Switched-Inductor Switched-Capacitor Based Bidirectional DC-DC Converter

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Abstract — *DC-DC converter is widely used in power electronics. It is used in different kind ofdistributed energy sources such as solar cell, hybrid electric vehicle. For interfacingmicro-gird with main power grid DC-DC converters are widely used. The main task ofthe converter is to step-up or step-down the input voltage. Here a bidirectional DC-DCconverter is designed. For Smart grid technology, innovation in bidirectional DC-DCconverter is one of the most essential parts. The converter topology contains switched-inductor and switched-capacitor network, which gives the advantage of high voltageconversion ratio without using a transformer. The active switched network employs twoinductors/capacitors that charges in parallel during switch on period and discharged in series during switch off period. The topology is simulated in MATLAB/SIMULINKR2017a software. It is observed that the efficiency of the converter is 98% for boostand 97% for buck operation. The converter is controlled using PIC16F877a controller.Experimental results obtained from a 5W converter prototype confirm the theoreticalconsiderations and the simulation results.*

Keywords — *Bidirectional DC-DC converter, switched-inductor, switched-capacitor.*

I. INTRODUCTION

Due to the rapidly increasing economy and enormous demand for energy, the global energy crisis has been aggravated. To deal with this energy problem, researches on environmental friendly system such as the electric vehicles and distributed power system [1]-[2] have been carried out. In these applications, an energy storage system like a battery system must be needed to save and use energy. Thus, a bidirectional DC-DC converter (BDC) which allows transfer power between two DC sources becomes an important topic of power electronics. The BDC is categorized into an isolated converter [3]-[4] and a non-isolated converter [5]-[6]. An isolated DC-DC converter uses an isolation transformer between the input and output, it has more than 4 switches, therefore it has higher conduction losses and lower efficiency compared to non-isolated converter. Non isolated converters have higher efficiency due to its simple structure [7]. The transformer based isolated converters is an attractive for high frequency and provide isolation between the source and load sides. Due to its large size, weight, cost and comparatively lower efficiency, the transformer-less type is much more attractive.

For the application of DC micro-grid and renewable energy systems BDC converter plays an important role in these days. These converters are oftenrequire in order to ensure the power from, to, or between various energy storageelements. Therefore, BDC converters placed between energy storage devices and DC busses, at different voltage levels, have become recently important research issues.When using renewable energy system along with a BDC converter and batteries is required to supply steady current to the applications. These converters are one of the most important energy conversion system,that are widely used in the applications such as plug-in hybrid electric vehicle (PHEV), fuel-cell vehicle, renewable energy system, and uninterruptible power supply (UPS) etc. These BDC converter acts as an energy exchange system from a low voltage battery to a DC-link [8].

In many cases, the bidirectional converters have to provide a high voltage ratiobetween input and output. Many applications require a DC bus supportingconnections to several renewable energy sources, storage systemsand loads. However, due to the intermittent nature of renewableenergy sources and load variations it is essential to stabilize thevoltage of the DC bus. Usually a battery is used to support theDC bus voltage, but their continuous charge and dischargecycling will affect his lifetime. Thus, the use of a storage systembased in supercapacitors provides an interesting alternative tostabilize the DC power grid[9]. Where supercapacitors are used as storage elements, a highvoltage ratio is required to allow a large voltage variation across the terminals, to fullyuse the energy storage capacity. In DC micro-grids, the DC-DC bidirectional convertersplay an important role in the control of the internal DC bus voltage and in maintainingthe system power balance [10]-[11]. For hybrid energy storage systems, in which bothbatteries and supercapacitors are used as energy storage devices, two or more bidirectional converters with coordinated control are included [12].

In this paper a BDC converter is designed for the application ofDC power grid voltage support based on supercapacitors. That is the proposed converter is supplied from supercapacitor to support the DC grid. Here buck operation to charge the supercapacitor and boost operation to support DC bus voltage. Supercapacitors are of low voltage devices, for this application such a high voltage conversion ratio is needed to support DC link. The main advantages of this converter is that high voltage conversion ratio, high efficiency and simple structure.

II. DESCRIPTION OF THE PROPOSED CONVERTER

Fig. 1 shows active switched-inductor/ switched capacitor based BDC converter. The circuit has four active switches, V_h is high side voltage and V_l is low side voltage.

