Dual Inductor Based Two Input Two Output DC-DC Converter and its Analysis for DC Microgrid Application

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Received 31 January 2022; Accepted 26 April 2022;
Publication 27 February 2023

Abstract

Two input two output DC-DC converters with two switched inductor structure are widespread in DC micro grid and Electric Vehicle (EV) applications with merits of solid structure, lower cost and high-power density. However, owing to the low voltage levels of the non-conventional sources used in the above applications, the significance of step up type DC-DC converters is so high. In this paper, a step up converter that is expert to deliver two different voltages at the output side from two different input energy sources is proposed as a new topology. It mainly contains two inductors for improving the voltage conversion ratio. Thorough analysis of converter has been performed with support of necessary equations and circuits. The performance assessment of DC-DC converter is done with simulation and experimental platforms and required waveforms are presented. A comparative study of the proposed converter is also fulfilled to signify the better features of the converter.

Keywords: Dual inductor based converter, multiport boost type DC-DC converter, theoretical analysis, microgrid/EV applications.

Distributed Generation & Alternative Energy Journal, Vol. 38_3, 943–964.
doi: 10.13052/dgaej2156-3306.38310

1 Introduction

In the existing situation, the usage of non-conventional sources has been radically boosted especially in the areas of DC microgrid, electric vehicle, fuel cell, etc. However, most of power converter interfaces have poor voltage profile. Hence the selection of suitable converter interface based on the application is highly important to realize efficient integration of various sources. A Two switch based boost converter for fuel cell powered vehicle application that has high gain relation has been discussed in [1]. A positive voltage two input two output converter that outshines the drawback of typical buck-boost converter with two inputs is presented in [2]. The creation of MIMO (Multi Input Multi Output) converters are proposed in [3] with low cost and simple structure. But most of the converters have the demerits of higher voltage and current stress on the switching devices and constrains on load currents and output voltages. In [4], various MIMO topologies that are operated in step up, step down operations are derived and analysed. However, thorough investigations on a particular topology is missing. A novel multi-port converter that has a single inductor structure is proposed in [5]. However, the number of power switches are high in the given converter that may increase the overall intricacy. A new concept of high boost multiport converter is narrated in [6] with capacitor-diode based voltage boosting cell. Even though the converter offers better voltage gain, the count of passive components and power switches are increased with the quantity of input sources that affects the system efficiency. Detailed analysis of various integrated multiport converters is presented in [7]. Various design equations are described for the investigation of each of the presented topologies. A single inductor based MIMO converter with double conversion elimination method is introduced in [8]. This method is used to achieve a reduction in double converted power by a significant amount. A two inductor based two input converter is introduced in [9]. It has compact structure and better voltage conversion ratio. However, the number of conducting devices are relatively high that may affect the loss values. A novel multi input high gain converter for cancelling ripples from input and to enhance the consumer's safety on load side along with high power density and efficiency is introduced in [10]. However, the presence of more number of coupled inductors and other components increases the overall circuit complexity and cost.

An overall overview and global picture of step up type converters to demonstrate the present relevance of high voltage gain in various applications are described in [11]. A boost type three input dual output converter and the theoretical studies are presented in [12]. In [13], a MIMO converter with a single inductor with detailed analysis is presented. Here, the two outputs and inputs can be easily removed and added deprived of altering the control strategy. The inputs and outputs are connected in series and are independent to each other. However, one of the source side switches is need to be turned on permanently to realize better voltage conversion ratio. This increases the overall losses of the converter. A multiport converter for EV application is narrated in [14]. The number of conduction devices is more in each working states of the converter that causes high conduction losses in the given converter. A non-isolated four port converter with the capability of bidirectional energy flow to charge the battery between diversified energy supplies is presented in [15]. However, more number of conducting devices in each working state causes high losses in the system.

