed, the voltage transfer ratio of the boost type AC/DC/AC direct converter is constrained to 0.866, and for the step-down type AC/DC/AC direct converter, the DC power supply requires a lot of batteries to obtain high DC voltage.

In Fig. 7, the proposed converter combines both the boost type AC/DC/AC direct converter and the step-down type AC/DC/AC direct converter into one converter. In other words, the proposed buck-boost type AC/DC/AC direct converter is composed by a boost type AC/DC/AC direct converter with an active snubber circuit. The proposed converter can operate as the boost type AC/DC/AC direct converter and the step-down type AC/DC/AC direct converter at a same time. The voltage transfer ratio in this proposed circuit is improved by using the active snubber circuit.

Figure 8 shows the equivalent circuits of the proposed converter. The rectifier stage converter is similar to a four phase current source rectifier including the active snubber. Therefore, the switches in the three-phase PWM rectifier and active snubber must be separately turned on in order to avoid a short circuit between the AC power supplies and the capacitor. When the DC/DC converter switch S_c is turned off, the proposed converter operates as a boost type AC/DC/AC direct converter. In this case, the DC/DC converter becomes a conventional snubber circuit, as shown in Fig. 8(a). On the other hand, the proposed converter operates as a conventional inverter with a boost chopper when the active snubber switch S_c is turned on as shown in Fig. 8(b). Note that all the switches in the rectifier will be turned off in this mode.

That is, the proposed circuit alternately operates as a boost type AC/DC/AC direct converter or an inverter with the boost chopper under a simultaneous control. The proposed converter can achieve a wide control range by controlling the active snubber circuit.

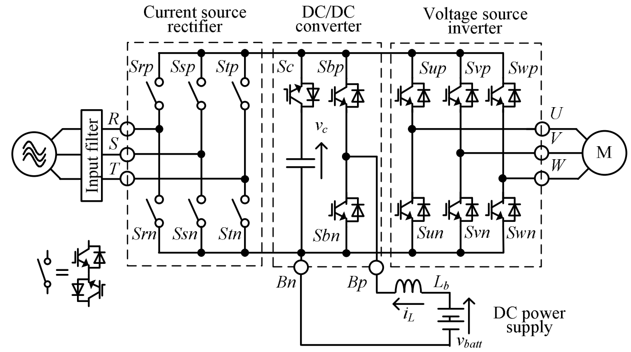
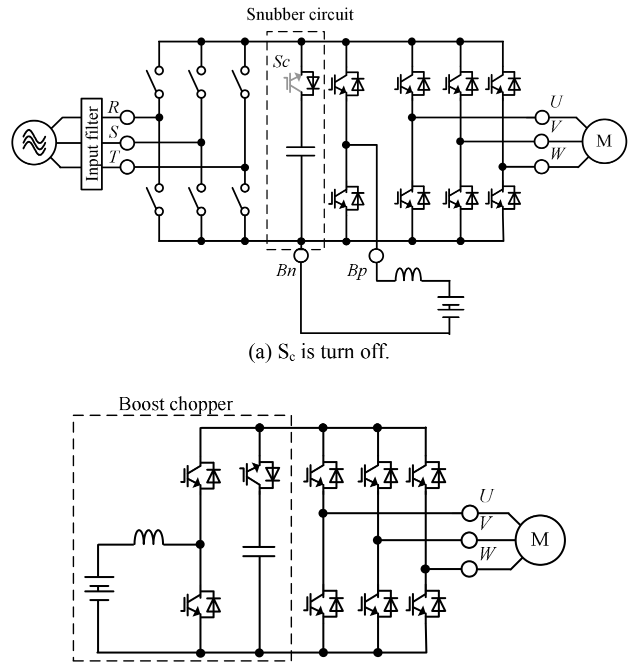


Fig. 7. Proposed circuit.



(a) S_c is turn off.

(b) S_c is turn on.

Fig. 8. Equivalent circuit of the proposed circuit.

