A Control Method for Buck-boost Type Direct Interface Converter With DC Power Supply

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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 combined 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 an active snubber. In addition, the proposed control method able to control the power distribution ratio and output voltage at a same time. The basic operation of the proposed method has confirmed by simulation and experimental results. Moreover, in order to confirm the validity of the proposed system, the mileage evaluation at 10-15 mode for a hybrid electric vehicle has been implemented based on the simulation.

1. 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 interferes in several subjects, such as down sizing, long life time and low costs.

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]-[4]. The utilization of these AC/AC direct converter in renewable energy systems can achieve the following; downsizing, long-life cycle and low costs.

There are some approaches to interface DC power supply using the matrix converter as mentioned in [5], [6]. 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 and the inverter. However, there are some disadvantages such as large size and constituting of many components. The inverter is used to interconnect with the DC power supply because the matrix converter has no DC component. As a result, this is a high cost structure in 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[7] and step-down type converter[8]. Since the IMC has a DC link part, it is easy to interconnect with a DC power supply. The proposed boost type converter connects a DC/DC converter using a chopper to the DC link part of the IMC. The inverter and the DC/DC converter operate at the same time as a four-phase voltage source inverter, including the DC/DC converter. With regard to the voltage relationship between the DC power supply and the DC link, the proposed circuit provides a boost up converter 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 and the input voltage, is well known as being constrained to 0.866.

The proposed step-down type converter interface the DC power supply using an active snubber circuit in the IMC. The active snubber circuit is composed by a capacitor connected to an IGBT in series. This snubber circuit with the IGBT works as a step-down chopper for the DC power supply. In addition, the voltage transfer ratio can be improved by the DC power supply. In the step-down type converter, 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 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 up by this DC/DC converter. That is, the proposed system covers the disadvantage of the boost type and step-down type from one to each other. The basic operation of the proposed method has confirmed by simulation and experimental results. Moreover, in order to confirm the validity of the proposed system, the mileage evaluation at 10-15 mode for a hybrid electric vehicle is implemented based on the simulation.

2. Circuit topology

A. AC and DC power supplies direct interface system

Figure 1 shows the block diagram of 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. Two types of the DC/DC converter, which are boost type converter and step-down type converter, can be applied to this system.

B. Boost type AC/DC/AC direct converter

Figure 2 shows the proposed boost type converter. 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”. 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 the problem. The voltage transfer ratio between the power grid to the motor, is constrained to 0.866 because the current source rectifier has no a boost up function. As a consequence, the output current of the IMC is higher than the back-to-back type converter, which consists of a voltage type PWM rectifier and an inverter, for the same output power. As a result, the motor loss and the converter loss are increased. Besides, the low voltage transfer ratio limits the applications of an IMC.

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

Figure 3 shows the proposed step-down type converter. The 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 4 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. Therefore, the switch in the three-phase PWM rectifier and DC/DC converter must be separately turned on in order to avoid a short circuit between the AC and DC power supplies. When the DC/DC converter switch S_{bp} is turned off, the proposed converter operates as a conventional IMC. In this case, the DC/DC converter becomes a conventional snubber circuit, as shown in Fig. 4(a). On the other hand, the proposed converter operates as a conventional inverter when the DC/DC converter switch S_{bp} is turned on, because 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. 4(b). That is, the proposed circuit operates as a conventional IMC or a conventional inverter alternately in sequence.

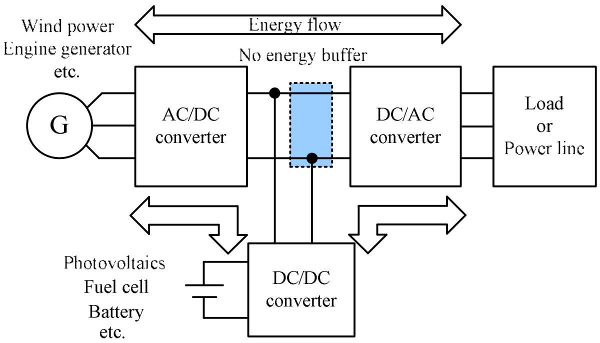


Fig. 1. Block diagram of AC and DC power supply interface system.

