Bulletin of Electrical Engineering and Informatics
Vol. 3, No. 4, December 2014, pp. 251~258
ISSN: 2089-3191

High-Conversion-Ratio Bidirectional DC–DC Converter with Dual Coupled Inductors

Omid Khezri*, Javad Javidan
Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran
*Corresponding author, e-mail: omidkhezri0055@gmail.com

Abstract

In this paper, a high-conversion-ratio bidirectional DC–DC converter with dual coupled inductors is proposed. In the boost mode, two capacitorsare parallel charged and series discharged by the dual coupled inductors. Thus, high step-up voltage gain can be achieved with an appropriate duty ratio. In the buckmode, two capacitorsare series charged and parallel discharged by the dual coupled inductors. The bidirectional converter can have high step-down voltage gain.The stress voltage of all switchescan be reduced, and the switching loss and efficiency can be improved. The operating principle and the steady-state analyses of the voltage gain are discussed. Finally, in 24V for low voltage, and 400V for high voltage, and 200W for output power, this converter simulated in MATLAB.

***Keywords**: Bidirectional, DC-DC converter, dual coupled inductors, high conversionratio*

1. Introduction

Renewable energy systems are morewidelyused in the world such as solar and wind energy [1]-[3]. However, photovoltaic (PV) solar or wind power cannot providesufficient power when the load is suddenly increased [4]-[6]. Because the renewable systems cannot provide a stablepower for user, the renewable energy systems and batterycan be employ for the hybrid power systems [7]. When therenewable energy systems cannot supply enough power forthe load, the battery must provide this power.If the power of the renewable energy systemscannot be used completely by the load, the excess energycan be used to charge the battery [8]-[10]. Because the bidirectionalDC–DC converters can transfer the power between two DCsources in either direction, these converters are widely usedfor renewable energy hybrid power systems, hybrid electricvehicle energy systems and uninterrupted power supplies [11]-[12].The topologies of these converters have the isolated andnon-isolated types for different applications.The isolatedtypes include the flyback type [13]-[14], forward-flyback type[15]-[16], half-bridge type [17]-[18] and full-bridge type [19].These converters can achieve high voltage gain byadjusting the turns ratio of the transformer. Thebidirectional flyback converter has the simple structure and easy control but the switches ofthis converter have highvoltage stresses. Thus, thisconverter is applied for lowpower applications.Toreduce thevoltage stresses on the switches, the energyregenerationtechniques used [20]. Thenon-isolated types include the multi-level type,switched-capacitor type, cuk/cuk type, sepic/zetatype, buck-boost type, coupled-inductor type, three-leveltype and conventional buck/boost type[21].In multi-level andswitched-capacitor types, if high voltage gain needed, more switches and capacitors are required.Also, the control circuits of these converters arecomplicated.For the cuk/cuk and sepic/zeta types, theefficiency are low because these converters cannot provide wide voltageconversion range [22]-[24]. The converter in [25] has the high convertion ratio but this converter unidirectional. Compare with [25], the proposed converter successfully developed to bidirectional dc-dc converter with a dual coupled inductors, and the switches voltage stressreduced and efficiency increase in boost and buck mode.

The proposed bidirectional converter is analysed, and its operation in boost and buck mode is described in section II. Steady-state analysis and equations of the boost and buck mode described in section III and Simulation results described in section IV.

Received October 15, 2014; Revised November 18, 2014; Accepted December 2, 2014

2. Operating Principle OfThe Proposed Converter

Figure 1 shows the circuit topology of the proposed converter.This converter consists of the dc input voltage V_L, the power switch S_1, S_2, S_7, two capacitors $C_1$and C_2, and the dual coupled inductors $N_P$and N_S.