A comprehensive review of various multiport converters used for renewable energy integration is described in [16]. The review investigates both isolated and non-isolated topologies in an elaborated manner. To elucidate the problem of hard switching operation, a three port soft switched converter is implemented in [17] with power flow to energy storage device from the output. However, the presence of auxiliary circuit increases the converter complexity. A novel multi input power converter has been explored in [18]. But it contains larger number of switches and storage elements that affects the overall converter efficiency and operation. A two input converter and the implementation of a closed loop control scheme for the converter is detailed in [19] with the explanation of output voltage regulation. A novel modified two input converter has been proposed in [20]. The converter analysis are presented with the support of experimental results. But the voltage gain of the converter is reasonably lesser. Henceforth, in this paper a novel two input two output dual inductor based converter is presented. The converter has

- Good voltage gain compared to typical boost converter
- Lesser voltage stress through the switching components
- Flexibility in the duty ratios to achieve better voltage gain
- Energy deposited in the inductor can be distributed to the load without any additional clamping circuit.
- Capability to incorporate two dissimilar voltage-current characteristic sources

2 Circuit Diagram

The circuit representation of two input two output two switched inductor converter is illustrated in Figure 1. The count of power switches is four,

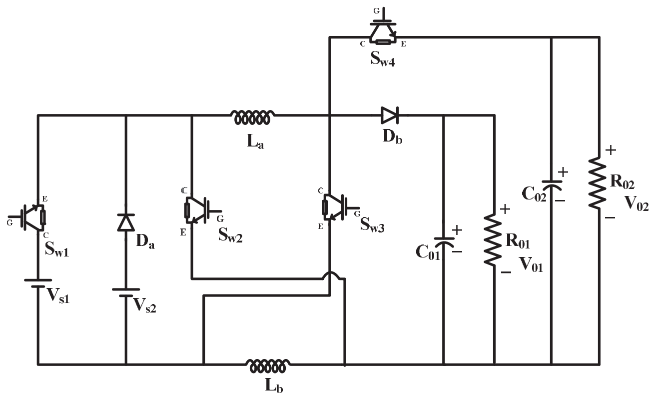


Figure 1 Proposed converter circuit diagram.

the count of diodes and inductors are two as shown in the circuit and the total count of capacitors are also two. The duty ratios of the switching pulses are selected as shown in Figure 2. Here the inductor operation is considered only in continuous conduction mode (CCM) even though it may operate in discontinuous mode based on the sources.

2.1 Mode I

The mode I operation circuit is given in Figure 3(a). Initially the input voltage V_{s1} charge the inductors L_a and L_b through the switches S_{w2} and S_{w3}, hence inductor current is linearly rising. The output capacitor C_{01} and C_{02} have been discharged at the same time to ensure the continuous supply to the load.

2.2 Mode II

The circuit in mode II is displayed in Figure 3(b), here the input voltage V_{s2} is used to charge the inductors L_a and L_b through the switches S_{w2} and S_{w3}.

Hence the inductor current is linearly rising. The output capacitor C_{01} and C_{02} have been discharged at the same time to supply the loads.

2.3 Mode III

The circuit of mode III operation is illustrated in Figure 3(c). Here the input voltage V_{s2} gives the continuous supply to the load through the inductor L_a, switch S_{w4} and energizes the capacitor C_{02}. Still the output capacitor C_{01} is used to supply the load by de-energizing its stored energy.

