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High Efficiency Buck-Boost Converters Using Series Compensation

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ABSTRACT-This paper proposesa new buck-boost DC/DCconverters,whichisconnectedinseriestothepowersupply.Theproposed circuit provides only differential voltage between theinputvoltageandtheoutputvoltagecommand.Thepowerratingofaconventionalcircuitisdominatedbytheinputvoltageortheoutput voltage. In contrast, the voltage rating of the proposedcircuit requires only the differential voltage between the inputand output voltage. In addition, the series converter generates apositive and negative voltage to realize boost mode and buckmode, respectively. As a result, the power rating of the DC/DCconverter can be drastically reduced. A new approach for seriescompensation converters is introduced in order to realize highefficiency and a reduction of power rating. Two new buck-boostconverters and their control methods are proposed based on anew concept in which the proposed circuits consist of an H-bridge circuit and a power assist circuit. The H-bridge circuit isusedinordertodeterminethepolarityofthedifferentialvoltage.The power assist circuit controls the DC voltage of the H-bridgecircuitdependingontheoutputvoltagecommand.Intheproposed circuit, a flyback converter and inverting chopper areused as the power assist circuit. Simulation and experimentalresults are shown in order to demonstrate the advantages of theproposed converters in comparison with a conventional buck-boost converter. A maximum efficiency of 98% was obtainedwith the proposed circuit. The proposed circuits can decreaselossesby2/3incomparisonwithaconventionalbuck-boostconverter. Therefore, the proposed converter can realize highefficiencyanddown-sizinginapplicationsthatrequiretheoutputvoltagetobeclosedtotheinputvoltage.
IndexDC/DCconverters,Highefficiency,batteryapplications,flybackconverter,invertingchopper

I. INTRODUCTION

Recently, most mobile equipments used battery as powersource.TheefficiencyofDC/DCconvertersbecomesanimportant issue, in order to maintain long working times forbatteries in mobile devices such as mobile phones, laptopcomputersandsoon.

A general conventional buck-boost DC/DC converter usesan inverting chopper or a combination chopper, which consistsof a buck copper and a boost chopper. The inverting chopperstores output energy in storage device, such as reactor orcapacitors. Therefore, the converter efficiency is decreasedsince the power loss occurs in the storage devices. On theother hands, because the combination chopper has two stagesfor conversion process, the converter efficiency decreases.ManycircuittopologiesofDC/DCconvertershavebeenstudiedinordertoobtainhighefficiency[1-3].Resonanttypeconverters,whichusezerocurrentswitchingorzerovoltageswitching, are a good solution to obtain high efficiency [5-6].Especially, the resonant converter is suitable for the DCDCconverterbecausetheDC/DCconverterrequireshighswitching frequency in order to realize downsizing and highspeed output voltage response. However, the number of partsinthecircuitincreases,becauseresonantconvertersrequireanadditional inductor or capacitor. Moreover, the voltage andcurrent rating of the DC/DC converter are dominated by theoutputvoltageratingandtheoutputcurrentratinginconventionalDC/DCconverters.

From the viewpoint of the battery application, the inputvoltage i.e. battery voltage, is almost constants under normaloperation. The battery voltage becomes markedly higher thannormalvoltageintheinitialconditionorovercha rgeoperation,and lower than the nominal voltage in the overdischarge.Therefore the efficiency for voltage at normal condition isveryimportant.

Insomebatteryapplications,theoutputvoltageisregulatedby the DC/DC converter as the output voltage is close to theinputvoltage.Inthiscase,theconventionalDC/DCconverterhas to convert all power regardless of

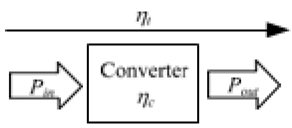
the output voltagebecausetheconventionalconverterisconnectedinparalleltoapowersupplyandaload.
Incontrast,therehavebeensometypesofseriesconvertersthat have been proposed for boost up converters [7]. Theoutput voltage of a series converter is obtained by adding theconverter voltage to the input voltage. Therefore, the converterpowerratingcanbesuppressedbecausethe convertervoltagebecomeslow.However,proposed typesofconverterscannotworkforstep-downoperation.Manybatteryapplicationsrequirebuck-boostoperationofthepowerconverter.
This paper proposes a new buck-boost converter that isconnected in series to the power supply. The proposed circuitprovides only differential voltage between the input voltageandtheoutputvoltagecommand.Asaresult,thepowerratingof the DC/DC converter is reduced drastically. Firstly, thispaper introduces an approach that uses series compensationconverters to obtain high efficiency and a reduction of powerrating. Two new types of buck-boost converters and theircontrol methods are proposed based on this new concept.Finally, simulation and experimental results are shown inordertodemonstratetheadvantagesoftheproposedconvertersincomparisonwithaconventionalbuck-boostconverter.