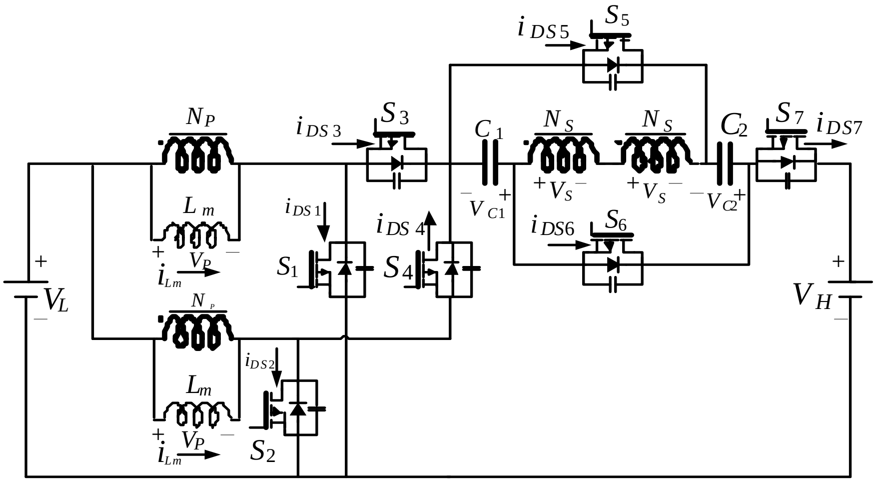


Figure 1. Circuit configuration of the bidirectional converter

In the boost mode, parallel-charged and seriesdischarged capacitors can achieve high stepup gain. Also in the buck mode, seriescharged and paralleldischarged capacitors can achieve high step-down gain. In the boost mode operation,S_1, S_2 is the main switch. The voltage across switches S_1, S_2 can bereduced. Since switches S_1, S_2has an low voltage level, the low conducting resistance $R_{DS(ON)}$ of the switch is used to reduce the conduction loss. In the buck mode operation, the coupled inductorsare used as a transformer. Thus, two capacitors C_1 and C_2 can be series charged byhigh voltage side and parallel discharged through the secondary side the main switches are S_3, S_4 and S_7. The switching loss is improved and the efficiency can be increased.

A. Boost-mode Operation

Figure 2(a) shows the waveforms and Figure 3 shows the current flow path of the proposed converter in boost mode. There are two operating modes in one switching period of the proposed converter. The main switch is s_1, s_2 for each modes. The operating modes are described as Figure 2.

1) Mode I $[t_0 - t_1]$:S_1, S_2, S_5, S_6 turn on and S_3, S_4, S_7 turn off in $t = t_0$.The current-flow path is shown in Fig. 3(a). The dc source $V_L$charges the magnetizing inductor L_m, and the charging capacitors $C_1$and C_2via the dual coupled inductors. Voltages $V_{C1}$and $V_{C2}$are equal to$2nV_L$ and two capacitors are charged in parallel. The output capacitor $C_H$provides energy to load R. This operating mode ends when switch $S_1, S_2$is turned off at$t = t_1$.
2) Mode II $[t_1 - t_2]$:S_3, S_4, S_7 turn on and S_1, S_2, S_5, S_6 turn off. The current flow path is shown in Figure 3(b). The dual coupled inductors, dc sourceV_L, and capacitors C_1 and C_2 are connected in series to charge the output capacitor C_H and load R. This operating mode ends when switch$S_3, S_4, S_7$is turned off at $t = t_2$and beginning of the next switching period.

