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Design and Analysis of a New Bidirectional DC-DC Converter with Improved Voltage Gain for Electric Vehicles

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ABSTRACT

The powers between two DC sources are transferred in either direction by using bidirectional DC-DC converters (BDCs). Such converters are commonly used in applications, such as fuel-cell hybrid power systems, hybrid electric vehicle energy systems, battery chargers, photovoltaic hybrid power systems, and uninterrupted power supplies. Here, a new bidirectional DC-DC converter with high voltage gain in both buck and boost operating modes is proposed. This new BDC is obtained by replacing all the diodes in the Single Switch Transformer less DC-DC converter that uses $L^2C^3D^2$ network, with switches and controlling their pulses in buck and boost modes. It has the advantages of a lower voltage stress across the power switches, a wide voltage-gain range, and an absolute common ground. The operating principle, the voltage and current stresses on the power switches, the comparisons with the other converters and the controller design are also mentioned. The simulation is carried out using MATLAB/SIMULINK R2017a. Using FPGA controller, the pulses for the switches are generated and they are driven using TLP250.

Keywords: *BDCs, hybrid electric vehicles, wide voltage gain, common ground*

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I. INTRODUCTION

With the increase of per capita car ownership in the world, the increase in use of fossil fuel and which results in green- house gas emission are having a severe effect on the climate and environment. This leads to the hike in efforts to decrease the dependency on the depleting fossil fuels and the growing usage of clean energy sources. A lot of researches have been focused on the electrification of transportation means. New energy vehicles, electric vehicles (EVs) with hybrid energy sources are an important player in the clean energy vehicles segment. These vehicles have advantages such as clean electrical energy generation with zero emissions, high energy conversion efficiency, and a higher range compared to battery- powered EVs. The voltage level of hybrid energy sources for EVs is relatively low. In order to realize the matching of the voltage levels between the hybrid energy sources and the high- voltage DC bus, as well as the bidirectional power flow of energy sources, a wide voltage-gain range bidirectional DC- DC converter is needed to interface the energy sources and the DC bus. Bidirectional DC-DC converters are used to transfer the power between two DC sources in either direction.

Many bidirectional DC-DC converters have been researched. In [1] presented a new single-switch high step-up DC-DC converter for fuel cell vehicles. The proposed topology utilizes a $L^2D^2C^2$ network to obtain high voltage gain and reduce the voltage stress on the power switch. Additionally, the proposed converter has a universal input voltage in order to suit the soft output characteristics of the fuel cell. This converter is used to interface fuel cell to the DC link of the inverter. A common ground switched-quasi-Z-source bidirectional DC-DC converter for electric vehicles with hybrid energy sources is explained in [2]. This converter is based on the traditional two-level quasi-Z-source bidirectional DC-DC converter, changing the position of the main power switch. It has the advantages of a wide voltage-gain range, a lower voltage stress across the power switches, and an absolute common ground. As a result, the proposed converter can select the power switches with the low rated voltage, and the low on-state resistance, which in turn can improve the conversion efficiency. Simultaneously, the voltage-gain of the proposed converter is just reduced a bit, which can still meet the requirement of the application of EVs with hybrid energy sources. The absolutely common ground also avoids the additional du/dt issue between the input and output grounds, which is beneficial for the operation of the proposed converter. In order to match voltages between the fuel cell stacks and the DC link bus of fuel cell vehicles [3], a single-switch Boost DC-DC converter with diode-capacitor modules was proposed. The capacitors are charged in parallel and discharged in series. The wide voltage-gain range can be obtained by using a simple structure. The voltage stress across all the semiconductors is half of the output voltage, the voltage-gain is 2/(1-d), which is double that of the conventional Boost DC-DC converter, and the variation of the potential difference between the input and output grounds is very small. The configuration of the converter is simple in [5]. The voltage gain of the proposed converter is higher than the conventional bidirectional DC-DC buck/boost converter in the step-up mode. In addition, the voltage gain is lower than the conventional buck/boost in step-down mode.