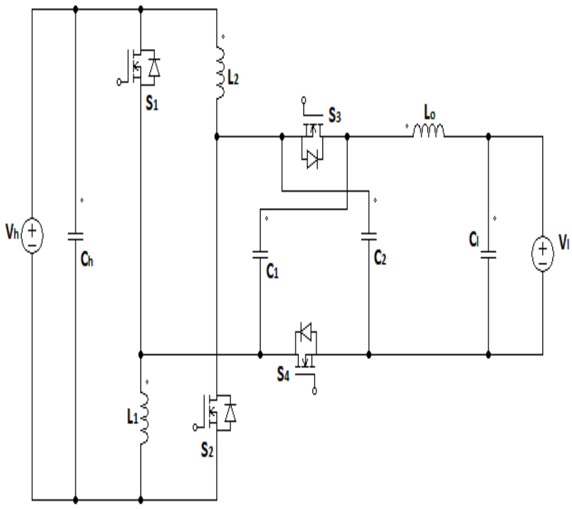

Fig 1: Bidirectional DC-DC Converter

The converter has switched-inductor and switched-capacitor structures which together contribute high voltage gain of the converter. Switches S_1 & S_2 and inductors L_1 & L_2 forming active switched-inductor network and switches S_3 & S_4 and capacitors C_1 & C_2 forms switched capacitor cell. For boost operation V_h becomes source side and V_l is the load side and vice versa for buck operation.

Bidirectional converter has buck and boost operations. There are two modes for each operation. Eachmodes are explained in the following section.

A. *Boost Operation*

For boost operation V_h acts as source and V_L. There are two modes of operation.

*1) **Stage 1:*** In this mode active switches S_1 & S_2 are in ON state, inductors L_1& L_2 charges through switches while capacitors C_1 and C_2 discharges shown in Fig. 2.

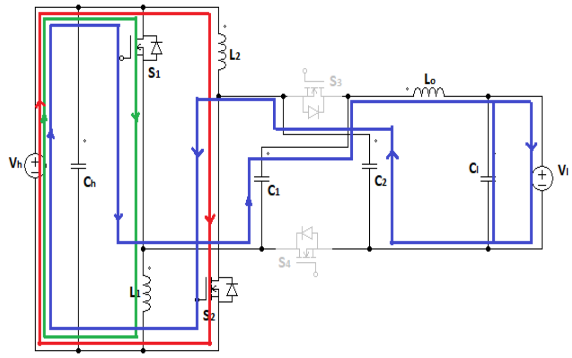

Fig 2: Stage 1

$$V_{L1} = V_{L2} = V_h \quad (1)$$

$$V_{L0} = V_h - 2V_c - V_0 \quad (2)$$

*2) **Stage 2:***Switches S_1& S_2 turned OFF and other two switches S3 & S4 gets turned ON in this state. Both inductors L_1& L_2 discharges and capacitors are charging. This mode shown in Fig. 3.

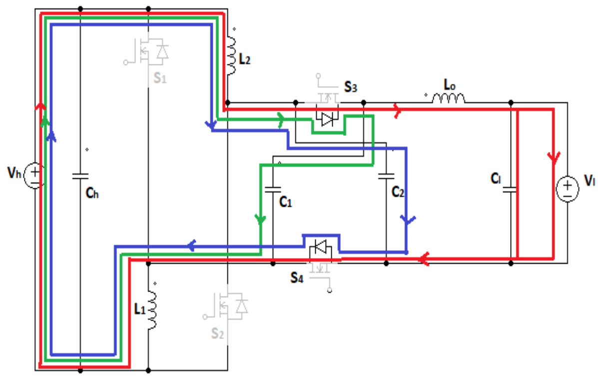

Fig 3: Stage 2

$$V_L = \frac{V_h + V_c}{2} \quad (3)$$

$$V_{L0} = V_h - 2V_L - V_l \quad (4)$$

By using volt-second balance principle and thus obtain

$$\frac{V_l}{V_h} = \frac{D(2D+3)}{1-D} \quad (5)$$

B. *Buck Operation*

There are two modes for buck operation, those are explained below.

*1)**Stage 1:*** In buck mode V_l acts as source and V_h as load. This mode is shown in Fig. 4 in which S_1 and S_2 are in ON state, inductors are discharging and capacitors are charging in this mode.