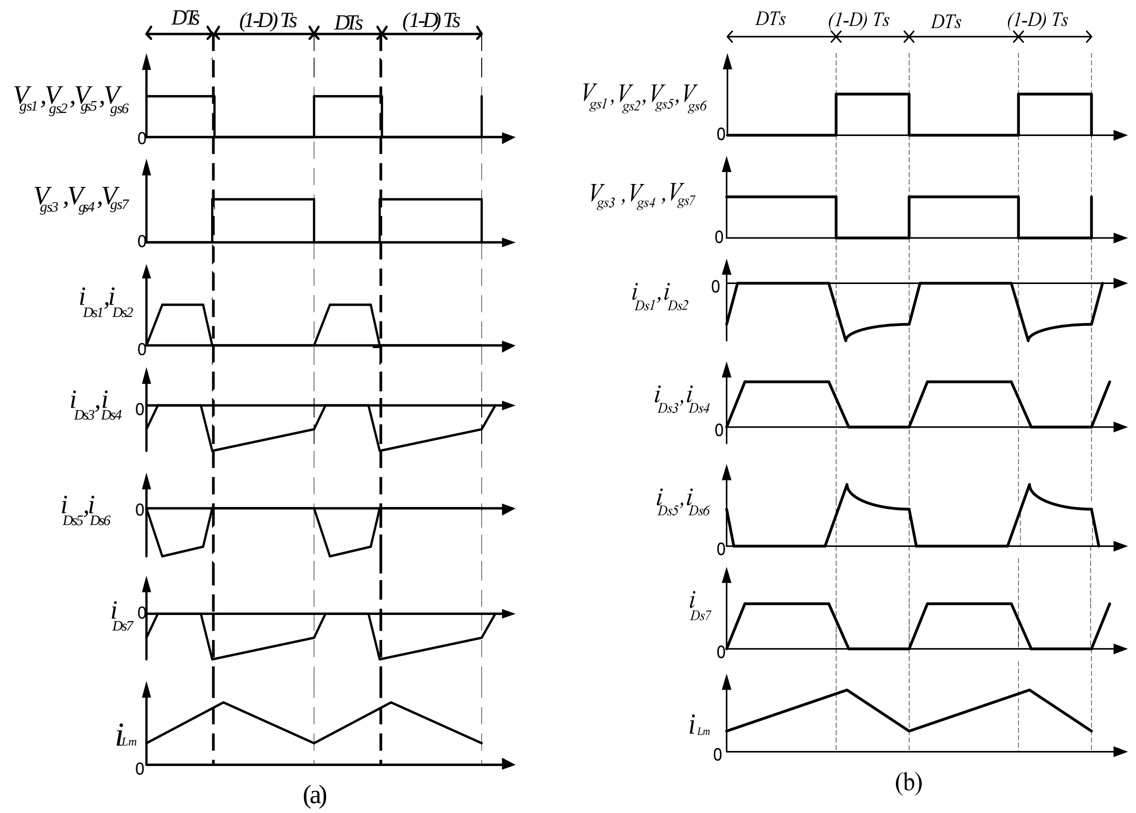


Figure 2. Waveforms of the bidirectional converter. (a) boost mode, (b) buck mode

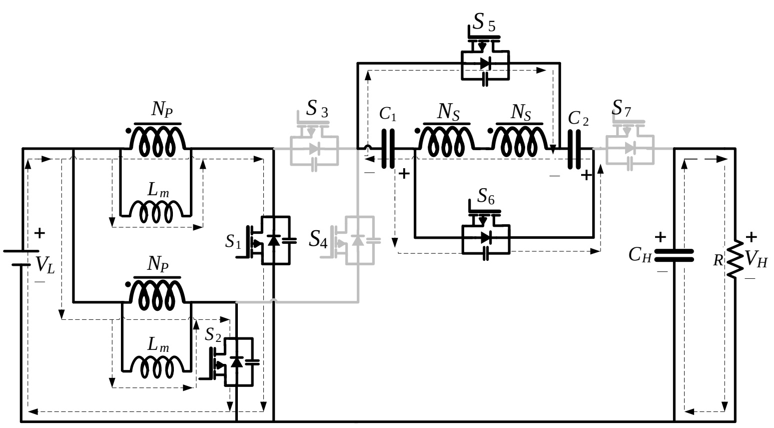


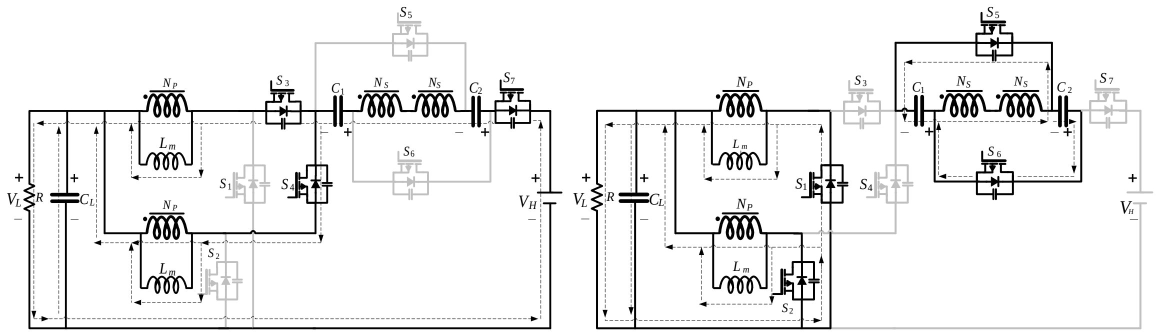
Figure 3. Current-flow path of the operating mode during one switching period in the boost mode