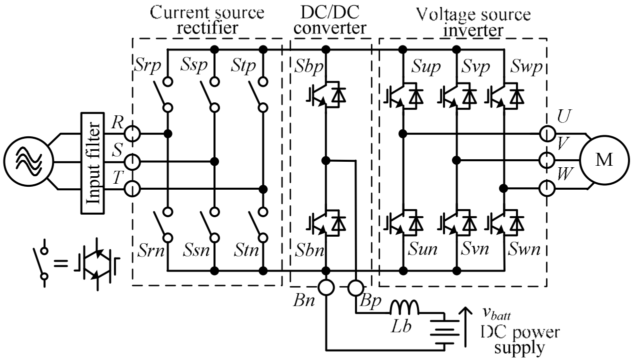


Fig. 2. Boost type AC/DC/AC direct converter.

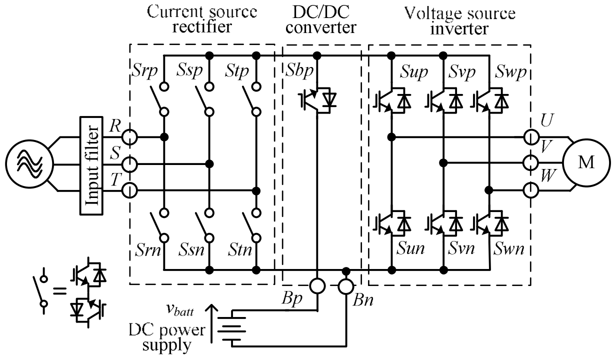
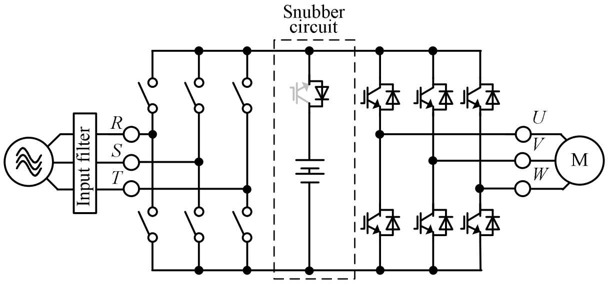
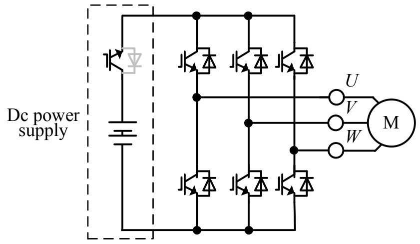


Fig. 3. Step down type AC/DC/AC direct converter.



(a) S_{bp} is turn off.



(b) S_{bp} is turn on.

Fig. 4. Equivalent circuit of the proposed circuit

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 Edc 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 becomes higher than the DC link voltage. Therefore, a lot of batteries need to be connected in series to provide high voltage DC power supply. In this case, battery volumes increase.

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

Figure6 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 a DC power supply of step-down type AC/DC/AC direct converter is requires by a lot of batteries to obtain high DC voltage.

Thus, the proposed converter combines both the boost type AC/DC/AC direct converter with step-down type AC/DC/AC direct 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 snnuber circuit. The proposed converter can operate as the boost type AC/DC/AC direct converter and step-down type AC/DC/AC direct converter. The proposed circuit improves the voltage transfer ratio by using an active snubber circuit.

Figure 7 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 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. 7(a). On the other hand, the proposed converter operates as a conventional inverter with boost copper when the active snubber switch Sc is turned on, because all switches in the rectifier are turned off, as shown in Fig. 7(b). That is, the proposed circuit operates as boost type AC/DC/AC direct converter or an inverter with boost chopper under alternately control.