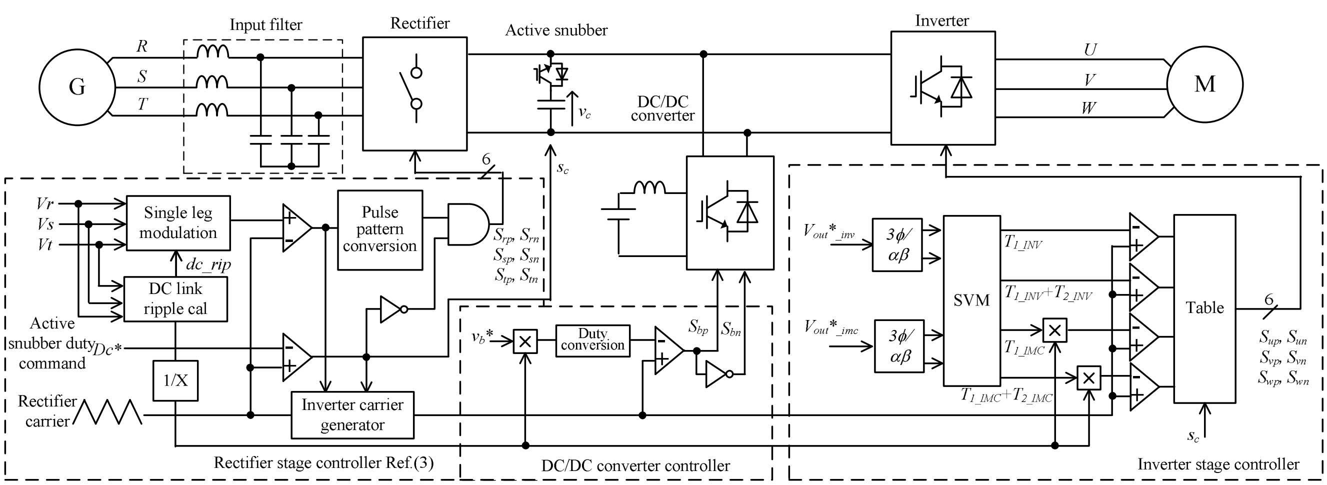


Fig. 9. Control block diagram of proposed converter.

IV. CONTROL STRATEGY

Figure 9 shows the control block diagram of the proposed converter. The proposed control method of the inverter stage is based on a space vector modulation. Therefore it is difficult to be added a DC/DC converter, because the space vector modulation is expressed by three dimensions[13].

Figure 10 following items in half control period; switching mode for each of the converter, and the carrier for inverter and DC/DC converter. The PWM pulse of the inverter and DC/DC converter carrier are obtained by comparison carriers and voltage command, which is calculated by the SVM. In the proposed method, the DC/DC converter applied the carrier comparison method using the carrier as shown in fig.10. The zero voltage vector of the inverter and the DC/DC converter lower arm switch s_{bn} have to be synchronized with the rectifier switching timing. Therefore, the inverter carrier is inverted when the active snubber switch is turned on. The ZCS of the rectifier stage is achieved at all time. That is, the proposed control method can control DC/DC converter independently.

Figure 11 shows the relationship between an output voltage command and a power distribution ratio for the proposed converter. The proposed converter has two types of operation modes. The operation mode is changed by the output voltage command v_{out}^* as follows.

A) $v_{out}^* \geq 0.866 v_{in}$: boost type operation mode

B) $v_{out}^* < 0.866 v_{in}$: buck-boost type operation mode

When the output voltage command is lower than 0.866 of the input voltage v_{in}, the proposed circuit operates as the boost type AC/DC/AC direct converter. In this case, the active snubber circuit is the same as a conventional snubber circuit. In other words, an active snubber duty command D_c^* is set to '0'. In addition, the DC/DC converter uses an ACR (Automated current regulator) to regulate battery current. The power distribution ratio is decided by the DC/DC converter current command.

On the other hand, the proposed converter operates as a buck-boost type AC/DC/AC direct converter when the output voltage command is higher than 0.866 of the input voltage v_{in}. In the proposed method, the power distribution ratio is decided by the active snubber duty ratio and the inverter stage output voltage v_{out}^*. In order to control the output voltage and the power distribution ratio at the same time, the output voltage command and the active snubber duty command is described as follows.