B. Buck-mode Operation

Figure 2(b) shows the waveforms, and Figure 7 shows the current flow path for each mode. The operating modes are described below.

1) Mode I $[t_0 - t_1]$:S_3, S_4, S_7 turn on and S_1, S_2, S_5, S_6 turn off. The current flow path is shown in Figure 4(a). Capacitors C_1, C_2 and the secondary side coil N_S are still charged in series by V_H, and the magnetizing inductor L_m is also charged. The output capacitor C_L provide the energy to load R. This operating mode ends when switch S_3, S_4, S_7 is turned off at $t = t_1$.

2) Mode II $[t_1 - t_2]$:S_1, S_2, S_5, S_6 turn on and S_3, S_4, S_7 turn off at $t = t_1$. The current flow path is shown in Figure 4(b). The energy of capacitors C_1 and C_2 discharges to the output capacitor C_L and load R through the dual coupled inductors. The magnetizing inductor L_m also discharges to the output.This operating mode ends when switch S_1, S_2 is turned off at $t = t_2$.



(a) (b)

Figure 4. Current-flow path of the operating mode during one switching period in the buckmode

3. Steady-State Analysis of the Proposed Converter

Afterthe mode analysis of the boost and buck mode operations, the following equations and voltage gain in the steadystate of the proposed converter can be derived.The equations of the turnratio of the coupled inductor aredefined as

$$n = \frac{N_s}{N_p} \quad (1)$$

A. Boost-mode Operation

There are two operating modes in one switching period of the proposed converter.In the time period of mode I, the following equations canbe written based on Figure 3(a). The voltage on the primary andsecondary sides of the dual coupled inductors are showed as

$$V_p^I = V_L \quad (2)$$

$$V_s^I = nV_p^I = nV_L \quad (3)$$

AlsoThe voltage ofcapacitorsC_1 and C_2 can be written as follows:

$$V_{c1} = V_{c2} = 2V_s^I = 2nV_L \quad (4)$$

Based on Figure 3(b), in modes II, the voltage on thesecondary side of the dual coupled inductors can be formulated asfollows:

$$2V_s^{II} = V_L - V_p^{II} + V_{c1} + V_{c2} - V_H \quad (5)$$

$$2nV_p^{II} = V_L - V_p^{II} + 4nV_L - V_H \quad (6)$$

$$V_p^{II} = \frac{(1 + 4n)V_L - V_H}{1 + 2n} \quad (7)$$

Using the volt-second balance principle on the magnetizing inductor L_m, the following is given:

$$\int_0^{DT_s} V_p^I \, dt + \int_{DT_s}^{T_s} V_p^{II} \, dt = 0 \quad (8)$$

Also, the voltage stress of the main switch S_1, S_2can be expressedas

$$V_p^{II} = V_L - V_{s1,s2} \tag{9}$$

Substituting (2) and (9) into (8), voltage stress is obtained as

$$V_{DS1,DS2} = \frac{V_L}{1-D} \tag{10}$$

Substituting (2) and (7) into (8), the voltage gain of the boost state operation is obtained as

$$M_{boost} = \frac{V_H}{V_L} = \frac{1+4n-2Dn}{1-D} \tag{11}$$

B. Buck-mode Operation

In the time period of mode I, the following equations canbe written based on Figure 4(a). The voltage on the primary andsecondary sides of the dual coupled inductors are showed as

$$2nV_s^I = V_L - V_p^I + V_{c1} + V_{c2} - V_H \tag{12}$$
$$2nV_p^I = V_L - V_p^I + 4nV_L - V_H \tag{13}$$