3. Control strategy

Figure 7 shows the control block diagram of the proposed converter. The proposed control method is based on the control method of a boost type AC/DC/AC direct converter[7]. The inverter stage and DC/DC converter stage can be controlled independently and to apply the carrier comparison method. In addition, the voltage transfer ratio of the proposed converter can improve by the active snubber circuit.

The proposed circuit has two types of operation modes. The operation mode is changed by the output voltage command v_{out}^{*} as follows.

(1) $v_{out}^{*} \geqq 0.866 v_{in}$: boost type operation mode

(2) $v_{out}^{*} < 0.866 v_{in}$: 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 becomes a conventional snubber circuit. In other words, active snubber duty command D_b^{*} becomes ‘0’. In addition, the

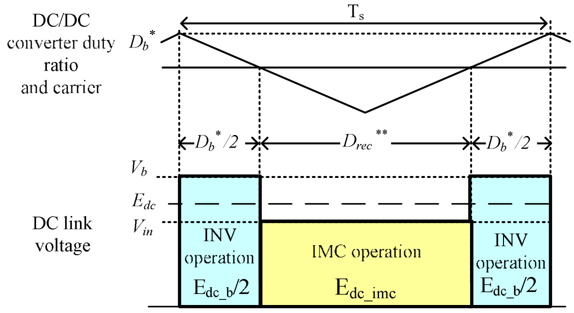


Fig. 5. Principle of the step-down type AC/DC/AC direct converter.

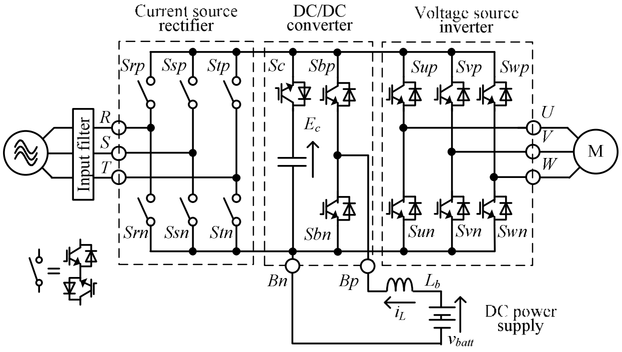
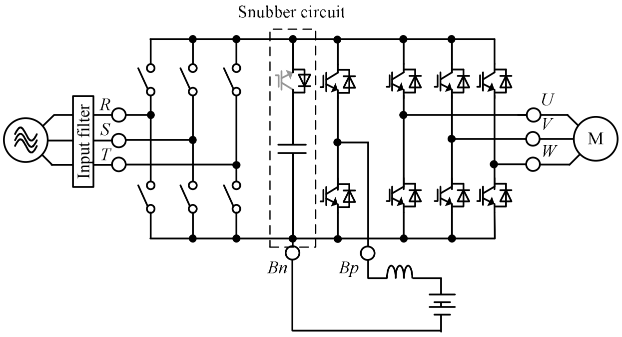
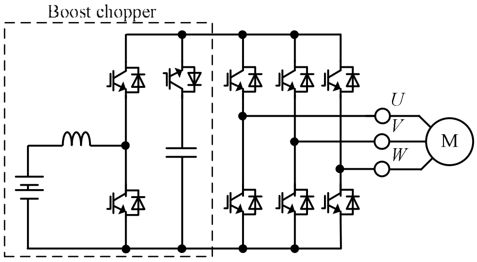


Fig. 6. Proposed circuit.



(a) S_c is turn off.



(b) S_c is turn on.

Fig. 7. Equivalent circuit of the proposed circuit.

DC/DC converter uses an ACR (Automated current regulator). 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 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}^*. 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_b, the output voltage is obtained by (2).

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

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 step-down type operation, λ_{bt} is the modulation index of the step-down type operation, E_c is the capacitor voltage of active snubber, E_{rec} is the output voltage of rectifier stage and the subscript '*' represents the command.