II. PROPOSEDBUCKBOOSTCONVERTERS

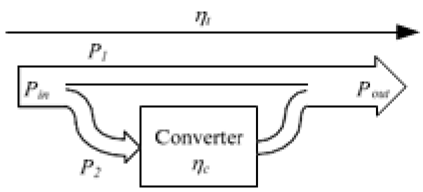
A. Seriescompensationconcept
Fig.1showspowerflowdiagramoftheconventional DC/DC converter and proposed series compensation DC/DCconverter. Fig. 2 shows the configuration of a conventionaloneandtheproposedone.Thepowerratingoftheconventional circuit is dominated by the input voltage or theoutput voltage. In contrast, the voltage rating of the proposedcircuitonlyrequiresthedifferentialvoltagebetweentheinputandoutputvoltage.Inaddition,theseriesconvertergeneratesapositiveandnegativevoltagetorealizeboostmodeandbuckmode,respectively.TheoutputvoltageV$_{out}$isobtainedby(1),using series converter output voltage $V_{conv}$and input voltageV_{in}.

$V_{out} \square V_{in} \square V_{conv}$ 1)

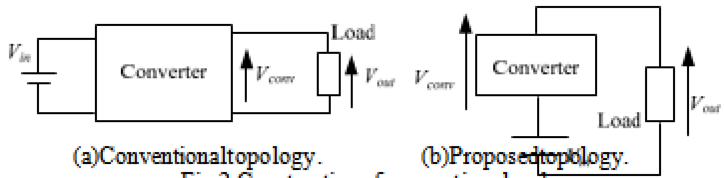
Forexample,iftheinputvoltagevariationis2.6Vto4.0Vand the output rating is 3.3 V, 1 A, then the power rating oftheconventionalconverteris3.3W.Incontrast,for theproposedconverter,itrequiresonly0.7W.
Theseriescompensationmethodcanobtainhighefficiency.Alloutputpowerissuppliedthroughtheconverterinaconventionalconfiguration,asshownbythepowerflowoftheconventionalconvertergiveninFig. 1.TheoutputpowerPoutisthenobtainedby(2),using theefficiency$\square_c$,andtheinput



(a)Conventionalconcept.



(b) Proposed concept.Fig.1.powerflowdia



(a)Conventionaltopology. (b)Proposedtopology.
Fig.2.Constructionofconventionalandproposedcircuit.

powerP_{in}.

P_{out} □ P_{in} □ □c

(2)

However,notalltheoutputpowerisdirectlysupplied inthe 90
proposedconverter,becausetheconvertercanadjustthesmalldifferentialvoltage.Asaresult,thetotalefficiencyofthe proposedconverterisobtainedby(3)ifthelossofthedirect 85
modepowerP_1canbeneglected.
0 10 20 30 40 50
Ratioofseriesconverteroutputpower[%]

Therefore,thetotalefficiencyobtainedbyusingtheproposed concept is improved, as shown by (4). It should benotedthattheproposedmethodissoeffectivethatthedifferentialvoltageissmall.

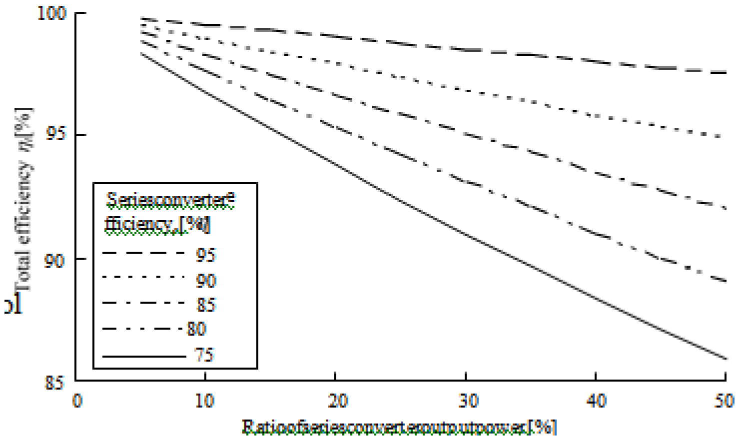


Fig.3.Relationbetweenoutputvoltageandefficiencyoftheproposedseriesconverter.

Fig.3.Relationbetweenoutputvoltageandefficiencyoftheproposedseriesconverter.

converterisappliedthelowconductionlossswitchingdevicessincethevoltageratingofthepowerdevices islowerthanthe

□□P_1□P_2□□c^t P□ P
P□ P P
(3)

conventional one.Asaresult,thelossof theseriesconverter becomesmallthen,thetotalefficiencyofthesystemis improved.