$$V_p^I = \frac{(1+4n)V_L - V_H}{1+2n} \tag{14}$$

The voltage on the primary and secondary sidesof the dual coupled inductorsin mode II can be written based on Figure 4(b):

$$V_p^{II} = V_L (15) V_s^{II} = nV_p^{II} = nV_L \tag{16}$$

Thus, the voltage of capacitors *C*2 and *C*3 is also derived onFig. 4(b). The voltage is expressed as

$$V_{c1} = V_{c2} = 2V_s^I = 2nV_L \tag{17}$$

Using the voltsecond balance principle on the magnetizing inductorL_m, the following is given:

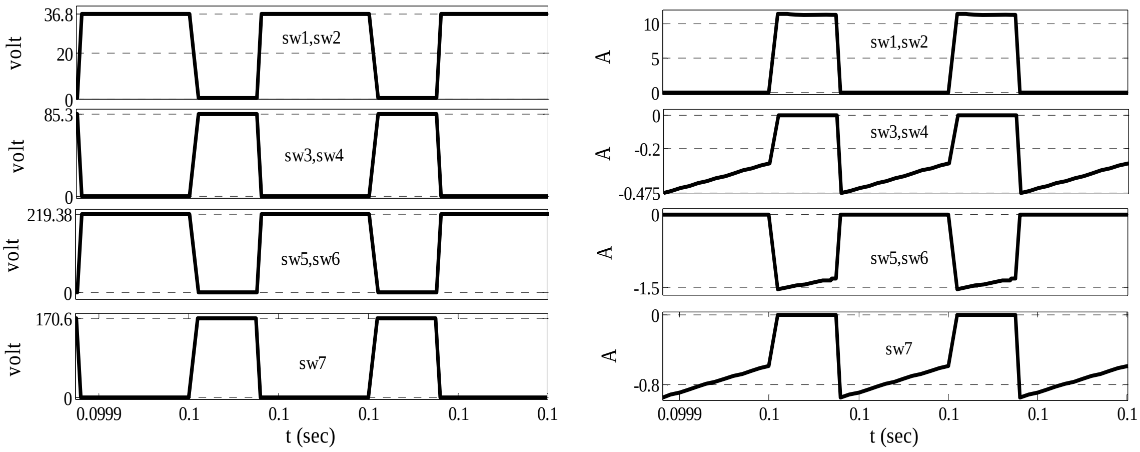
$$\int_0^{DT_s} V_p^I\,dt + \int_{DT_s}^{T_s} V_p^{II}\,dt = 0 \tag{18}$$

Substituting (12) and (13) into (16), the voltage gain ofthe buck-mode operation is obtained as