In the buck-boost type operation, the power distribution ratio is controlled by the operation time division of each operation mode. The output voltage is obtained by the average output voltage of inverter stage for the boost type mode and step-down type mode. Thus, when the active snubber duty is defined as D_c, the output voltage is obtained by (2).

$$v_{out} = \lambda_{sdt}^* D_c^* \frac{E_c}{2} + \lambda_{bt}^* (1 - D_c^*) \frac{E_{rec}}{2} = D_b^* v_{sdt\_out} + (1 - D_c^*) v_{bt\_out} \quad (2),$$

where, v_{out} is the inverter stage output voltage of the proposed circuit, v_{bt_out} is the inverter stage output voltage of the boost type operation, v_{sdt_out} is the inverter stage output voltage of step-down type operation, λ_{sdt} is the modulation index of the boost type operation, λ_{bt} is the modulation index of the step-down type operation, v_c is the capacitor voltage of active snubber, E_{rec} is the output voltage of rectifier stage and the subscript '*' represents the command.

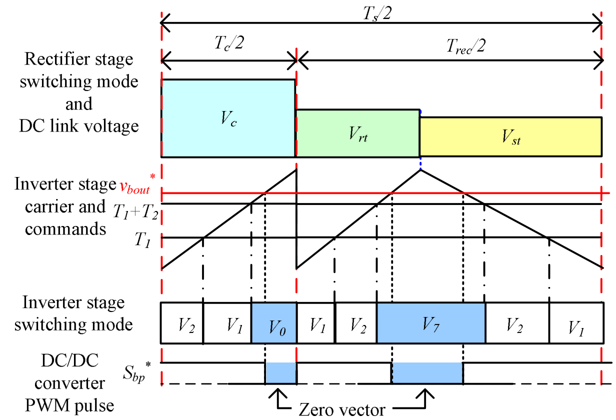


Fig. 10. Relation between inverter carrier, rectifier pulse and DC/DC converter pulse.

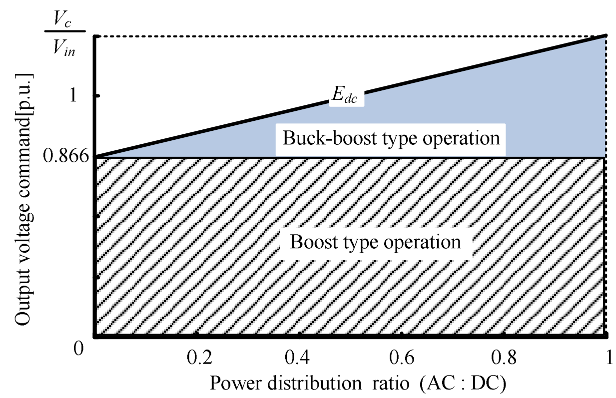


Fig. 11. Relation between output voltage command and power distribution ratio.

The power distribution ratio is calculated by multiplying the output voltage of each operation and the active snubber duty ratio D_c^*. Then, the power distribution ratio is expressed by (3) when the instantaneous power is assumed to constant during one carrier cycle.

$$P_{sdt}^* : P_{bt}^* = D_c^* v_{sdt\_out}^* : (1 - D_c^*) v_{bt\_out} \quad (3),$$

where, P_{std} is the output power of the boost type operation and P_{bt} is the output power of the boost type operation.

The operation time ratio of the active snubber circuit D_c can be determined by (4).

$$D_c^* = \frac{v_{bt\_out}^* P_{sdt}^*}{v_{sdt\_out}^* P_{bt}^* + v_{bt\_out}^* P_{sdt}^*} \quad (4).$$

Thus, the output voltage of the proposed converter is constrained by the power distribution ratio. In order to control the output voltage and the power distribution ratio at the same time, the output voltage command v_{out}^* and the active snubber duty command D_c^* of the active snubber circuit is formed in (5) from (2) and (4).

$$v_{sdt\_out}^* = \frac{v_{out}^* P_{sdt}^*}{P_{sdt}^* + P_{bt}^*(1 - \frac{v_{out}^*}{v_{bt\_out}^*})} \quad (5).$$

The modulation index of the inverter can be determined by (6) from (5).

$$\lambda_{sdt}^* = \frac{v_{out}^* P_{sdt}^*}{P_{sdt}^* + P_{bt}^*(1 - \frac{v_{out}^*}{v_{bt\_out}^*})} \frac{2}{v_c} \quad (6).$$

In addition, an active snubber capacitor voltage v_c is controlled by AVR (Automated voltage regulator). It is noted that the modulation index λ_{bt} is fixed at '1' to output a maximum voltage. Therefore, the power distribution ratio and the output voltage can be controlled at the same time. The relationship between the output voltage and the active snubber duty ratio is shown in Fig. 11.