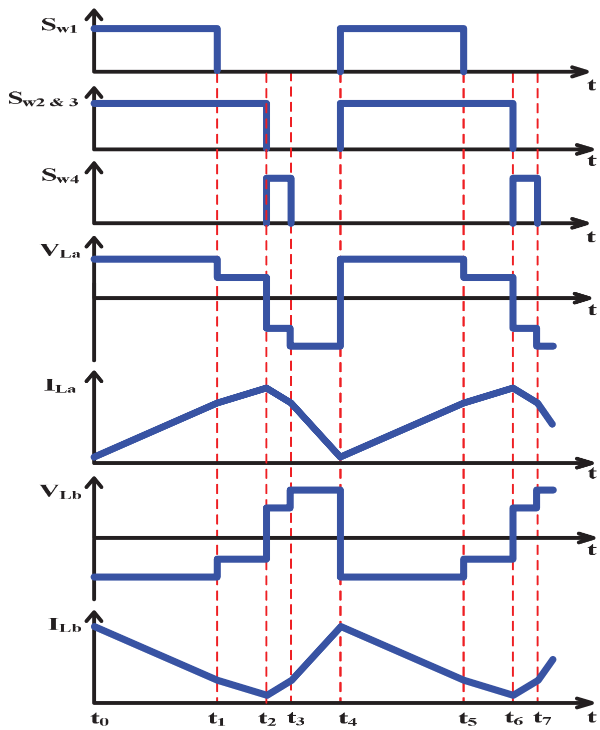
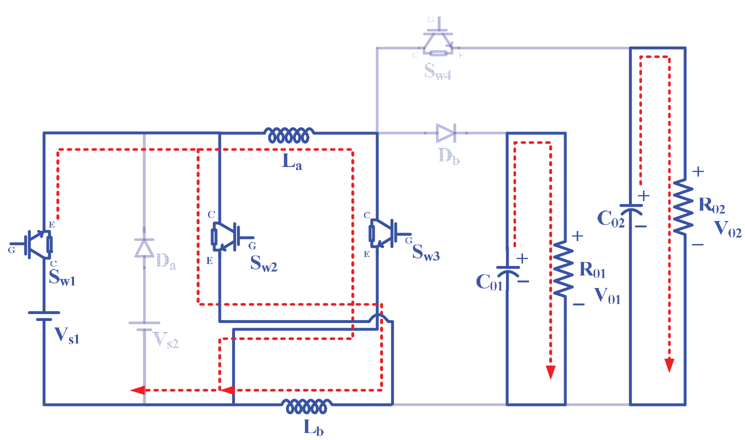
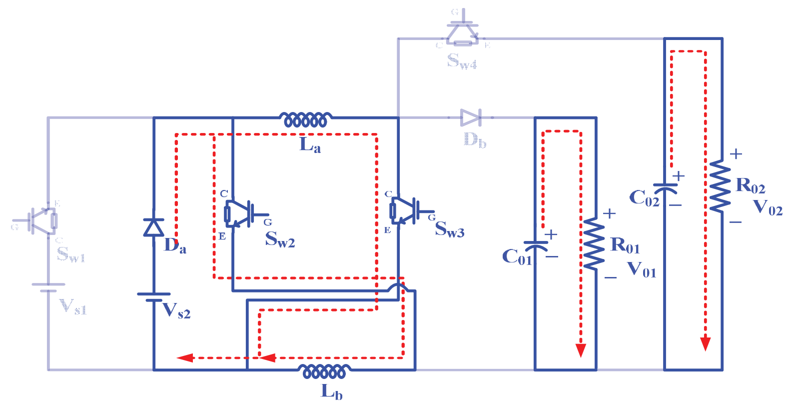


Figure 2 Analytical waveform for the proposed converter.

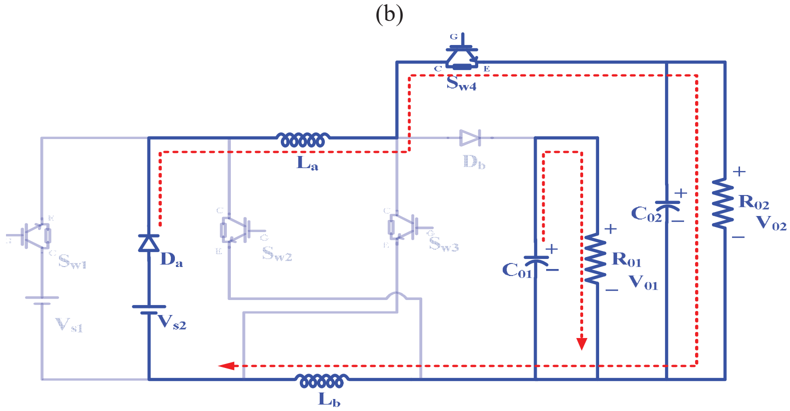


(a)

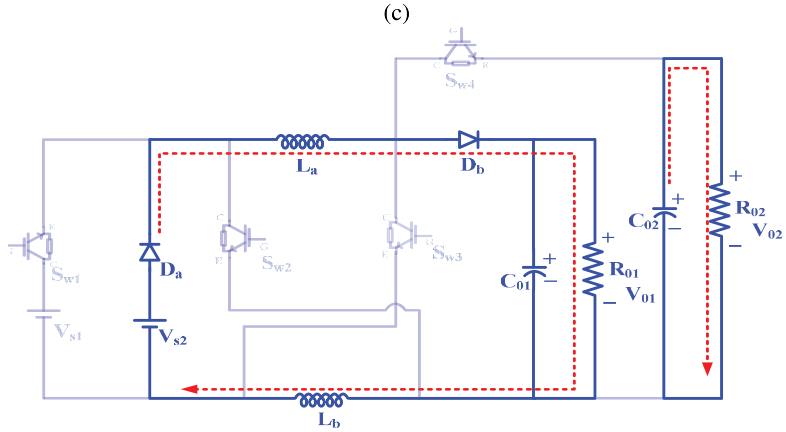
Figure 3 Continued



(b)



(c)



(d)

Figure 3 The corresponding circuits for different operating modes (a) mode I (b) mode II (c) mode III (d) mode IV.