$$M_{buck} = \frac{V_L}{V_H} = \frac{D}{1+2n+2nD} \tag{19}$$

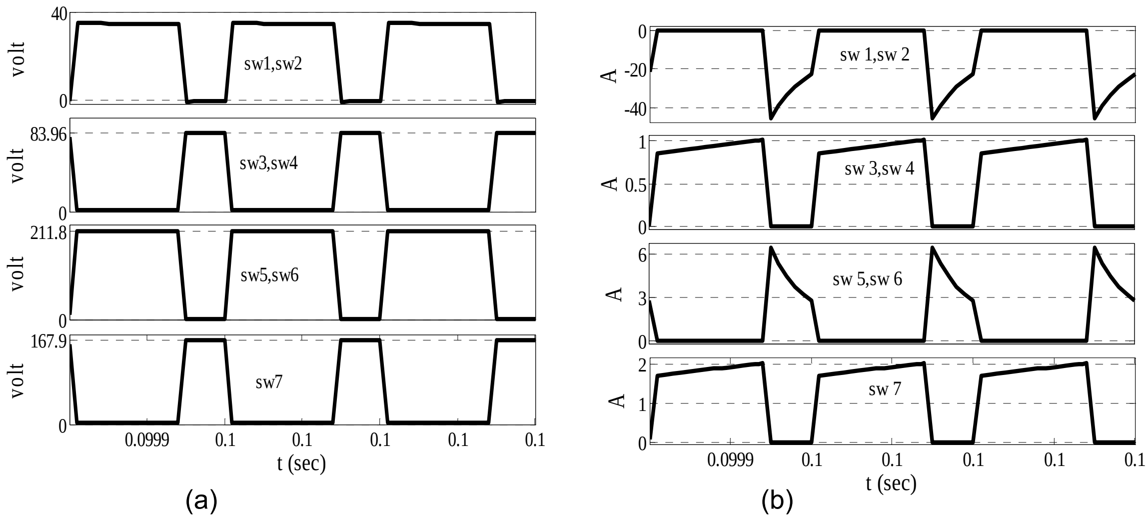
4. Simulation Results

Toillustrate the performance and the functions of theproposed converter, this converter is implemented in the MATLAB. The specifications are:
1) dc voltage V_L is 24 V and $V_H$is 400 V;
2) output power: 200 W;
3) switching frequency: 50 kHz;
4) Coupled inductor: $N_p : N_s = 1:3$, L_m= 120μH;
5) CapacitorsC_1 and C_2 is 470 μF;
6) MOSFETsS_1, S_2, S_3, S_4: IRFP4568PBF;S_5, S_6:IXFK64N50P;S_7: IXFK64N60P;



(a) (b)

Figure 5. Experiment results in the boost mode under full load *P*o = 200 W. (a) voltage stress of switches, (b) current of switches.



(a) (b)

Figure 6. Experiment results in the buck mode under full load *P*o = 200 W.(a) voltage stress of switches,(b) current of switches.

In Figure (5), the waveforms are the boost mode operationat full load *Po* = 200 W,$V_{in} = 24$ V, and $V_{out} = 400$ V. Thewaveforms illustratethat the steady-state analysis of theboost mode is correct. According to (11) and specifications, the duty cycle is 34.5%. Figure 5(a) illustratewaveform of voltage stress of switches.According to (10) stress voltage ofmain switchesS_1, S_2 equal in 36.65 V. Because the proposed converter works in the boost mode, stress voltage in low side switch S_1, S_2 reduced. Figure 5(b) illustrate waveform of current of switches. Because the proposed converter works in the boost mode, stress voltage in low side switchesS_1, S_2 reduced.

In Figure (6), the waveforms are the buckmode operation at full load *Po* = 200 W,$V_{in} = 400$ V, and $V_{out} = 24$ V.According to (19) and specifications, the duty cycle is 65.5%. Figure 6(a) illustratewaveform of voltage stress of switches. Stress voltage ofmain switch S_7 is 165 V. Fig 6(b) illustrate waveform of current of switches.Because the proposed converter worksin the buck mode, stress voltage in high side switch S_7 reduced.

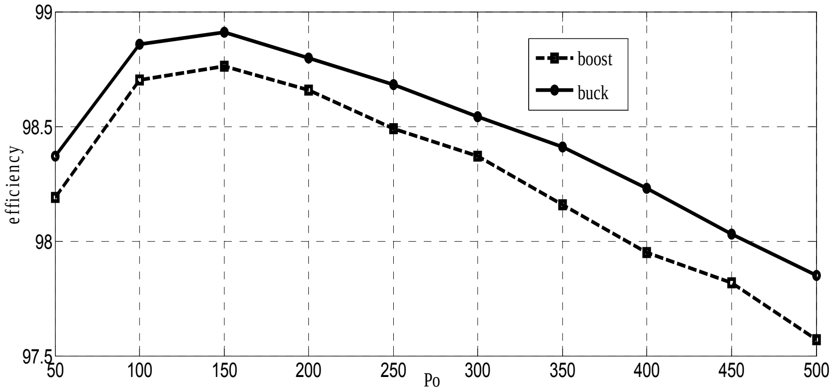
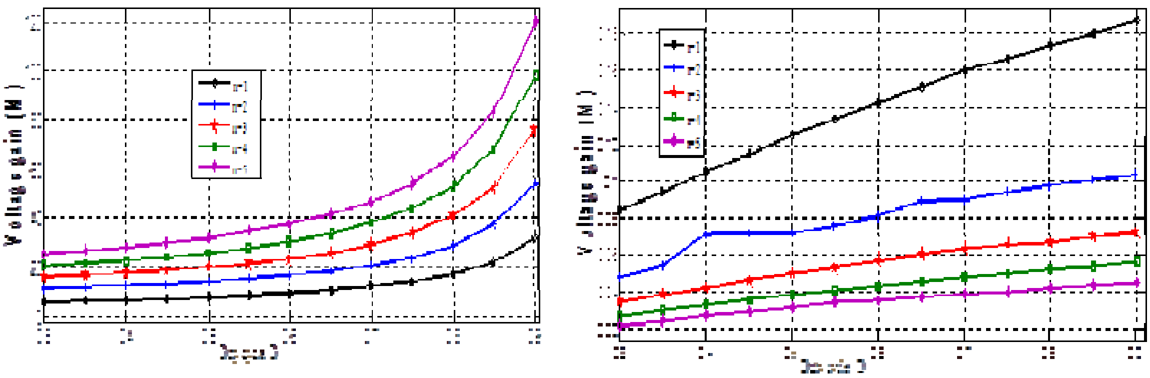