□ □1 2□ □1
(4)
P_2 P_2

Fig.3showsthetheoreticaltotalefficiencyoftheproposedbuckboostconverter.Theefficiencyiscalculatedbasedon(3)for each series converter efficiency. Even though the seriesconverter efficiency is no so high, high total efficiency isobtained at the low output power ratio to series converterpowerintheoutputpower.Astheoutputpowerratioincrease,the total efficiency is decreasing because the converter lossincreases. Thepointsubjectstoincreasingtheefficiencyarethesswitchinglossandchoiceofthepowerdevice.Theconduction lossisdominatedbythecurrent.Thelossisnotreducingeventhoughthepowerratingofconverterbecomessmall.However,thevoltageratingofthepowerdeviceintheseriesconverterisonlydifferentialvoltage,thereforetheswitchinglossissmallerthantheconventionalcircuit.Moreover,theseries

B. Circuitconfigurationsbasedontheproposedconcept

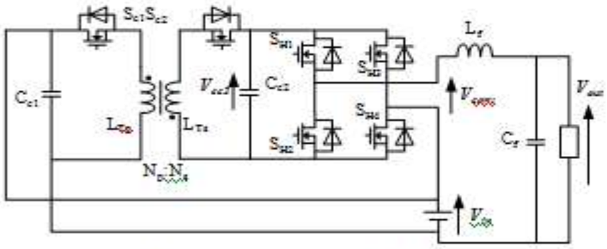


Fig.4.ProposedcircuitI(Flybackconverter).

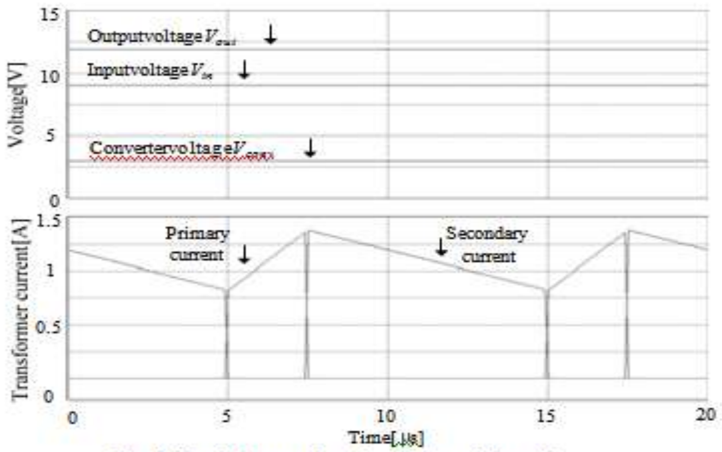


Fig.5.Simulationresultsoftheproposedcircuit I.

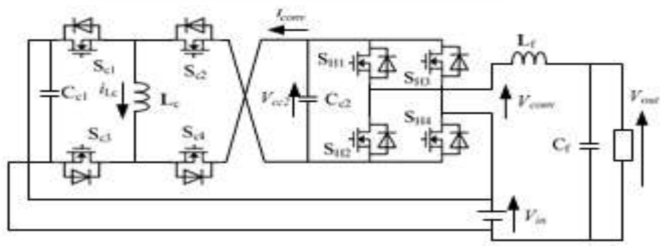


Fig.6.ProposedcircuitII(Invertingconverter).

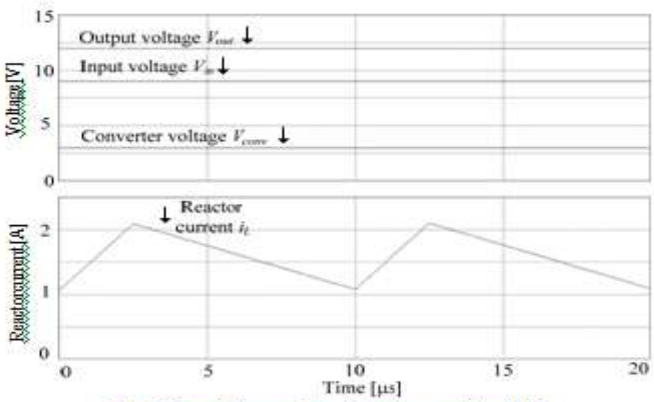


Fig.7.SimulationresultsoftheproposedcircuitII.