2.4 Mode IV

The circuit in mode IV is revealed in Figure 3(d). Here V_{s2} is the input voltage that gives the supply to the load R_{O1} through the inductor L_a, diode D_b and also energizes the capacitor C_{01}. At the same time output capacitor C_{02} dissipates its stored energy to deliver energy to the load R_{O2}.

3 Analysis of a Converter

The necessary equations of the converter in various working modes have been derived and presented in this session.

In mode I, voltages across the inductors are

$$V_{La} = V_{s1} \tag{1}$$

$$V_{Lb} = -V_{s1} \tag{2}$$

In this mode, the switch voltages of S_{W1}, S_{W2}, S_{W3} and S_{W4} and diode voltages of D_a and D_b are extracted as

$$V_{Sw1} = V_{Sw2} = V_{Sw3} = 0 \tag{3}$$

$$V_{Sw4} = V_{C2} - (V_{C1} + V_{s1}) \tag{4}$$

$$V_{da} = -V_{s2} \tag{5}$$

$$V_{db} = -(V_{s1} - V_{01}) \tag{6}$$

In mode II, voltages across the inductors are

$$V_{La} = V_{s2} \tag{7}$$

$$V_{Lb} = -V_{s2} \tag{8}$$

In this mode, the switch voltages of S_{W1}, S_{W2}, S_{W3} and S_{W4} and diode voltages of D_a and D_b are extracted as

$$V_{Sw1} = V_{s1} - V_{s2} \tag{9}$$

$$V_{Sw2} = V_{Sw3} = 0 \tag{10}$$

$$V_{Sw4} = V_{C2} - (V_{C1} + V_{s2}) \tag{11}$$

$$V_{da} = 0 \tag{12}$$

$$V_{db} = -(V_{s2} + V_{01}) \tag{13}$$

In mode III, voltages across the inductors are

$$V_{La} = \frac{1}{2}(V_{s2} - V_{02}) \tag{14}$$

$$V_{Lb} = \frac{1}{2}(V_{02} - V_{s2}) \tag{15}$$

In this mode, the switch voltages of S_{W1}, S_{W2}, S_{W3} and S_{W4} and diode voltages of D_a and D_b are extracted as

$$V_{Sw1} = V_{s1} - V_{s2} \tag{16}$$

$$V_{Sw2} = V_{Sw3} = V_{s2} + V_{Lb} \tag{17}$$

$$V_{Sw4} = 0 \tag{18}$$

$$V_{da} = 0 \tag{19}$$

$$V_{db} = (V_{02} - V_{01}) \tag{20}$$

In mode IV, voltages across the inductors are

$$V_{La} = \frac{1}{2}(V_{s2} - V_{01}) \tag{21}$$

$$V_{Lb} = \frac{1}{2}(V_{01} - V_{s2}) \tag{22}$$

In this mode, the switch voltages of S_{W1}, S_{W2}, S_{W3} and S_{W4} and diode voltages of D_a and D_b are extracted as

$$V_{Sw1} = V_{s1} - V_{s2} \tag{23}$$

$$V_{Sw2} = V_{Sw3} = V_{s2} + V_{Lb} \tag{24}$$

$$V_{Sw4} = V_{01} - V_{02} \tag{25}$$

$$V_{da} = V_{db} = 0 \tag{26}$$

4 Simulation/Experimental Results

4.1 Simulation Results

In the Simulink/MATLAB platform, the simulation analysis of the introduced converter is done. The parameter values for the simulation/experimental

Table 1 Simulation/experimental parameters

Simulation Parameters		
S. No	Parameters	Specification
1.	Input Voltages (V_{s1}, V_{s2})	24 V, 12 V
2.	Inductor (L_a & L_b)	5 mH
3.	Switching Frequency (f_s)	20 kHz
4.	Duty ratio (D_1, D_2, D_3, D_4)	50%, 70%, 70%, 10%
5.	Output Capacitor (C_{01}, C_{02})	47 μF
6.	Output Voltages (V_{01}, V_{02})	118 V, 60 V
7.	Load Resistors (R_{01}, R_{02})	100 Ω