Figure 7. Experimental efficiency in the boost and buck mode

Figure (7) shows the measured efficiency of proposed converter in boost and buck mode at $V_L = 24$ V and $V_H = 400$ V.the maximum efficiency inthe boost mode is98.76% at$P_o = 150$ W and full load efficiency is 98.66%at$P_o = 200$ W. The maximum efficiency inthe buck mode is 98.91% at $P_o = 150$ W and full load efficiency is 98.8% at$P_o = 200$ W.



(a) (b)

Figure 8. Voltage gain curves under different turn ratio. (a) boost mode, (b) buck mode.

Figure (8) shows the voltage gain versus the duty cycle under various turns ratio of coupled inductors in the boost mode.in the boost mode, if the turn ratio increases, voltage gain will also be increased

Figure (9) shows the voltage gain versus the duty cycle under various turns ratio of coupled inductors in the buck mode.in thebuck mode, if the turn ratio increases, voltage gain will be decreases.

5. Conclusion

This paper has proposed a high-efficiency, and high step-up and step-down bidirectional dc–dc converter. This converter successfully developed a high-voltage gain bidirectional dc-dc converter by input-parallel output-series in the boost mode and input-series output-parallel in the buck mode.By using the two capacitors charged in parallel and discharged in series by the dual coupled inductors, high conversion ratio and high efficiency has been achieved. The voltage gain increased by using a dual coupled inductor with a low turn ratio. Simulation results show that the efficiency at full load $P_o = 200$ W is 98.66% in the boost mode and 98.8% in the buck mode.

