A New Approach for High Efficiency Buck-Boost DC/DC Converters Using Series Compensation

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Abstract - **This paper proposes a new buck-boost DC/DC converters, which is connected in series to the power supply. The proposed circuit provides only differential voltage between the input voltage and the output voltage command. The power rating of a conventional circuit is dominated by the input voltage or the output voltage. In contrast, the voltage rating of the proposed circuit requires only the differential voltage between the input and output voltage. In addition, the series converter generates a positive and negative voltage to realize boost mode and buck mode, respectively. As a result, the power rating of the DC/DC converter can be drastically reduced. A new approach for series compensation converters is introduced in order to realize high efficiency and a reduction of power rating. Two new buck-boost converters and their control methods are proposed based on a new concept in which the proposed circuits consist of an H-bridge circuit and a power assist circuit. The H-bridge circuit is used in order to determine the polarity of the differential voltage. The power assist circuit controls the DC voltage of the H-bridge circuit depending on the output voltage command. In the proposed circuit, a flyback converter and inverting chopper are used as the power assist circuit. Simulation and experimental results are shown in order to demonstrate the advantages of the proposed converters in comparison with a conventional buck-boost converter. A maximum efficiency of 98% was obtained with the proposed circuit. The proposed circuits can decrease losses by 2/3 in comparison with a conventional buck-boost converter. Therefore, the proposed converter can realize high efficiency and down-sizing in applications that require the output voltage to be closed to the input voltage.**

Index DC/DC converters, High efficiency, battery applications, flyback converter, inverting chopper

I. INTRODUCTION

Recently, most mobile equipments used battery as power source. The efficiency of DC/DC converters becomes an important issue, in order to maintain long working times for batteries in mobile devices such as mobile phones, laptop computers and so on.

A general conventional buck-boost DC/DC converter uses an inverting chopper or a combination chopper, which consists of a buck copper and a boost chopper. The inverting chopper stores output energy in storage device, such as reactor or capacitors. Therefore, the converter efficiency is decreased since the power loss occurs in the storage devices. On the other hands, because the combination chopper has two stages for conversion process, the converter efficiency decreases. Many circuit topologies of DC/DC converters have been studied in order to obtain high efficiency [1-3]. Resonant type converters, which use zero current switching or zero voltage switching, are a good solution to obtain high efficiency [5-6]. Especially, the resonant converter is suitable for the DCDC converter because the DC/DC converter requires high switching frequency in order to realize downsizing and high speed output voltage response. However, the number of parts in the circuit increases, because resonant converters require an additional inductor or capacitor. Moreover, the voltage and current rating of the DC/DC converter are dominated by the output voltage rating and the output current rating in conventional DC/DC converters.

From the viewpoint of the battery application, the input voltage i.e. battery voltage, is almost constants under normal operation. The battery voltage becomes markedly higher than normal voltage in the initial condition or overcharge operation, and lower than the nominal voltage in the overdischarge. Therefore the efficiency for voltage at normal condition is very important.

In some battery applications, the output voltage is regulated by the DC/DC converter as the output voltage is close to the input voltage. In this case, the conventional DC/DC converter has to convert all power regardless of the output voltage because the conventional converter is connected in parallel to a power supply and a load.

In contrast, there have been some types of series converters that have been proposed for boost up converters [7]. The output voltage of a series converter is obtained by adding the converter voltage to the input voltage. Therefore, the converter power rating can be suppressed because the converter voltage becomes low. However, proposed types of converters can not work for step-down operation. Many battery applications require buck-boost operation of the power converter.

This paper proposes a new buck-boost converter that is connected in series to the power supply. The proposed circuit provides only differential voltage between the input voltage and the output voltage command. As a result, the power rating of the DC/DC converter is reduced drastically. Firstly, this paper introduces an approach that uses series compensation converters to obtain high efficiency and a reduction of power rating. Two new types of buck-boost converters and their control methods are proposed based on this new concept. Finally, simulation and experimental results are shown in order to demonstrate the advantages of the proposed converters in comparison with a conventional buck-boost converter.