analysis are listed in the Table 1. The working of the inductor is in continuous conduction mode and waveforms generated in the software simulation like voltage and current of inductors, capacitors, load, etc, are displayed in Figure 4. The simulation waveforms for the load currents and voltages across R_{01} and R_{02} are shown in the Figure 4(a & b). The voltages across the loads R_{01} and R_{02} are 118 V and 60 V correspondingly for the given converter and the respective output load current values are 1.3 A and 0.7 A. The capacitor current and voltage waveforms are revealed in Figure 4(c & d). The voltage across C_{01} and C_{02} are 118 V and 60 V correspondingly for the given converter with a maximum ripple content of 3 V across them. Here one of the output voltage is considered as 118 V since it is a standard DC microgrid specification.

During the first three modes of operation capacitor C_{01} is used to discharge the energy to the load R_{01} and in fourth mode of operation, the capacitor C_{01} is charged through the diodes D_a, D_b and Inductor L_a from the input source V_{s2}. During first two modes and the fourth mode of operation capacitor C_{02} is used to discharge the energy to the load R_{02} and in the third operating mode, the capacitor C_{02} is getting charged through the diode D_a, inductor L_a and switch S_{W4} from the input sources V_{s2}. The respective average current values of the capacitors C_{01} and C_{02} are 5 A. The inductor current and voltage waveforms obtained from the simulation circuit are shown in the Figure 4(e & f). The voltage across L_a is charged with 24 V and 12 V in first two working modes and de-energized with the voltage of -24 V and -50 V correspondingly in the final two working modes. At the same time inductor L_b is charged with negative polarity (i.e., -24 V and -12 V) in first two working modes and de-energized with the voltage of 24 V and 50 V respectively (due to the position of inductor L_b in the circuit) in the final modes of operations and the corresponding average current for the