Fig. 4 and Fig. 6 show two types of proposed circuit usingthe proposed concept. The series converter needs a powerassistcircuitinordertochargeordischargethe voltageofthecapacitorC_{C2}.Aflybackconverterandi nvertingconverterareusedasthepowerassistcircuit, asshowninFig.4andFig.6,respectively. The proposed circuits have to isolate the seriesvoltage to the input voltage in order to avoid a short circuitbetween the input voltage and series voltage. The flybacktransformer is used for the isolation in the proposed circuit I.Ontheotherhands,theshortcircuitisavoidedbythe switchesS_{C2}andS_{C4}intheproposedcircuitII.

TheH-bridgecircuitisusedtodeterminethepolarityofthedifferentialvoltage.Thus,theH-bridgecircuitselectsonlytheboostmodeatpositivedifferentialvoltageorbuckmodeat

negativedifferentialvoltage.Thepowerassistcircuitcontrol

V_{CC2} dependsontheoutputvoltagecommand.Therefore,low

conduction loss and low voltage rating switching devices canbe used in the H-bridge circuit. Also, a switching device withlow current rating and low switching loss characteristics canbeselectedforthepowerassistcircuit.

Fig. 5 and Fig. 7 are shown the simulation results for theproposed circuits. Since the proposed circuits operate as thebuck-boost converter, the reactor current i_{Lc}in the proposedcircuit II is similar to the flyback transformer current in theproposedcircuitI.Inaddition,theoutputvoltageis controlledto reference voltage 12V by power assist circuit. Therefore,theinvertingchopperusingtheswitchS_{c2} andS_{c4}canbeusedastheseriesconverter.

These simulation resultscan confirm that theproposedseriescompensationmethodhasvalidity.

C. Controlmethodfortheproposedcircuits

Fig.8showscontrolblockdiagramsfortheproposedcircuitII, the inverting chopper type. Basically, the output voltage isadjusted by the DC capacitor voltage V_{CC2}in Fig. 4 and 5.However, it is difficult to control the output voltage when thedifferentialvoltageisclosetozero,becausenonlinearcomponents, such as the effects of dead time periodanddevicecharacteristicsdisturbtheoutputvoltagecontrol.Therefore,whentheinputvoltageisneartotheoutputvoltage,the output voltage will be controlled by PWM using the H-bridge circuit. In the small differential voltage region, the DCcapacitorvoltageV_{CC2}iscontrolledtoaconstantvalueandH-bridgeiscontrolledasaquadrantchopper,whichcangenerateand regenerate the power. The threshold voltage V_{cng}meansthevoltagestartingswitchingoperationinH-bridgepart.When the differential voltage is less than V_{cng}, $V_{CC2}$is held toV_{cng}, and the series converter output voltage $V_{conv}$is controlledby PWM modulation of H-bridge part. The threshold voltageV_{cng}has to be set larger than non-linear error voltage in theseries converters. The switching loss of the H-bridge circuitwill be small, because the DC voltage $V_{CC2}$of the H-bridgecircuitislow.

Fig. 9 and Fig. 10 show the comparison of theoutputvoltage waveform with and without PWM modulation at lowdifferentialvoltagerespectively.Theoutputvoltageiskeptataconstantvoltageof12V,althoughtheinputvoltageincreasedfrom10Vto14Vanddecreasesfrom14Vto10V.In particular, when the input voltage is closed to 12 V, anoutput voltage oscillation occurs when PWM is not used, asshowninFig.9.Themaximumerroroftheoutputvoltageis 1.2V.However,theoscillationcanbesuppressedtolessthan 0.1VbytheproposedPWMcontrol,usinganH-bridgecircuitas shown in Fig. 10. It should be noted that the control of theproposed circuit I could apply the same strategy as shown inFig.8.

D. Designoftheproposedcircuit.

Therearetwooperationmodesinseriesconverter,theboostmodeandthebuckmode.Theproposedcircuitisdesigned

individually for boost mode and buck mode. Then, dominantparametervaluesareadopted.Itisnotedthatthedesignoftheproposed circuit II is only explained in this paper because thedesignoftwoproposedcircuitsisalmostsame.Table2showsthespecificationsoftheexperimentalcircuit.

1) Boostmode

Toimproveefficiency,thereactorcurrentisneededtokeepcontinuous.Therefore,thelargestcalculatedinductanceundertheconditionsisadopted.Theinductancebecomesmaximumvaluewhenthestorageenergyisatmaximum.Inboostmode,thereactorstorageenergybecomesmaximumvaluewhentheinput voltage isminimum value.In case of Table 2, theminimuminputvoltageis6V,andtheoutputvoltageisconstant 12V, then, the series converter output voltage isdifferential voltage 6V. Therefore, the series converter inputandoutputvoltageis6V.ThedutyratioDisobtainedby(5), usingswitchontimeton,andofftimet$_{off}$.