V. EXPERIMENTAL RESULTS

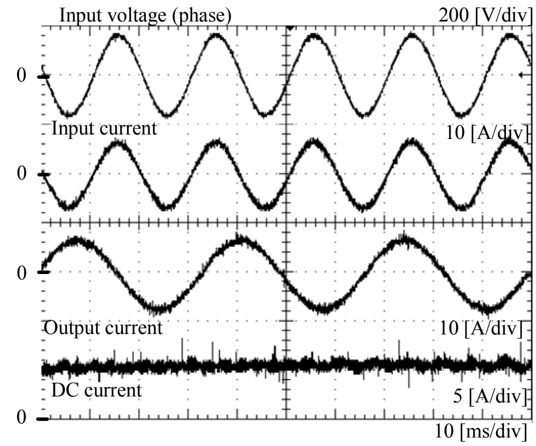
Table 1 provides the parameters and conditions for the simulation and the experimental. The operation of the proposed circuit is demonstrated by the simulation and experimental results.

First, the basic operation waveforms of the previous proposed converters are shown in Figure 12. Fig. 12(a) demonstrates the waveforms of the boost type AC/DC/AC direct converter; and Fig. 12(b) shows the waveforms for the step-down type AC/DC/AC direct converter. The input current and the output current show good sinusoidal waveforms for both the operation modes, and the DC current represents the battery current. As a result, in Fig. 12(a), it is confirmed that the total harmonic distortion (THD) of the input current, the output current and DC output current is 2.4%, 1.9% and 1.9% respectively. The input power factor is 99% and the efficiency is 96.3%. On the other side, the step down type converter shows the THD of the input current, the output current and the DC output current THD is 2.4%, 1.9% and 1.9%, the input power factor is 99% and the efficiency is 95.2% as shown in Fig. 12(b).

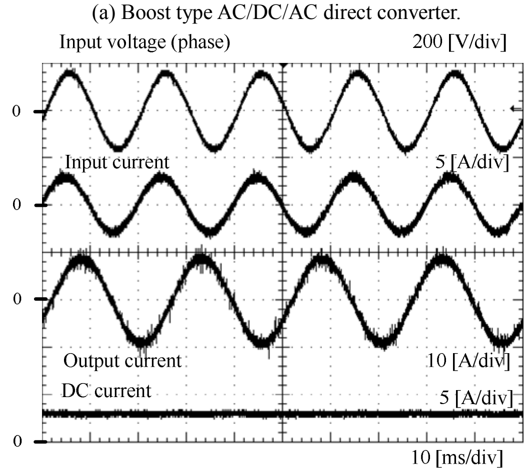
Figure 13 shows the waveform of the proposed control strategy. The dot line in the middle shows the change of the operation. At first, the proposed converter operates as the boost type AC/DC/AC direct converter. After that, the proposed converter operates as the buck-boost type AC/DC/AC direct converter. Sinusoidal waveforms without distortion are obtained for the input current and the output voltage. In Fig. (13), there is no sag occurs in the voltage and current when the operation mode is attempting a change. The output voltage of the boost type operation is 161 V. On the other hands the output voltage of the buck-boost type

Table 1. Experimental parameters.

Input voltage	200[V]	LC filter	2 [mH]
Input frequency	50[Hz]		6.6 [μF]
Carrier frequency	7.5[kHz]	Cut-off frequency	1[kHz]
Output frequency	40[Hz]	load	R-L
DC power supply	100[V]	Commutation time	2.5 [μs]



(a) Boost type AC/DC/AC direct converter.