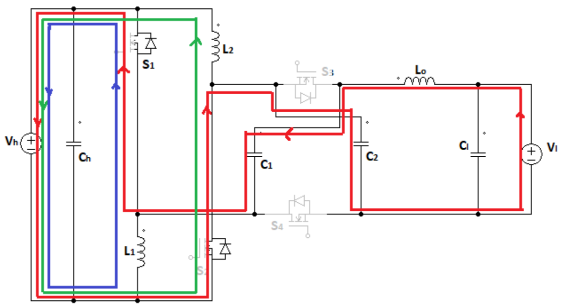

Fig 4: Stage 1

*2)**Stage 2:*** Fig. 5 Stage 2 in buck operation. Here S_3 and S_4 gets turned ON and other two switches in OFF state. Both the inductors are charging and capacitors are discharging through the load.

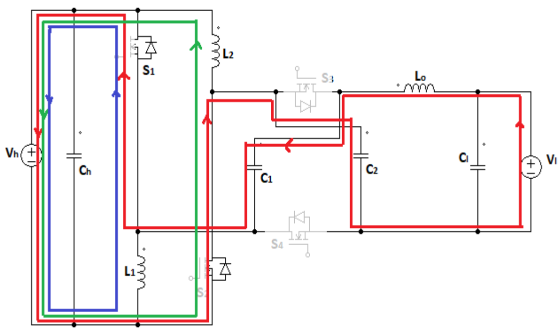

Fig 5: Stage 2

The maximum current values of inductors are calculated by (I_{LP} &I_{LOP}) adding their ripples to their respective minimum values ($I_{L(\min)}$&$I_{LO(min)}$).

$$I_{LP} = I_{L1P} = I_{L2P} = \frac{V_h D}{f_s L} + I_{L(min)} \qquad (6)$$

$$I_{LPO} = \frac{2V_h D}{f_s L_O} + I_{LO(min)} \qquad (7)$$

$$I_{L(min)} = I_{L1(min)} = I_{L2(min)} = \frac{V_h + V_C D_x}{2 f_s L} + I_{LP} \qquad (8)$$

$$I_{LO(min)} = \frac{-(V_C + V_l) D_x}{f_s L_O} + I_{LOP} \qquad (9)$$

Current through L_O

$$I_{LO(min)} = -I_{L(min)} \qquad (10)$$

Combining (6) and (8)

$$D_x = \frac{-2V_h D}{V_h + V_C} \qquad (11)$$

Associate (7),(9) and (11)

$$V_C = \frac{-(V_O + V_h)}{2} \qquad (12)$$

Replacing (12) in (2)

$$V_{LO} = 2V_l$$

And thus obtain

$$L_O = \frac{2V_h D}{f_s \Delta I_{LO}} \qquad (13)$$

Where

$$I_{LO} = \frac{1-D}{2D+3} * \frac{P_O}{V_h D} \qquad (14)$$

$$L = \frac{V_h D}{f_s \Delta I_L} \qquad (15)$$

$$I_h = (2I_L + I_{LO})D + I_L(1-D) \qquad (16)$$

$$I_L = \frac{3D+2}{2D^2+5D+3} * \frac{P_O}{V_h} \qquad (17)$$

$$C = \frac{(1-D)D}{(2D^2+3D) f_s \Delta V_C} * \frac{P_O}{V_h} \qquad (18)$$

Also

$$V_C = \frac{V_h(1+D)}{(1-D)} \qquad (19)$$

III. SIMULATION AND EXPERIMENTAL RESULTS

In order to validate the performance of the proposed bidirectional DC-DC converter, MATLAB simulations and experiments are carried out. The designed parameters are listed in TABLE I. Duty ratio for switches S_1 and S_2 are given as 75% and for remaining two switches is 25% for both buck and boost operation. In boost mode the R load is selected as 933Ω and that of buck mode it is 5Ω. The simulation results are shown below

TABLE I
SIMULATION PARAMETERS

System Specification	Parameters
Low Side Voltage (V_l)	32 V
High Side Voltage (V_h)	432 V
Switching Frequency (f_s)	50 kHz
Rated Power (P)	200 W
L_1 and L_2	410 µH
L_o	5.93 mH
C_o, C1 and C_2	1 µF

A. Simulation Results of Boost Mode

Bidirectional converter is working in boost mode with an input voltage of 32 V. An output voltage of 411.8 V is getting in the load side. Here 933Ω resistance load is used. Voltage and current waveforms of input and output are given in Fig. 6. Output voltage and current ripples are also shown in the same figure, it is found that ripples are less than 1%.