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II. PROPOSED BUCK BOOST CONVERTERS

A. *Series Compensation Concept*

Fig. 1 shows power flow diagram of the conventional DC/DC converter and proposed series compensation DC/DC converter. Fig. 2 shows the configuration of a conventional one and the proposed one. The power rating of the conventional circuit is dominated by the input voltage or the output voltage. In contrast, the voltage rating of the proposed circuit only requires the differential voltage between the input and output voltage. In addition, the series converter generates a positive and negative voltage to realize boost mode and buck mode, respectively. The output voltage V_{out} is obtained by (1), using series converter output voltage V_{conv} and input voltage V_{in}.

$$V_{out} = V_{in} \pm V_{conv} \tag{1}$$

For example, if the input voltage variation is 2.6 V to 4.0 V and the output rating is 3.3 V, 1 A, then the power rating of the conventional converter is 3.3 W. In contrast, for the proposed converter, it requires only 0.7 W.

The series compensation method can obtain high efficiency. All output power is supplied through the converter in a conventional configuration, as shown by the power flow of the conventional converter given in Fig. 1. The output power Pout is then obtained by (2), using the efficiency η_c, and the input power P_{in}.

$$P_{out} = P_{in} \cdot \eta_c \tag{2}$$

However, not all the output power is directly supplied in the proposed converter, because the converter can adjust the small differential voltage. As a result, the total efficiency of the proposed converter is obtained by (3) if the loss of the direct mode power P_1 can be neglected.

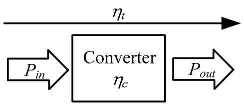
Therefore, the total efficiency obtained by using the proposed concept is improved, as shown by (4). It should be noted that the proposed method is so effective that the differential voltage is small.

$$\eta_t = \frac{P_1 + P_2 \cdot \eta_c}{P_1 + P_2} \tag{3}$$

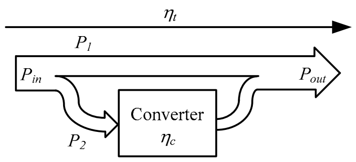
$$\eta_c > \frac{P_1 + P_2}{P_2}\eta - \frac{P_1}{P_2} \tag{4}$$

Fig. 3 shows the theoretical total efficiency of the proposed buck boost converter. The efficiency is calculated based on (3) for each series converter efficiency. Even though the series converter efficiency is no so high, high total efficiency is obtained at the low output power ratio to series converter power in the output power. As the output power ratio increase, the total efficiency is decreasing because the converter loss increases.

The point subjects to increasing the efficiency are the switching loss and choice of the power device. The conduction loss is dominated by the current. The loss is not reducing even though the power rating of converter becomes small. However, the voltage rating of the power device in the series converter is only differential voltage, therefore the switching loss is smaller than the conventional circuit. Moreover, the series converter is applied the low conduction loss switching devices since the voltage rating of the power devices is lower than the conventional one. As a result, the loss of the series converter become small then, the total efficiency of the system is improved.

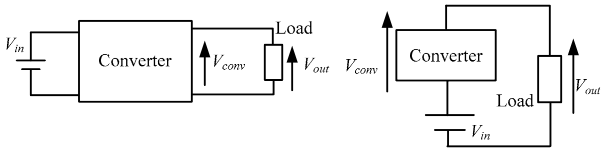


(a) Conventional concept.



(b) Proposed concept.

Fig. 1. power flow diagrams.



(a) Conventional topology. (b) Proposed topology.

Fig. 2. Construction of conventional and proposed circuit.

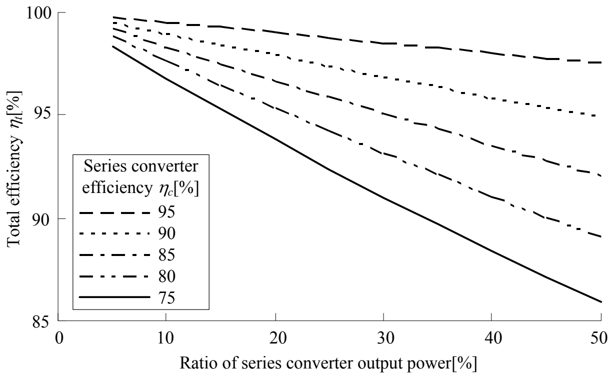


Fig. 3. Relation between output voltage and efficiency of the proposed series converter.