InputvoltageVin[V]	10to 14
Outputvoltage V_{out}[V]	12

OutputpowerP_{out}[W]	14
Switchingfrequency f_{sw}[kHz]	100
Controlchangeovervoltage V_{cng}[V]	1
ACRintegrationtime [ms]	0.375
AVRintegrationtime [ms]	3.75
ACRproportionalgain[pu]	0.22
AVRproportionalgain[pu]	4.03

OnresistanceofFET [mΩ]	12
ForwardVoltagedropofdiode[V]	0.5
L_f[μH]	22
C_f[μF]	2200
L_c[μH]	22
C_{c1},C_{c2}[μF]	2200
H-bridgepropotional gain[pu]	2.0
H-bridge integrationtime[ms]	0.72

Table1.Conditionofsimulation.

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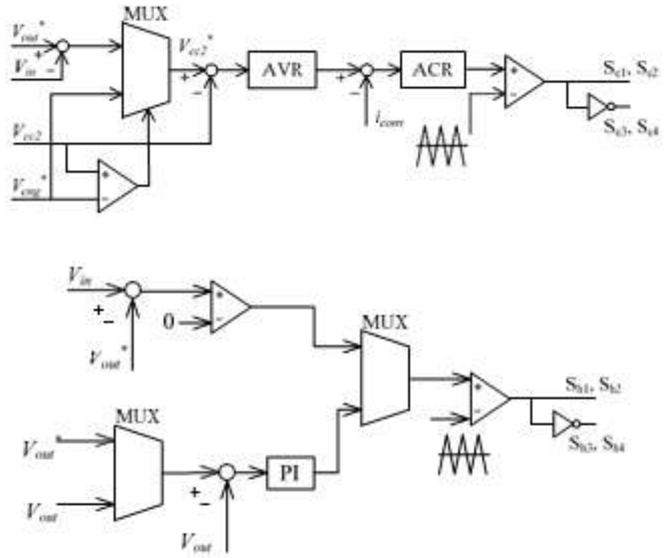
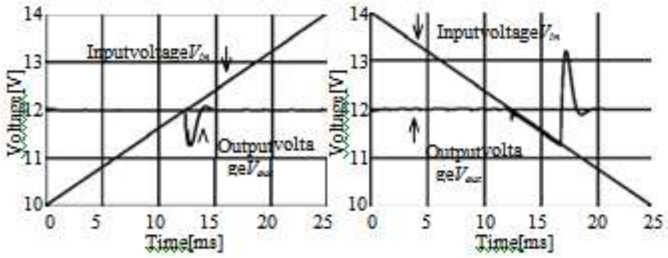
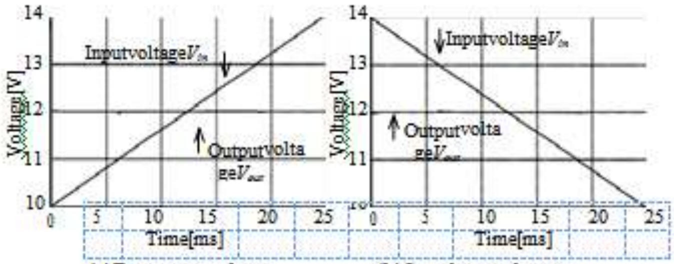


Fig.8.Proposedcontroldiagram.



(a) Boosttostepdown.

(b)Stepdowntoboost.Fi g.9.VoltagewaveformswithPIcontrolonly



(a)Boosttostepdown. (b)Stepdowntoboost.

Fig.10.VoltagewaveformswithP Icontrolandproposedmethod.

(5)

t_{on} □ t_{off} V_{in} □ □ V □ V_{conv} □ $_{in}$

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

PL
1 2
2Lci1P –
fsw
V2t2 f
inon sw
2L
(6)

c
Next,theseriesconverteroutputvoltageisobtainedby(7),using maximum output current I_{out}. Then the series converteroutputpoweriscontrolledbystorageenergyofreactor.
V2t2f

Pconv
Vconv
Iout
inon sw
2L
(7)

c
From(6)and(7),theinductanceoftheseriesconverterreactorisobtainedby(8).

22 Vt f
L in on sw 9[H]

(8)

c 2V I

2) Buckmode
convout

The reactor storage energy becomes the maximum valueswhen the input voltage is at maximum value. In condition ofTable2,themaximuminputvoltageis18V,theseriesconverter output voltage is 6V. Similarly to boost mode, theinductanceofthebuckmodeiscalculatedas40 H by(8).Thebuck mode inductance is larger than the boost mode one.Thereforethebuckmodevalueisadopted.