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

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

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

From Eq.(4), the operation time ratio of the active snubber circuit D_b can be determined by Eq.(4).

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

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 active snubber duty command D_b^* of the active snubber circuit is leaded by (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 inverter can be determined by Eq.(6) from Eq.(5).

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

In addition, 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 maximum voltage. Therefore, the power distribution ratio and the output voltage can control at same time. The relation between the output voltage and the active snubber duty ratio is shown in fig. 9.

4. Simulation and experimental results

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

Figure 10 shows the simulation results of the proposed control strategy. In the simulation, an ideal current source load and a main circuit are used to confirm the proposed strategy. At first, the proposed converter operates as the boost type AC/DC/AC direct converter. After 0.05msec, the proposed converter operate as the buck-boost type AC/DC/AC direct converter. Good sinusoidal waveforms are obtained for the input current and the output voltage. The total harmonic distortion

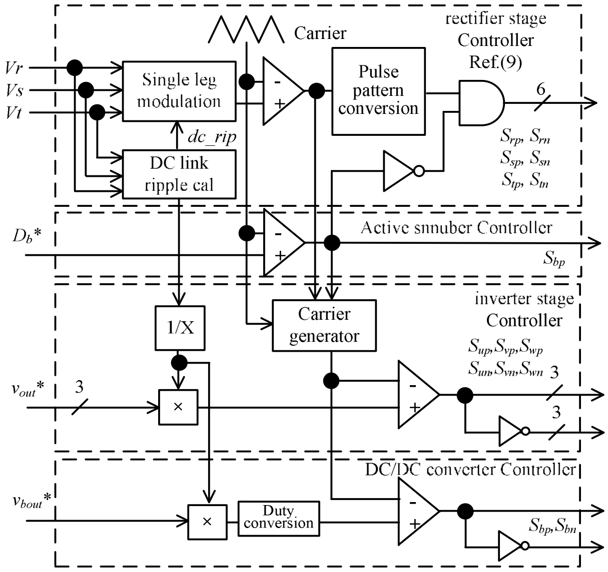


Fig. 8. Control block diagram of the buck-boost AC/DC/AC direct converter.

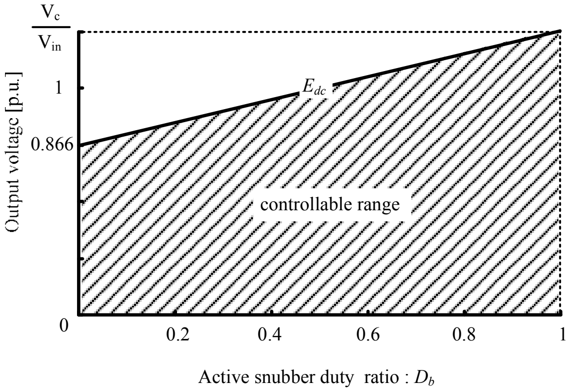


Fig. 9. Relation between output voltage and active snubber duty ratio.

(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.

Figure 12 shows the waveform of the basic operation for the proposed circuit. Figure 12(a) is obtained in the single operation of the boost type AC/DC/AC direct converter; fig. 12(b) is obtained in the single operation of the step-down type AC/DC/AC direct converter. Good sinusoidal waveforms and DC waveform are obtained for the input and output current of the both operation mode as shown in Fig. 11. As a results in fig. 11(a), it is confirmed that the input, output and dc output current T.H.D. are 2.4%, 1.9%, 1.9% respectively. The input power factor is 99% and efficiency is 96.3%. Moreover, the input, output and dc output current T.H.D. are 2.4%, 1.9%, 1.9%, the input power factor is 99% and efficiency is 95.2% as shown in fig. 11(b).

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

5. Loss comparison of hybrid system

This chapter shows a comparison between the converter loss of an IMC and a Buck to Buck converter (BTB) to confirm the validity of the proposed system for a HEV system. The converter loss of an IMC and a BTB system are calculated for 10-15 mode of the HEV. It is noted that battery power of the HEV system is not considered in this comparison. The converter loss is calculated by PSIM(*powersim Inc.*), as refer to [9].