References

[1] C Cecati, F Ciancetta, and P Siano. "A multilevel inverter for photovoltaic systems with fuzzy logic control". *IEEE Trans. Ind. Electron*. 2010; 57(12): 4115–4125.
[2] Ghadimi, Noradin. "Using HBMO Algorithm to Optimal Sizing & Sitting of Distributed Generation in Power System". *Bulletin of Electrical Engineering and Informatics 3.* 2014; 1.
[3] R Seyezhai, HarineeHarinee, Nagarajan Nagarajan. "Simulation and Implementation of Soft-Switched Interleaved DC-DC Boost Converter for Fuel Cell Systems". *BEEI*. 2012; 1(3).
[4] JY Lee and SN Hwang. "Non-isolated high-gain boost converter using voltage-stacking cell". *Electron. Lett*. 2008; 44(10): 644–645.
[5] R Seyezhai, R Anitha, S Mahalakshmi, M Bhavani. "High Gain Interleaved Boost Converter for Fuel Cell Applications". *BEEI*. 2013; 2(4).
[6] Luiz Henrique SC Barreto, Paulo Peixoto Praca, Demercil S Oliveira Jr, and Ranoyca NAL Silva. "High-voltage gain boost converter based on three-state commutation cell for battery charging using PV panels in a single conversion stage". *IEEE Trans. Power Electron*. 2014; 29(1): 150–158.
[7] Nagulapati Kiran. "Sliding Mode Control of Buck Converter". *BEEI.* 2014; 3(1).
[8] R Gules, JDP Pacheco, HL Hey, and J Imhoff. "A maximum power point tracking system with parallel connection for PV stand-alone applications". *IEEE Trans. Ind. Electron.* 2008; 55(7): 2674–2683.
[9] Ghadimi N. An adaptive neuro-fuzzy inference system for islanding detection in wind turbine as distributed generation. Complexity.doi: 10.1002/cplx.21537. 2014.
[10] RY Duan and JD Lee. "High-efficiency bidirectional dc–dc converter with coupled inductor". *IET Power Electron.* 2012; 5(1): 115–123.
[11] H Tao, JL Duarte, and MAM Hendrix. "Line-interactive UPS using a fuel cell as the primary source". *IEEE Trans. Ind. Electron*. 2008; 55(8): 3012–3021.
[12] YP Hsieh, JF Chen, TJ Liang, LS Yang. "Novel high step-up DC-DC converter for distributed generation system". *IEEE Trans. Ind. Electron*. 2013; 60(4): 1473-1482.
[13] Venkatesan K. '*Current mode controlled bidirectional flybackconverter*'. Proc. IEEE PESC. 1989: 835–842.
[14] Chen G, Lee YS, Hui SYR, Xu D, Wang Y. 'Actively clampedbidirectional flyback converter'. *IEEE Trans. Ind. Electron*. 2000; 47(4): 770–779.
[15] Huber L, Jovanovic MM. 'Forward-flyback converter withcurrent-doubler rectifier: analysis, design, and evaluation results'. *IEEE Trans. Power Electron*. 1999; 14(1): 184–192.
[16] Zhang F, Yan Y. 'Novel forward–flyback hybrid bidirectionalDC–DC converter'. *IEEE Trans. Ind. Electron*. 2009; 56(5): 1578–1584.
[17] Li H, Peng FZ, Lawler JS. 'A natural ZVS medium-power bidirectional DC–DC converter with minimum number of devices'. *IEEE Trans. Ind. Appl*. 2003; 39(2): 525–535.
[18] Peng FZ, Li H, Su GJ, Lawler JS. 'A new ZVS bidirectional DC–DC converter for fuel cell and battery Application'. *IEEE Trans. Power Electron*. 2004; 19(1): 54–65.
[19] Lin BR, Huang CL, Lee YE. 'Asymmetrical pulse-width modulation bidirectional DC–DC converter'. *IET Power Electron*. 2008; 1(3): 336–347.
[20] Mi C, Bai H, Wang C, Gargies S. 'Operation, design and control of dual H-bridge-based isolated bidirectional DC–DC converter'. *IET Power Electron*. 2008; 1(4): 507–517.
[21] Khan FH, Tolbert LM, Webb WE. 'Hybrid electric vehicle power management solutions based on isolated and nonisolated configurations of multilevel modular capacitor-clamped converter'. *IEEE Trans. Ind.Electron*. 2009; 56(8): 3079–3095.
[22] Monge SB, Alepuz S, Bordonau J. 'A bidirectional multilevelboost–buck DC–DC converter'. *IEEE Trans. Power Electron*. 2011; 26(8): 2172–2183.
[23] Peng FZ, Zhang F, Qian Z. 'A magnetic-less DC–DC converter fordual-voltage automotive systems'. *IEEE Trans. Ind. Appl*. 2003; 39(2): 511–518.
[24] Lee YS, Chiu YY. 'Zero-current-switching switched-capacitorbidirectional DC–DC converter'. *IEE Proc. Inst. Elect. Eng. Electr.Power Appl*., 2005; 152(6): 1525–153015.
[25] Ko YP, Lee YS, Chao WH. 'Analysis, design and implementationof fuzzy logic controlled quasi-resonant zero-current switchingswitched-capacitor bidirectional converter'. *IET Power Electron*. 2011; 4(6): 683–692.
[26] X Hu, Ch Gong. "A High Gain Input-Parallel Output-Series DC/DC Converter with Dual Coupled-Inductors". *IEEE Trans, Ind, Electron*. 2014; 50(1).