III. EXPERIMENTALRESULTS

To confirm the validity of the proposed converter concept,the proposed converter was tested under the experimentalconditionsshowninTable2.Itshouldbenotedthatthecircuitparameterschosenistoconfirmbasicoperation,andoptimizationwasnotconsidered.Inaddition,theconventionalcombination buck boost converter, which uses a step-downconverter and a boost-up converter, as shown in Fig. 11 istested in order to compare the efficiency.It is noted that thereactorintheconventionalcircuitisdesignedasfollows.

In conventional combination chopper, the reactor has thefunctionsofsmoothingtheoutputcurrentandenergystorage.The inductance value is designed in allowance. The rectorcurrentbecomesdiscontinuousinlightloadregion.The

discontinuouscurrentcausesincreasinglossandunstableoutputvoltageduetononlinearcontrol.

The ripple current is needed at minimum value when theoutputcurrentisminimumatoutputpower5W,outputcurrent417mA.The peak to peak value of the ripple current of areactor is limited to 40% of output current, then the ripplecurrent is 166mA because the output current is 417mA atoutput power 5W.In addition, the reactor voltage becomesmaximum value when the input voltage is at maximum valueof18V.Inthiscondition,theinductanceofthereactoris calculatedby(9).

Table3.Circuitparameter.

Propo sedcir	LT 1	40µH
	LT 2	40µH
	Np	5
	Ns	5
	Cc	2200

cuitI	1	μF
	Cc 2	220μ F
	Lf	2μH
	C_f	470μ F

Propo sedcir cuitII	L_c	22μH
	Cc 1	470μ F
	Cc 2	2200 μF
	L_f	22μH
	Cf	1000 μF
Convent ionalcirc uit	L	220μ H
	C	2200 μF

Table2.Specificationsofexperimentalcircuit.

InputvoltageV$_{in}$[V]	6〜18
Outputvoltage V_{out}[V]	12
OutputpowerP$_{out}$[W]	5〜30
Switching frequency f_{sw}[kHz]	100

 V V t 18 12   0.667 10 6 10
in
L
 I
out

out(P P)
on
0.166
 240[H]
(9)

A. Experimentalresults

Figures12and13showthecurrentwaveformsofproposedcir Fig. 12 and 13 show the current waveforms of proposedcircuitsIandII,respectively.Thecurrentpolaritydependsontheoperationmode;buckorboost.Thetransformerandreactorweredesignedsothatthepowerassistcircuitoperatesin current continuous mode. These results confirmed that theproposedassistcircuitacceptsbidirectionalpowerflow,without unnecessary surges or oscillations in the reactor ortransformercurrent.Inaddition,theshortcurrentof thepowersupplydoesnot appearinthewaveforms.Therefore, theflybackconverterandtheinvertingchopperwiththeisolationswitchcanbeusedinaseriesconverter.

Fig. 14 presents a comparison between the efficiency of aconventionalbuckboostconverterandtheproposedconvertersatconstantload.Amaximumefficiency ofapproximately 98% was obtained for both of the proposedcircuits.Fortheconventionalconverterisapproximately94%.

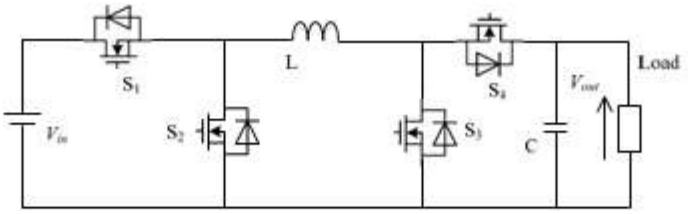
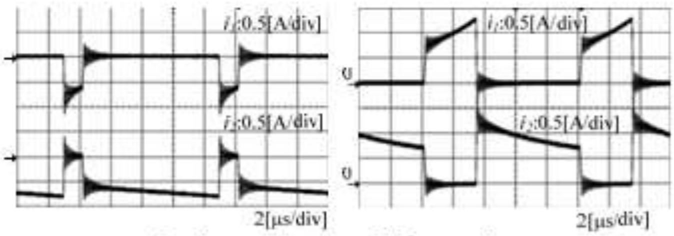
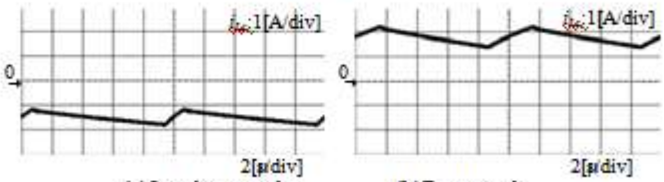


Fig.11.Configurationofaconventionalcombinationchopper.