B. *Circuit Configurations Based on the Proposed Concept*

Fig. 4 and Fig. 6 show two types of proposed circuit using the proposed concept. The series converter needs a power assist circuit in order to charge or discharge the voltage of the capacitor C_{C2}. A flyback converter and inverting converter are used as the power assist circuit, as shown in Fig. 4 and Fig. 6, respectively. The proposed circuits have to isolate the series voltage to the input voltage in order to avoid a short circuit between the input voltage and series voltage. The flyback transformer is used for the isolation in the proposed circuit I. On the other hands, the short circuit is avoided by the switches S_{C2} and S_{C4} in the proposed circuit II.

The H-bridge circuit is used to determine the polarity of the differential voltage. Thus, the H-bridge circuit selects only the boost mode at positive differential voltage or buck mode at negative differential voltage. The power assist circuit control V_{CC2} depends on the output voltage command. Therefore, low conduction loss and low voltage rating switching devices can be used in the H-bridge circuit. Also, a switching device with low current rating and low switching loss characteristics can be selected for the power assist circuit.

Fig. 5 and Fig. 7 are shown the simulation results for the proposed circuits. Since the proposed circuits operate as the buck-boost converter, the reactor current i_{Lc} in the proposed circuit II is similar to the flyback transformer current in the proposed circuit I. In addition, the output voltage is controlled to reference voltage 12V by power assist circuit. Therefore, the inverting chopper using the switch S_{c2} and S_{c4} can be used as the series converter.

These simulation results can confirm that the proposed series compensation method has validity.

C. Control Method for the Proposed Circuits

Fig. 8 shows control block diagrams for the proposed circuit II, the inverting chopper type. Basically, the output voltage is adjusted by the DC capacitor voltage V_{CC2} in Fig. 4 and 5. However, it is difficult to control the output voltage when the differential voltage is close to zero, because non linear components, such as the effects of dead time period and device characteristics disturb the output voltage control. Therefore, when the input voltage is near to the output voltage, the output voltage will be controlled by PWM using the H-bridge circuit. In the small differential voltage region, the DC capacitor voltage V_{CC2} is controlled to a constant value and H-bridge is controlled as a quadrant chopper, which can generate and regenerate the power. The threshold voltage V_{cng} means the voltage starting switching operation in H-bridge part. When the differential voltage is less than V_{cng}, V_{CC2} is held to V_{cng}, and the series converter output voltage V_{conv} is controlled by PWM modulation of H-bridge part. The threshold voltage V_{cng} has to be set larger than non-linear error voltage in the series converters. The switching loss of the H-bridge circuit will be small, because the DC voltage V_{CC2} of the H-bridge circuit is low.

Fig. 9 and Fig. 10 show the comparison of the output voltage waveform with and without PWM modulation at low differential voltage respectively. The output voltage is kept at a constant voltage of 12 V, although the input voltage increased from 10 V to 14 V and decreases from 14 V to 10 V. In particular, when the input voltage is closed to 12 V, an output voltage oscillation occurs when PWM is not used, as shown in Fig. 9. The maximum error of the output voltage is 1.2 V. However, the oscillation can be suppressed to less than 0.1 V by the proposed PWM control, using an H-bridge circuit as shown in Fig. 10. It should be noted that the control of the proposed circuit I could apply the same strategy as shown in Fig. 8.

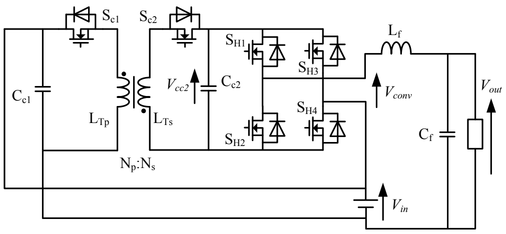


Fig. 4. Proposed circuit I (Flyback converter).

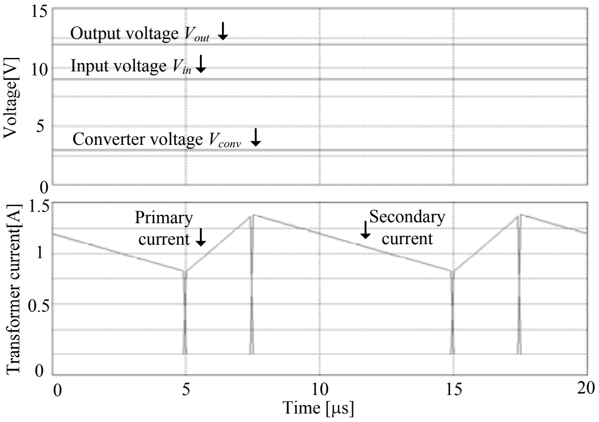


Fig. 5. Simulation results of the proposed circuit I.