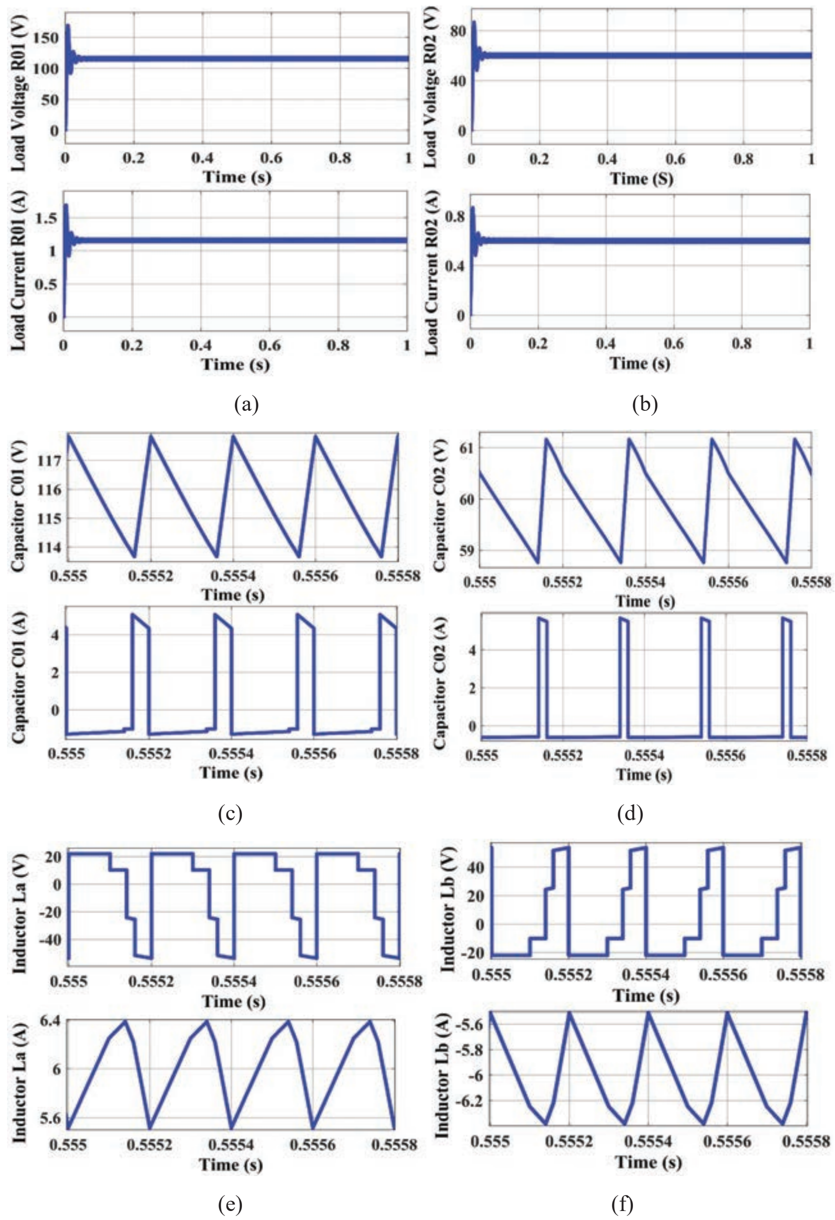


Figure 4 Simulation results (a) load voltage and current through R_{O1} (b) load voltage and current through R_{O2} (c) voltage and current through C_{O1} (d) voltage and current through C_{O2} (e) voltage and current across L_a (f) voltage and current across L_b.

both inductors L_a and L_b are 6 A. Here 0.8 A is the ripple content in inductor current and 3 V is the ripple content in capacitor voltage.

The simulation waveforms for the diode voltage and currents across the D_a and D_b are revealed in Figure 5(a & b). The voltage across the Diode D_a is -12 V (i.e., V_{S2}–V_{S1}) for the first mode of operation and in the other three modes, the diode D_a is in ON state, hence the voltage is zero. Also, the voltage across the diode D_b is -148 V, -120 V and -50 V for the first three modes of operations and in fourth mode diode D_b is in ON state, hence the voltage is zero. The respective average currents through both diodes are 8 A. The simulation waveforms for the switch voltages and currents are shown in Figure 5(c–f). The voltage across S_{W2} and S_{W3} are 62 V (Figure 5(d&e)) in last two working modes. In last three working modes, the voltage stress across S_{W1} (Figure 5(c)) is observed as 12 V (i.e., (i.e., V_{S1}–V_{S2}) and the voltage across the switch S_{W4} (Figure 5(f)) is observed as -82 V (V_{O2}–(V_{S1} + V_{O1})) in mode I, -70 V (V_{O2}–(V_{S2} + V_{O1})) in mode II, 58 V(V_{O1}–V_{O2}) in mode IV. In mode III, since the switch is conducting, the voltage stress is zero. The average current following through all the switches are 6 A.

4.2 Experimental Results

To assess the working of projected converter in real time conditions, hardware prototype has been developed and experimental waveforms are analysed. The output voltage waveforms are displayed in Figure 6(a). The switching frequency of 20 KHz is opted for the pulse generation. The experimental waveform analysis is exactly matching with the results attained from the simulation. The hardware waveforms of inductors, capacitors, diodes and switches are also strictly adhere with the simulation results and are shown in Figure 6(b–f). From Figure 6(a) it is clearly noticed that the load voltage across the loads R_{01} and R_{02} are 118 V and 60 V respectively and that satisfies the converter performance in a realistic condition. Similarly, the charging and discharging status of both the inductors are exactly matched with the simulation waveforms as shown in Figure 6(c).

The relative analysis of introduced converter is done in terms of component counts (passive and active components), the count of input sources and output ports with other projected converter topologies in the literature and the results are represented in Table 2. The study of comparison discloses that the presented converter has lower count of the components when compared with other topologies, so that overall circuit complexity and losses can be reduced to a great extent.