(a) Stepdownmode. (b)Boostmode.

Fig.12.Currentwaveformsoftheflybacktransformerintheproposedcircuit I.



(a)Stepdownmode. (b)Boostmode.

Fig.13.CurrentwaveformsofthereactorintheproposedcircuitII

In other words, the converter loss decrease from 6% to 2 %,theproposedcircuitcanimprovetheconverterloss to1/3.Theinputvoltageissoclosetotheoutputvoltage,sothatconverter efficiency is even more improved, as shown in Fig.14.

Fig. 15 shows the efficiency with load variation for theconventional converter and the proposed converters. In bothboostmodeandbuckmode,efficiencyimprovementispossible.InFig.15,theefficiencyofthebuck modeishigherthantheboostmodeonebecausetheinputpowerintheboostmode is larger than the buck mode. The power loss in theseries converter is provided from power source in the boostmode.Incontrast,theregenerationpowerinthe buckmodeisdisappeared by the circuit power loss. Therefore, the currentflowingtotheseriesconverterintheboostmodeisdecreasedtobuckmodeone.

Fig. 16 shows the voltage waveform of $V_{out}$for load stepresponse. The load is changed from 5W to 14W. When theloadconditionisrapidlychanged,theoutputvoltageoscillation can be suppressed to less than 0.2 V. The outputvoltage oscillation can be improved by refinement of thecontrolstrategyoftheseriesconverter.

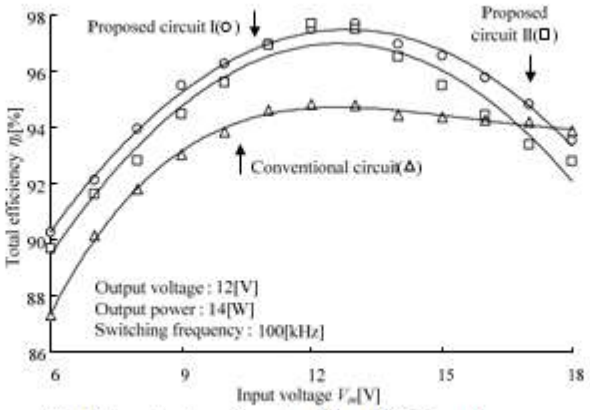
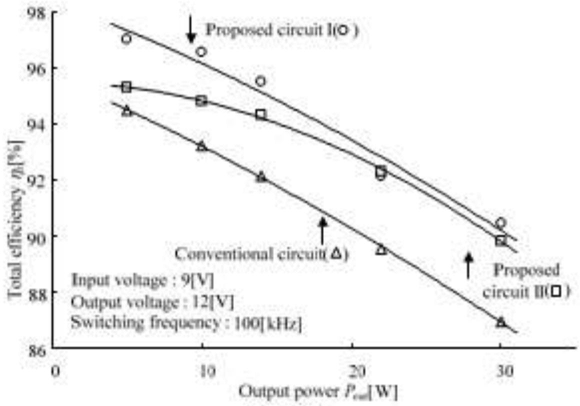
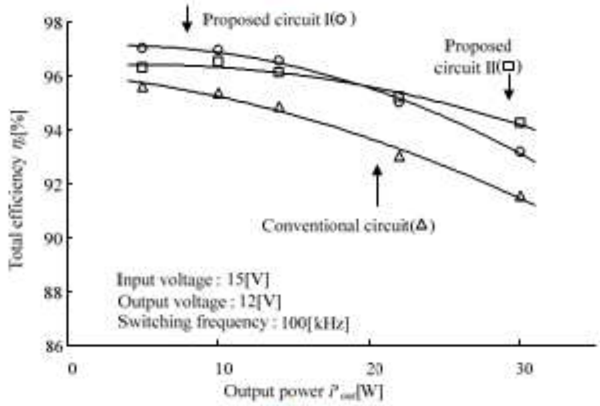


Fig.14.Inputvoltagecharacteristicsofefficiencyη_t.



(a)V_{in}=9V



(b)V_{in}=15V

Fig.15.Loadcharacteristicsoftotalefficiencyη_t.

.

differential voltage in PWM control region of the H bridgepart. The output voltage is kept at 12 V of a constant voltage,although the input voltage increases from 10 V to 14 V ordecreases from 14 V to 10 V. In particular, when the inputvoltageiscloseto12V,thecontroloutputvoltag eisdisturbedby the non linear components, such as dead-time and powerdevicecharacteristics.However,theoscillati oncanbesuppressedtolessthan0.2VbyproposedP WMcontrolofH-bridgeasshowninFig.17.