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

Fig. 12. Experimental waveform

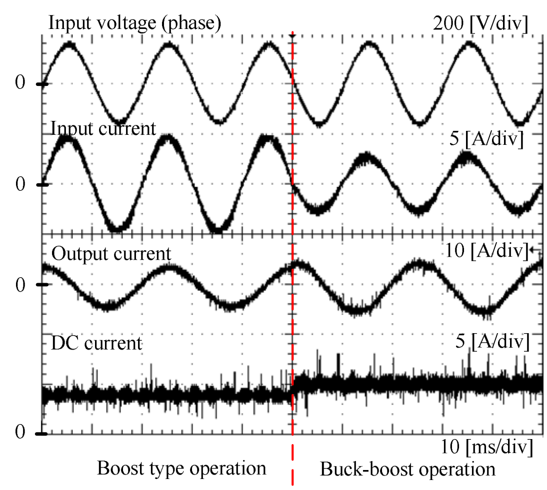


Fig. 13. Experimental waveform of proposed circuit.

operation is 180 V. The output voltage range is confirmed has been improved in the proposed circuit.

Figure 14 shows the THD of the input current, the output current and the DC input current which is 1.4%, 1.8% and 2.3%, respectively. In addition, the dead time error compensation is already applied in the FPGA control as reported in Ref. [11]. Therefore the proposed converter can obtain a low THD values for these current. It is noted that the DC current THD is defined by (7).

$$I_{dc\_THD} = \frac{I_{dc\_H}}{I_{dc}} \quad (7),$$

where, I_{dc} is the RMS value in the DC current and I_{dc_H} is the RMS value in the DC current harmonics.

Figure 15 shows the efficiency and the input power factor of the proposed circuit under two circumstances. In Fig.15(a), all the switches in the chopper are turned off, battery voltage is neglected in this condition. That is, the converter consists of the indirect matrix converter and the active snubber only. The obtained data shows that the input power factor is 99% and efficiency is 95.4%. It is noted that the efficiency of a conventional multi-power supply interface converter with a large electrolytic capacitor is approximately 93%. Fig.15(b) shows the second circumstances where the inverter side is taken off from the converter by switching off all the IGBTs in the inverter. Then, the DC/DC converter is operating in boost type mode. The data shows the input power factor is over 99% and the maximum efficiency is 93.7%.

In this result, the efficiency drops due to the increment of the conduction loss in the DC/DC converter. The conduction loss becomes larger because of the output voltage of the DC/DC converter is lower than the inverter output voltage, which is set to 100 V. For that reason, the current in the DC/DC converter will force to increase. In addition, the efficiency of the indirect matrix converter can be improved by the applying the reverse blocking IGBTs into the rectifier stage.

Figure 16 shows the relationship between the efficiency and the power distribution ratio. In this result, the total output power is about 1.2kW, the DC/DC converter operates in charge mode and the inverter operates in motoring mode. The maximum efficiency is 95.4 % when the power distribution ratio is “0”, that is the generator is 100% supplying the input power. On the other hand, when the power distribution ratio is “1”, where the battery is providing 100% of the input power, the efficiency is 93.7%. In this experimental condition, the total efficiency of the proposed circuit becomes higher when the power distribution ratio is lower.

Figure 17 shows the loss analysis comparison between the proposed circuit and the BTB system that is simulated from a circuit simulator (PSIM, Powersim Technologis Inc) and DLL file (Dynamic Link Library)[12]. In this result, the power distribution ratio is “0.5”. The switching losses do not occur in the rectifier stage of the proposed system because of applying the zero current switching. The proposed system decreases the switching loss in the rectifier stage by about 2/3 in compared with the rectifier stage of the BTB system. In the view of