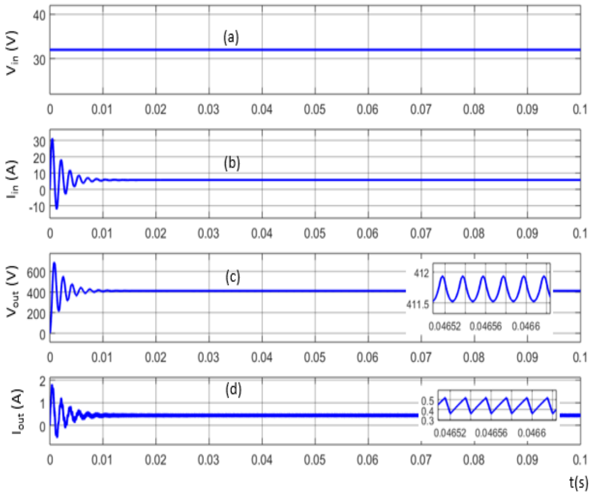

Fig 6: (a)Input Voltage (b)Input Current (c)Output Voltage (d)Output Current

Gate pulses for switches and corresponding voltage stresses are shown in Fig. 7. For switches S_1 and S_2 75% duty ratio is chosen and voltage stress is nearly 29% of output voltage and for switches S_3 and S_4 duty ratio is 25% and voltage stress is 60% of output voltage.

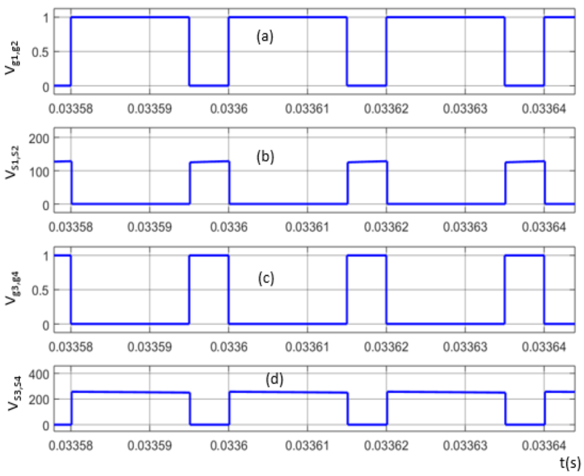

Fig 7: (a)Gate Pulse for Switches S_1 and S_2 (b)Voltage Stress for S_1 and S_2 (c)Gate Pulse for Switches S_3 and S_4 (b)Voltage Stress for S_3 and S_4

Voltage across capacitors and current through inductors are shown in Fig. 8.

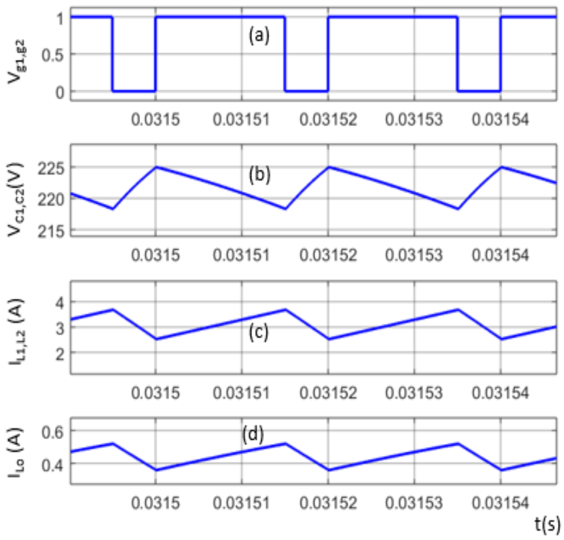

Fig 8: (a)Gate Pulse for Switches S_1 and S_2 (b)Voltage across capacitors (c)&(d)Current through inductors

B. Simulation Results of Buck Mode

The simulation results of bidirectional converter operating in buck mode is shown here. R load of 5Ω is used in the load side for an input voltage of 432 V. Output voltage obtained from simulation is 33.17V.

Fig. 9 shows input and output voltage and current waveforms. Ripples of voltage and current are also given which are less than 1%.