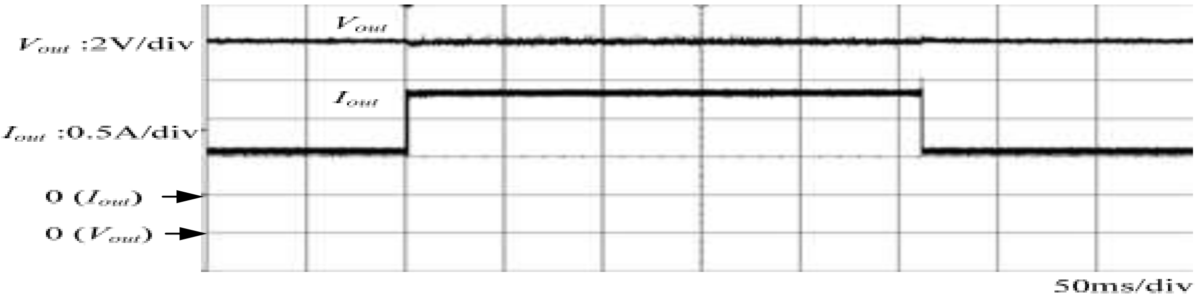
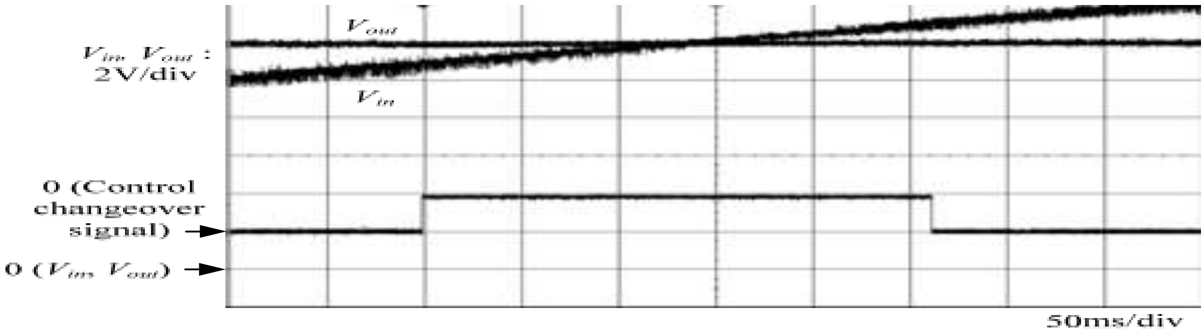
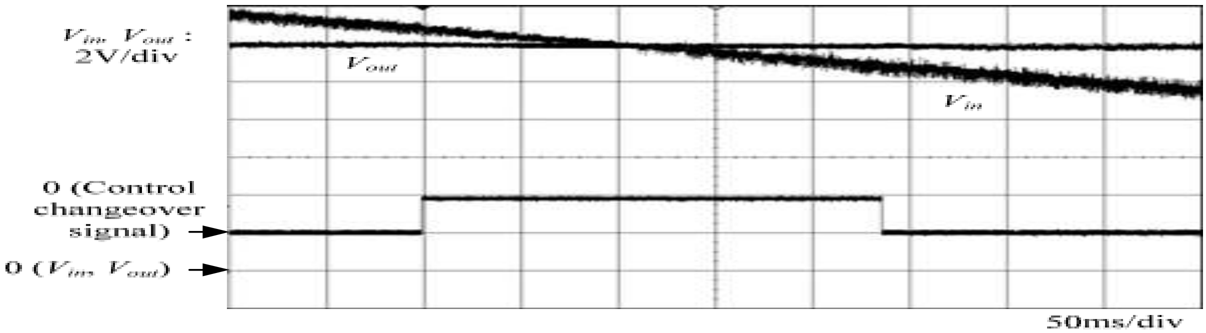


Fig.16.Outputvoltagewaveformforsteploadresponse.



(a)Boosttostepdown.



(b)Stepdowntoboost.

Fig.17.Outputvoltagewaveformatlowdifferentialvoltage.

IV. CONCLUSION

Inthispaper,aseriestypebuck-boostconverterisproposedthat uses an H-bridge circuit and a power assist circuit withsmall power rating. A flyback converter and an invertingconverterwereusedaspowerassistcircuits. Theexperimentalresults confirmed that the proposed circuits could decreaselossesby2/3atthemaximumefficiencypoint.Therefore,theproposed converter can realize high efficiency and down-sizingforuseinapplicationsthatrequiretheoutputvoltagetobeclosetotheinputvoltage.

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