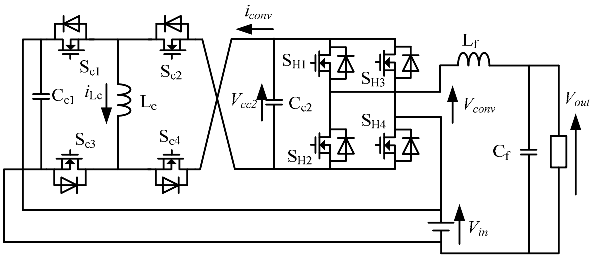


Fig. 6. Proposed circuit II(Inverting converter).

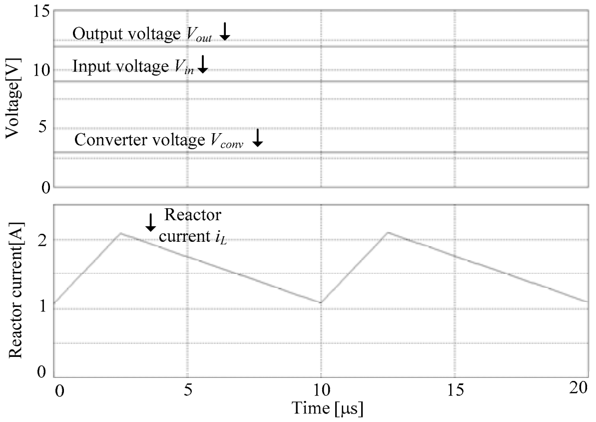


Fig. 7. Simulation results of the proposed circuit II.

D. Design of the Proposed Circuit.

There are two operation modes in series converter, the boost mode and the buck mode. The proposed circuit is designed individually for boost mode and buck mode. Then, dominant parameter values are adopted. It is noted that the design of the proposed circuit II is only explained in this paper because the design of two proposed circuits is almost same. Table 2 shows the specifications of the experimental circuit.

1) Boost mode

To improve efficiency, the reactor current is needed to keep continuous. Therefore, the largest calculated inductance under the conditions is adopted. The inductance becomes maximum value when the storage energy is at maximum. In boost mode, the reactor storage energy becomes maximum value when the input voltage is minimum value. In case of Table 2, the minimum input voltage is 6V, and the output voltage is constant 12V, then, the series converter output voltage is differential voltage 6V. Therefore, the series converter input and output voltage is 6V. The duty ratio D is obtained by (5), using switch on time ton, and off time t_{off}.

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{\left(V_{in} - V_{conv}\right)}{V_{in} + \left(V_{in} - V_{conv}\right)} = 0.5 \tag{5}$$

In this condition, the reactor storage power is obtained by (6), using the reactor current peak value i_{1P}, and switching frequency f_{sw}.

$$P_L = \frac{1}{2} L_c i_{1P}{}^2 f_{sw} = \frac{V_{in}^2 t_{on}^2 f_{sw}}{2L_c} \tag{6}$$

Next, the series converter output voltage is obtained by (7), using maximum output current I_{out}. Then the series converter output power is controlled by storage energy of reactor.

$$P_{conv} = V_{conv} I_{out} = \frac{V_{in}^2 t_{on}^2 f_{sw}}{2L_c} \tag{7}$$

From (6) and (7), the inductance of the series converter reactor is obtained by (8).

$$L_c = \frac{V_{in}^2 t_{on}^2 f_{sw}}{2 V_{conv} I_{out}} = 9[\mu H] \tag{8}$$

2) Buck mode

The reactor storage energy becomes the maximum values when the input voltage is at maximum value. In condition of Table 2, the maximum input voltage is 18V, the series converter output voltage is 6V. Similarly to boost mode, the inductance of the buck mode is calculated as 40μH by (8). The buck mode inductance is larger than the boost mode one. Therefore the buck mode value is adopted.

III. EXPERIMENTAL RESULTS

To confirm the validity of the proposed converter concept, the proposed converter was tested under the experimental conditions shown in Table 2. It should be noted that the circuit parameters chosen is to confirm basic operation, and optimization was not considered. In addition, the conventional combination buck boost converter, which uses a step-down converter and a boost-up converter, as shown in Fig. 11 is tested in order to compare the efficiency. It is noted that the reactor in the conventional circuit is designed as follows.