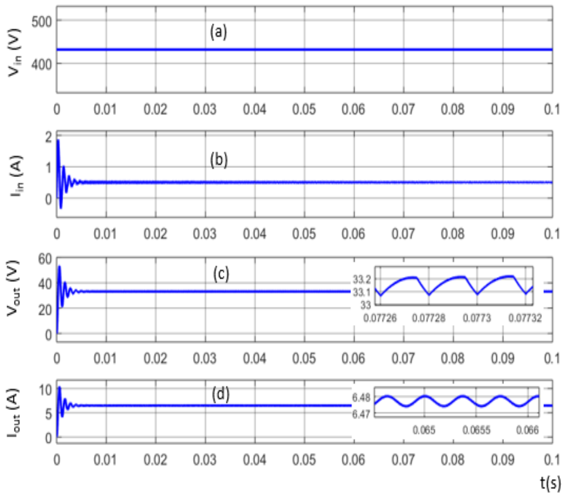

Fig 9: (a)Input Voltage (b)Input Current (c)Output Voltage (d)Output Current

Voltage across capacitors and current through inductors are shown in Fig. 10. Gate pulses for all switches and voltage stresses are same as in boost operation.

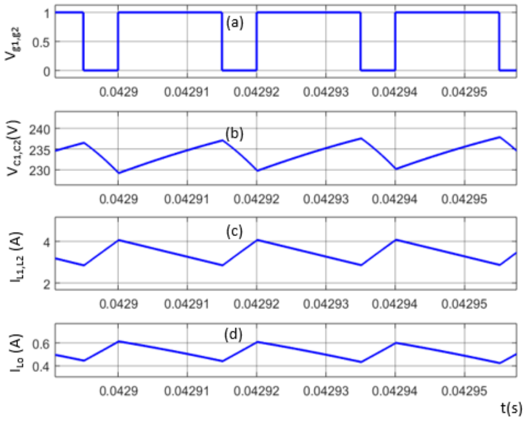

Fig 10: (a)Gate Pulse for Switches S_1 and S_2 (b)Voltage across capacitors (c)&(d)Current through inductors

C. Analysis of the Converter

Voltage gain versus duty ratio curve is plotted in Fig. 11. Here voltage gain increases as duty ratio increases for boost operation, while voltage gain decreasing with respect to duty ratio for buck operation.

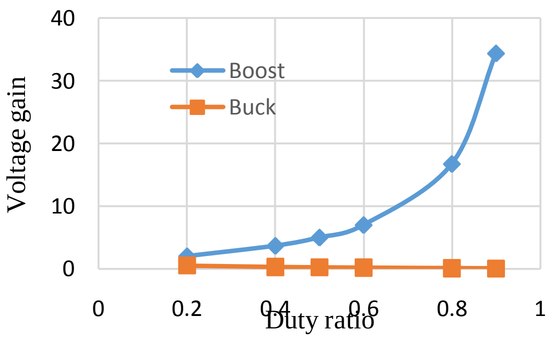

Fig 11: Voltage gain Vs Duty ratio

The variation of efficiency with load is shown in Fig. 12 and Fig. 13. For boost operation efficiency increases slightly with respect to load in Fig.12, while efficiency is decreasing in buck operation shown in Fig. 13.