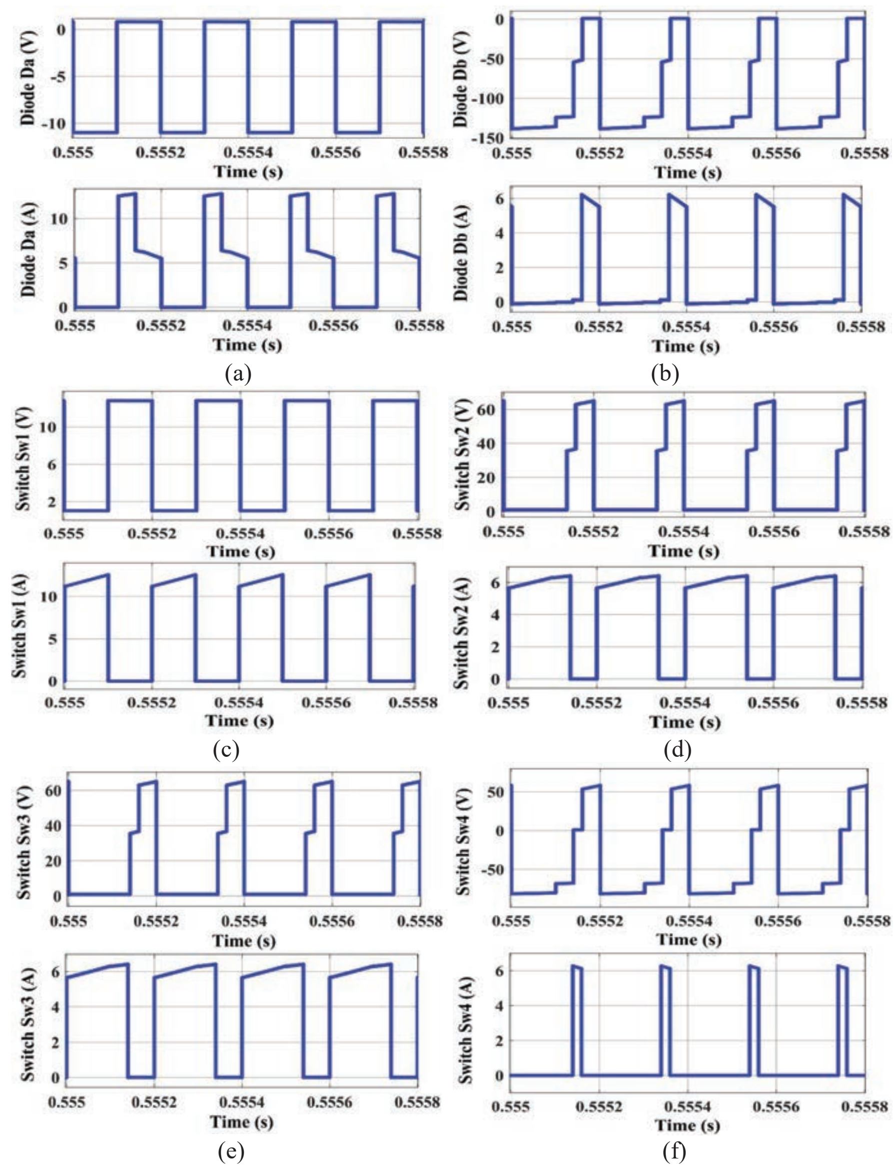
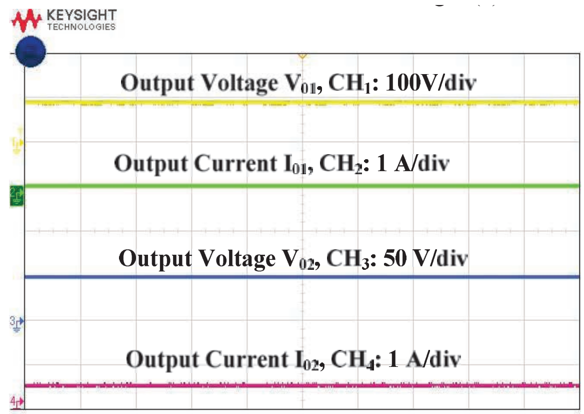
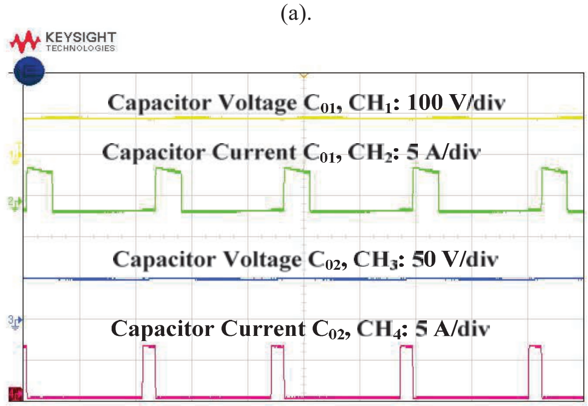


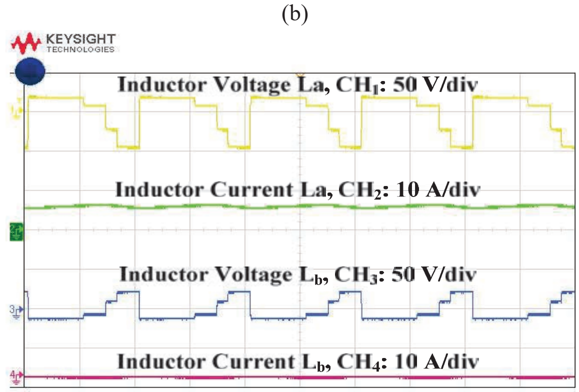
Figure 5 Voltage and current waveforms obtained from simulation analysis (a) for D_a (b) for D_b (c) for S_{W1} (d) for S_{W2} (e) for S_{W3} (f) for S_{W4}.