Figure 12 shows the configuration for the loss calculation method. At first, power semiconductor characteristics for the switching loss and conduction loss are measured by a chopper test under the various current and voltage. Next, the instantaneous values of the current and the voltage at the switch timing are captured to the DLL (dynamic linked library) file. In the DLL file, the power semiconductor characteristics and a loss calculation program are described as below. The switching loss is estimated by referring to the values of the voltage and current, which are obtained by the chopper test results. The conduction loss is estimated by the V-I characteristics from the current value. This method can estimate the power semiconductor loss regardless of the circuit configuration.

Figure 13 shows the 10-15 mode cycle, which is one of the test driving patterns for the vehicle to measure fuel expenses[10]. The calculation parameters are refried by "Toyota Prius[11]" as shown in Table 2. The requirement motor power is calculated by the driving pattern and the weight of the vehicle. The assumed conditions of the fuel expenses calculation are as follows.

1) The generator voltage is converted in proportion to the buck e.m.f. of 150V when the vehicle speed is 70km/h.
2) The motor buck e.m.f. is supposed to 0.866 times of generator buck EMF.
3) For the DC link voltage of the BTB system, the generator buck e.m.f. is set to 1.5 times higher by the PWM rectifier.
4) The wind drags the rolling friction, and other resistances for the drive are neglected.
5) The converter loss consists of only switching loss and conduction loss.

Table1 Experimental parameter.

Input voltage	200[V]	LC filter	2 [mH]
Input frequency	50[Hz]		13.2 [μF]
Carrier frequency	7.5[kHz]	Cut-off frequency	1[kHz]
Output frequency	40[Hz]	load	R-L
DC power supply	350[V]	Commutation time	2.5 [μs]
Power ratio (AC:DC)		1:2	

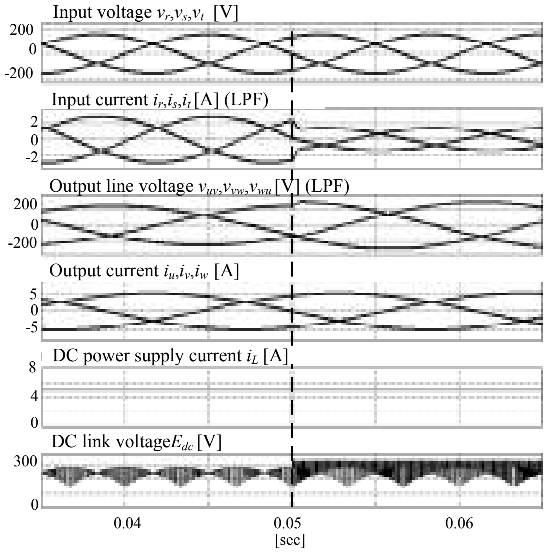
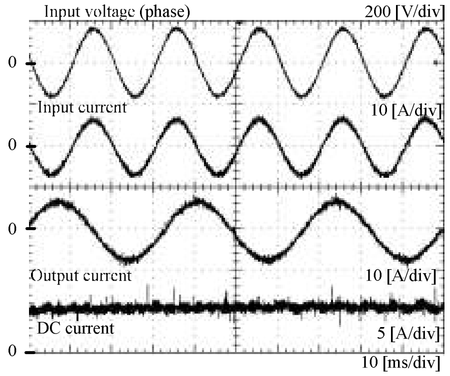
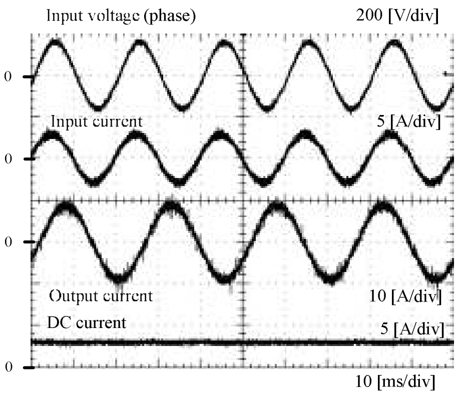