In conventional combination chopper, the reactor has the functions of smoothing the output current and energy storage. The inductance value is designed in allowance. The rector current becomes discontinuous in light load region. The

Table 1. Condition of simulation.

Input voltage V_{in}[V]	10 to 14	On resistance of FET [mΩ]	12
Output voltage V_{out}[V]	12	Forward Voltage drop of diode[V]	0.5
Output power P_{out}[W]	14	L_f[μH]	22
Switching frequency f_{sw}[kHz]	100	C_f[μF]	2200
Control changeover voltage V_{cng}[V]	1	L_c[μH]	22
ACR integration time[ms]	0.375	C_{c1}, C_{c2}[μF]	2200
AVR integration time[ms]	3.75	H-bridge propotional gain[pu]	2.0
ACR proportional gain[pu]	0.22	H-bridge integration time[ms]	0.72
AVR proportional gain[pu]	4.03		

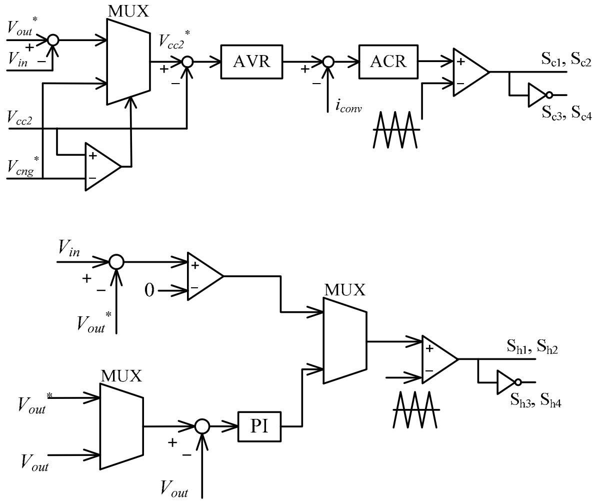
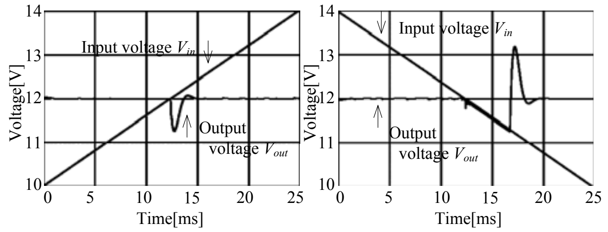
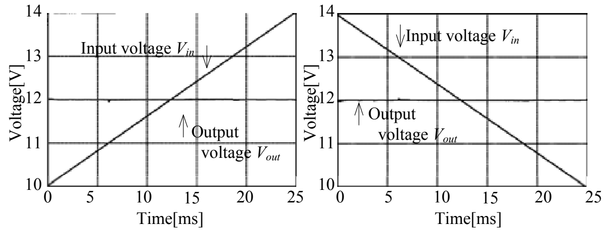


Fig.8. Proposed control diagram.



(a) Boost to step down. (b) Step down to boost.

Fig. 9. Voltage waveforms with PI control only



(a) Boost to step down. (b) Step down to boost.

Fig. 10. Voltage waveforms
with PI control and proposed method.

discontinuous current causes increasing loss and unstable output voltage due to nonlinear control.

The ripple current is needed at minimum value when the output current is minimum at output power 5W, output current 417mA.The peak to peak value of the ripple current of a reactor is limited to 40% of output current, then the ripple current is 166mA because the output current is 417mA at output power 5W. In addition, the reactor voltage becomes maximum value when the input voltage is at maximum value of 18V. In this condition, the inductance of the reactor is calculated by (9).

$$L = \frac{(V_{in} - V_{out})t_{on}}{\Delta I_{out(P-P)}} = \frac{(18-12)\cdot(0.667\times 10\times 10^{-6})}{0.166} = 240[\mu H] \tag{9}$$

A. Experimental Results

Figures 12 and 13 show the current waveforms of proposed cir Fig. 12 and 13 show the current waveforms of proposed circuits I and II, respectively. The current polarity depends on the operation mode; buck or boost. The transformer and reactor were designed so that the power assist circuit operates in current continuous mode. These results confirmed that the proposed assist circuit accepts bidirectional power flow, without unnecessary surges or oscillations in the reactor or transformer current. In addition, the short current of the power supply does not appear in the waveforms. Therefore, the flyback converter and the inverting chopper with the isolation switch can be used in a series converter.