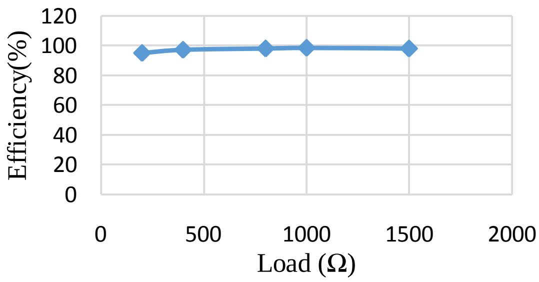

Fig 12: Efficiency Vs R load for Boost Operation

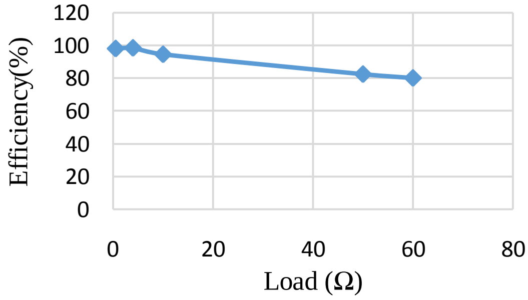

Fig13: Efficiency Vs R load for Buck Operation

IV. EXPERIMENTAL RESULTS

Inorder to verify the performance of the bidirectional DC-DC converter the experimental setup is implemented. A 5W prototype is implemented in the laboratory.The prototype with the parameters given in TABLE II was built. The power supply consist of astep down transformer, full bridge diode rectifier, filter capacitor and a regulator IC (7812). IRF540 MOSFET is used as switches. TLP250 driver isused to drive the MOSFET. To generate the switching signal PIC16F8771A was programmed in the laboratory and necessary waveforms are obtained. The switches are working in 10kHz frequency and have a duty ratio of 0.75 and 0.25. An output voltage of 4.73V is obtained from buck operation and 24.6V obtained from boost operation. The experimental test setup is presented in Fig. 14 and results of buck and boost operations are given in Fig. 15 and Fig. 16 respectively.

TABLE II
COMPONENTS USED FOR PROTOTYPE

Components	Ratings
Low Side Voltage (V_l)	2 V
High Side Voltage (V_h)	27 V
Switching Frequency (f_s)	10 kHz
Rated Power (P)	5 W
L_1 and L_2	446 µH
L_o	4.63 mH
C_0, C1 and C_2	20 µF

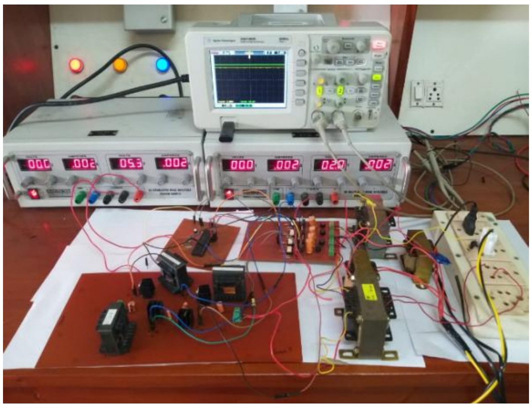

Fig 14: Experimental Setup

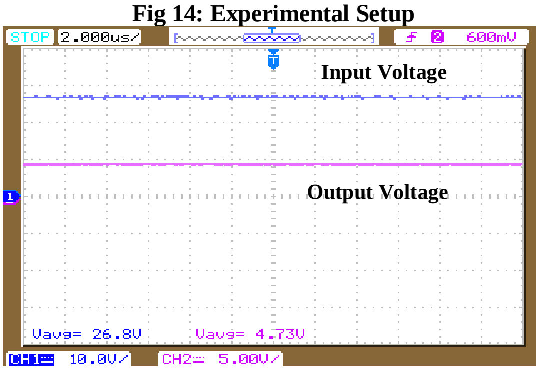

Fig 15: Output Voltage for Buck Operation

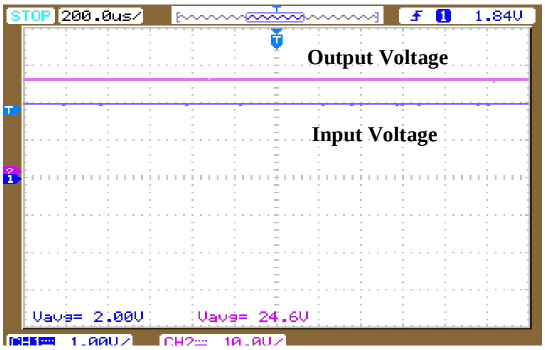

Fig 16: Output Voltage for Boost Operation

V. CONCLUSIONS

In this project a bidirectional DC-DC converter with switched-inductor and switched-capacitor cell is presented. The DC-DC converter presented here has a high step-up conversion ratio of12.86 in boost mode and high step-down conversion ratio of 0.076 in buck mode. The converter using a reduced number ofsemiconductors and a simple structure, which provides current flow just in two switchesduring the switch-on stage. It connects a low voltage super capacitor anda high voltage DC bus allowing bidirectional energytransfer, and smooth transition between the step-up and thestep-down mode. Smaller blocking voltage across the switches which is nearly 32% of output voltage. The converter has an efficiency of 98% in boost mode and 97%in buck mode. The experimental prototype of the bidirectional converter is implemented and output voltages are verified.

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