Fig. 10. Simuration waveform



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



(b) Step down type AC/DC/AC direct converter.
Fig. 11. Experimental waveform

Figure 14 shows the loss calculation results based on the 10-15 mode cycle. The power loss of the IMC is lower than the BTB system regardless the speed and torque. Table 3 indicates the total energy loss, the total efficiency and fuel expense of the proposed system in comparison to the BTB. The loss energy is improved by approximately 30% by applying the IMC. The energy conversion efficiency is improved by approximately 3%. These results confirm the validity of the IMC when the IMC applies HEV system. It should be noted that the performance of IMC is decreased when the battery power ratio is increasing.

6. Conclusion

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, the validity of the IMC applying in HEV system has confirmed. The basic operation of the proposed method has confirmed by simulation and experimental results.

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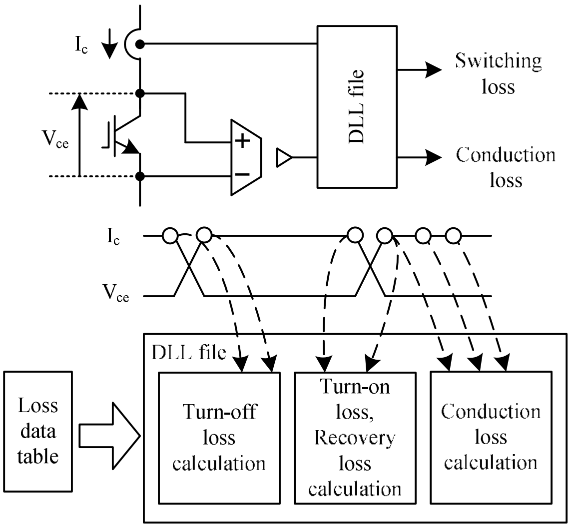

Fig. 12. Principle of loss calculation mehod.

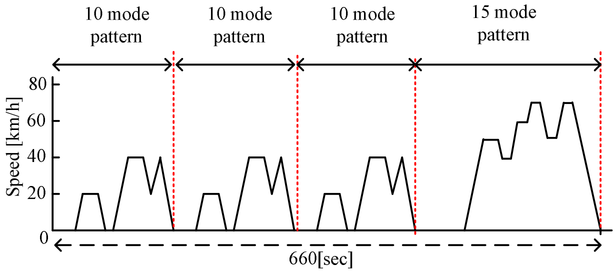

Fig.13. 10-15mode running pattern.

Table 2. Calculation parameter.

Car weight[11]	1280 kg	Car width[11]	1725 mm
Car heigh[11]	1490 mm	Fuel expenses[11]	35.5 km/L
Max motor output power [11]	50 kW	Coefficient of wind drag[11]	0.26
Coefficient of rolling friction		0.01	

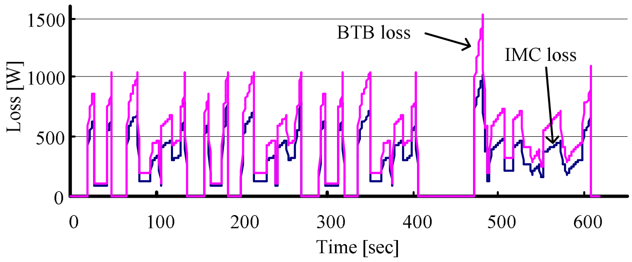

Fig.14. 10-15 mode loss calculation result.

Table 3. Calculation results*.

	IMC	BTB
Loss energy kJ	156.6	223.4
Energy conversion efficiency %	93.1	90.6
Fuel expenses km/L	36.6	35.5

* In these results, all motor energy is provided by a generator.