Fig. 14 presents a comparison between the efficiency of a conventional buck boost converter and the proposed converters at constant load. A maximum efficiency of approximately 98% was obtained for both of the proposed circuits. For the conventional converter is approximately 94%. In other words, the converter loss decrease from 6% to 2 %, the proposed circuit can improve the converter loss to 1/3. The input voltage is so close to the output voltage, so that converter efficiency is even more improved, as shown in Fig. 14.

Fig. 15 shows the efficiency with load variation for the conventional converter and the proposed converters. In both boost mode and buck mode, efficiency improvement is possible. In Fig. 15, the efficiency of the buck mode is higher than the boost mode one because the input power in the boost mode is larger than the buck mode. The power loss in the series converter is provided from power source in the boost mode. In contrast, the regeneration power in the buck mode is disappeared by the circuit power loss. Therefore, the current flowing to the series converter in the boost mode is decreased to buck mode one.

Fig. 16 shows the voltage waveform of V_{out} for load step response. The load is changed from 5W to 14W. When the load condition is rapidly changed, the output voltage oscillation can be suppressed to less than 0.2 V. The output voltage oscillation can be improved by refinement of the control strategy of the series converter.

Table 2. Specifications of experimental circuit.

Input voltage V_{in}[V]	6～18
Output voltage V_{out}[V]	12
Output power P_{out}[W]	5～30
Switching frequency f_{sw}[kHz]	100

Table 3. Circuit parameter.

Proposed circuit I	L_{T1}	40μH
	L_{T2}	40μH
	Np	5
	Ns	5
	C_{c1}	2200μF
	C_{c2}	220μF
	L_f	2μH
	C_f	470μF

Proposed circuit II	L_c	22μH
	C_{c1}	470μF
	C_{c2}	2200μF
	L_f	22μH
	C_f	1000μF
Conventional circuit	L	220μH
	C	2200μF

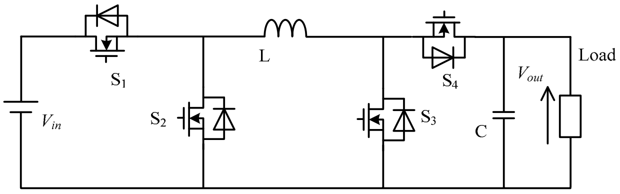
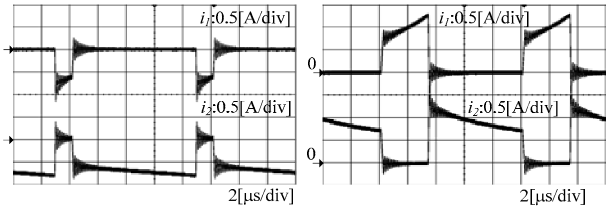
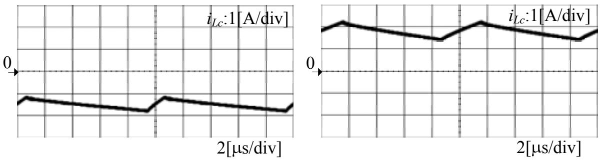


Fig. 11. Configuration of a conventional combination chopper.



(a)Step down mode. (b)Boost mode.

Fig. 12. Current waveforms of the flyback transformer in the proposed circuit 1.



(a)Step down mode. (b)Boost mode.

Fig. 13. Current waveforms of the reactor in the proposed circuit II

Fig. 17 shows the output voltage waveform at low differential voltage in PWM control region of the H bridge part. The output voltage is kept at 12 V of a constant voltage, although the input voltage increases from 10 V to 14 V or decreases from 14 V to 10 V. In particular, when the input voltage is close to 12 V, the control output voltage is disturbed by the non linear components, such as dead-time and power device characteristics. However, the oscillation can be suppressed to less than 0.2 V by proposed PWM control of H-bridge as shown in Fig. 17.