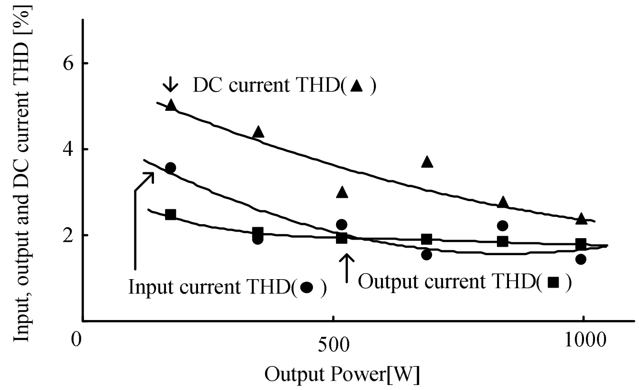
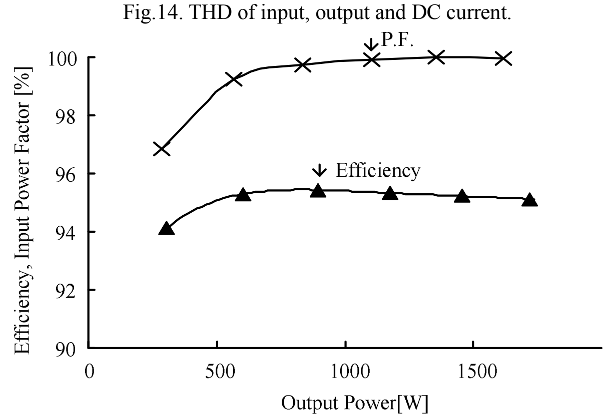
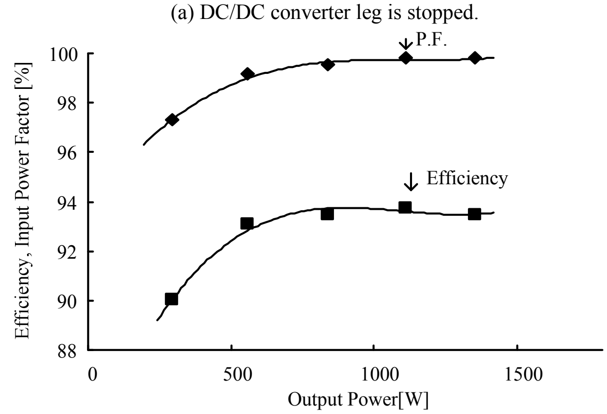


Fig.14. THD of input, output and DC current.



(a) DC/DC converter leg is stopped.



(b) Inverter leg is stopped.

Fig.15. Efficiency and input power factor.

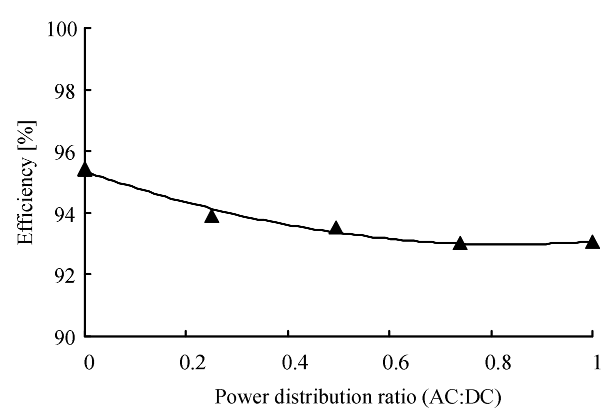


Fig.16. relation between efficiency and output power ratio.

inverter and DC/DC converter, the losses are almost the same at both systems since the output power of the inverter and the DC/DC converter is about the same. From the comparison, the proposed converter can obtain higher efficiency in compared to the BTB system.

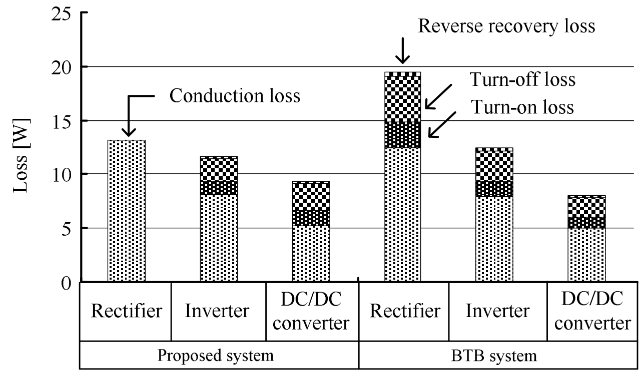


Fig.17. relation between efficiency and output power ratio.

VI. CONCLUSIONS

This paper proposes the novel control method and the converter which is combined by the boost type converter and step-down type converter. The proposed converter connects an active snubber to the DC link of the boost type converter. The voltage transfer ratio of the boost type converter can be improved by this active snubber. In addition, proposed control method is based on the space vector modulation (SVM). The proposed control method can control DC/DC converter and the inverter independently. 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%.The basic operation of the proposed method has confirmed by experimental results and loss analysis results.

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