(a).

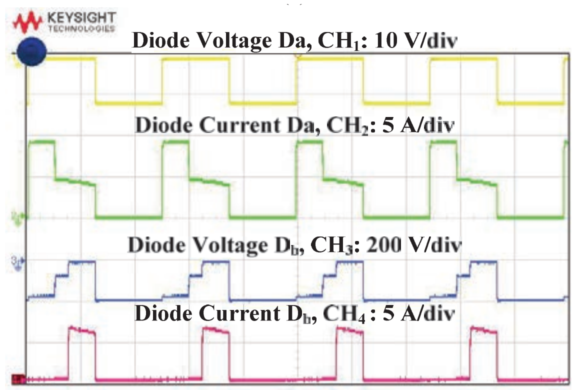


(b)

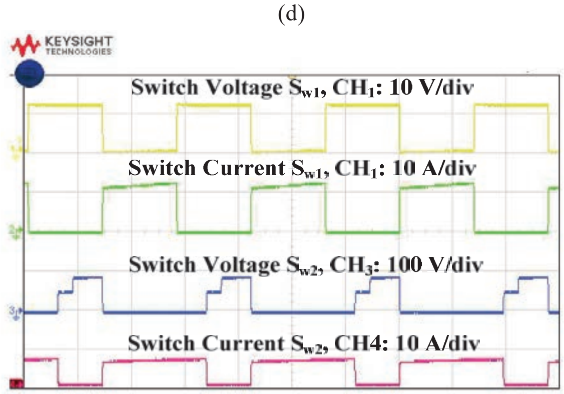


(c)

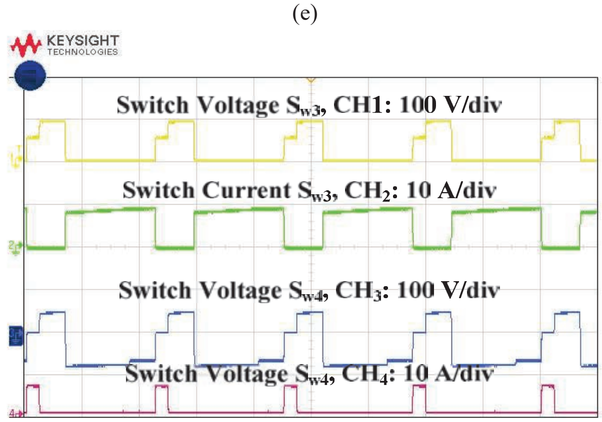
Figure 6 Continued



(d)



(e)



(f)

Figure 6 (a–f). Experimental waveforms of various voltages and currents.

Table 2 Comparison table with other converters

Component Comparison							
S. No	Parameters	Presented Converter	[2]	[10]	[13]	[14]	[17]
1.	Switch counts	4	3	2	4	4	6
2.	Diode counts	2	5	2	4	5	3
3.	Inductors counts	2	2	6	1	2	2
4.	Capacitors counts	2	1	4	2	2	5
5.	Total Elements	10	12	15	13	16	17
6.	Output voltage levels	2	1	1	2	1	1
7.	Input Sources	2	2	2	2	3	2

5 Conclusion

In this paper, a dual inductor based two input two output boost type DC-DC converter is introduced to achieve higher voltage gain with lower component counts and better performance that can be incorporated for electric vehicle/DC microgrid applications. The power switches in the given converter are well suited to operate with flexible duty ratios which is one of the significant advantages of the converter. Thorough analysis of the converter in steady state condition is presented with the help of supporting circuits and equations. Then the converter performance is evaluated under simulation and experimental backgrounds and the waveforms are described. Finally, the converter is compared with other well-known topologies based on the number of ports, passive and active component counts etc., and from the analysis it is found that the introduced converter has reasonably lower part count that reduces the overall circuit intricacy and enhances the converter role in the applications of dc microgrid, EV etc.

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