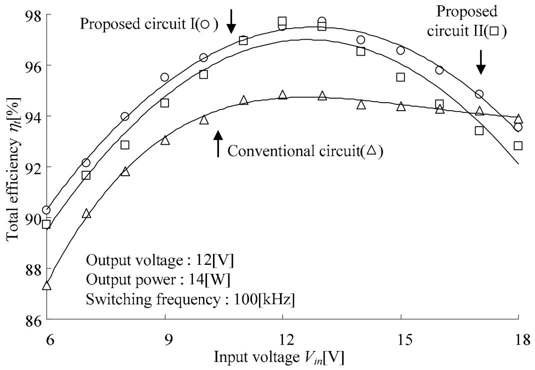
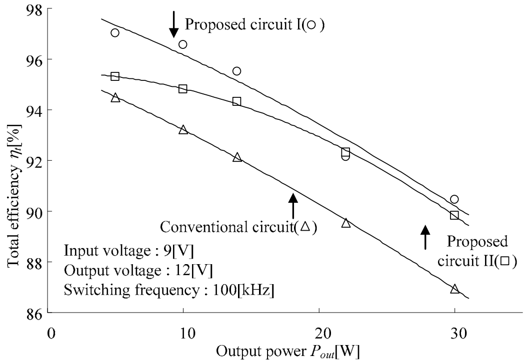
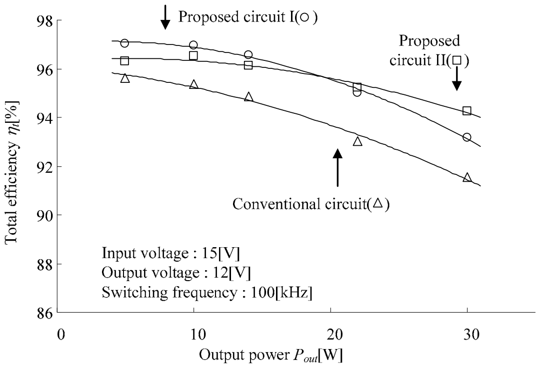


Fig. 14. Input voltage characteristics of efficiency η_t.



(a) V_{in}=9V



(b) V_{in}=15V

Fig. 15. Load characteristics of total efficiency η_t.

IV. CONCLUSION

In this paper, a series type buck-boost converter is proposed that uses an H-bridge circuit and a power assist circuit with small power rating. A flyback converter and an inverting converter were used as power assist circuits. The experimental results confirmed that the proposed circuits could decrease losses by 2/3 at the maximum efficiency point. Therefore, the proposed converter can realize high efficiency and downsizing for use in applications that require the output voltage to be close to the input voltage.

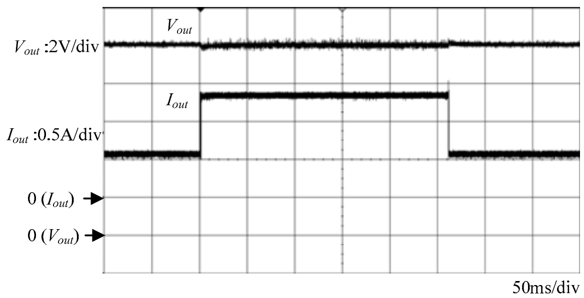
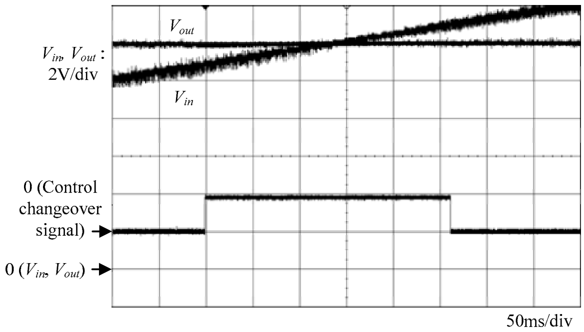
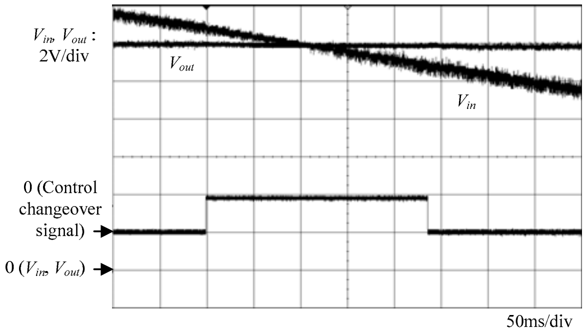


Fig. 16 . Output voltage waveform for step load response.



(a) Boost to step down.



(b) Step down to boost.

Fig. 17. Output voltage waveform at low differential voltage.

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