Because of better gain performance of the proposed converter in comparison of the conventional converter it can work in wide voltage range than conventional converter. Therefore, the proposed converter is applicable than conventional bidirectional converter. Owing to simple structure, the control of the proposed converter is quite easy. In this paper a new Transformerless Bidirectional DC-DC converter with high voltage gain in both buck and boost operating modes is proposed. This new BDC is obtained by controlling the pulses of the power switches in buck and boost modes. It has the advantages of a wide voltage-gain range, a lower voltage stress across the power switches, and an absolute common ground.

The structure of the paper is organized as follows. Section 2 introduces the configuration of the proposed converter and analyzes the operating principle in detail. The design and analysis of the converter are given in Section 3. The experimental results and analysis are shown in Section 4. Finally, Section 5 presents conclusions.

II. CONFIGURATION AND OPERATING PRINCIPLE OF THE PROPOSED CONVERTER

A. *Configuration of the Proposed Converter*

Fig.1 shows the circuit diagram of the new transformerless bidirectional DC-DC converter. This topology can be used in hybrid electric vehicles with battery-supercapacitor combination. The converter has four power switches namely S_1, S_{a1}, S_{a2} and S_2, high or low voltage side filter capacitors, three inductors (L_1,L_2 and L_3), four capacitors (C_1, C_2, C_3 and C_4) , and R represents a resistive load. The converter can operate either in the step-up (Boost) or in the step-down (Buck) mode, enabling the bidirectional power flow between the high- voltage and low-voltage sides.

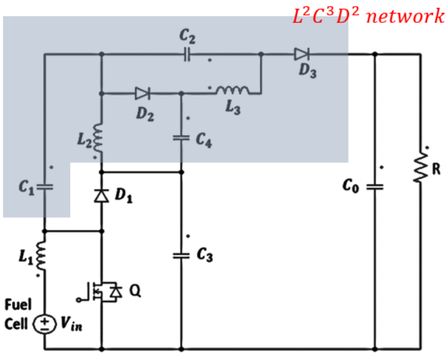

Fig. 1. Transformerless Bidirectional DC-DC Converter

B. Operating Principle of the Proposed Converter

The two main operating modes Mode I and Mode II of the proposed converter are analyzed as follows:

Mode I. Boost Mode of the Proposed Converter

In boost operating mode, S_1 operates as the main power switch and Sa_1, Sa_2 and S_2 are the synchronous rectifiers.

The typical waveforms of the proposed converter in continuous conduction mode (CCM) are shown in Fig.2, and the corresponding current flow paths in each switching states are illustrated in Fig.3 and Fig 4.

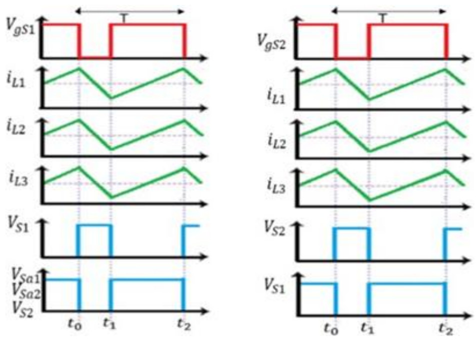

Fig. 2. Typical waveforms of the proposed converter. (a)Step-up mode (b) Step-down mode

SWITCHING STATE 1: (t_1-t_2)

This switching state takes place when the gate voltage V_{gs1} of the power switch SI is high with duty ratio D =70% and S_1 is turned on. Also, switches S_{a1}, S_{a2} and S_2 are OFF, i.e., no pulses are given to these switches. In this switching state, the three inductors L_1, L_2 and L_3 are charging, C_3 and C_4 are discharging, C_1 and C_2 are charging, and C_0 is discharging.

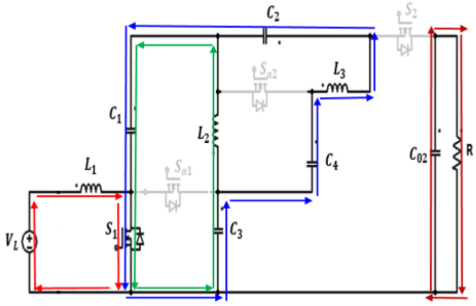

Fig. 3.Current-flow paths of the converter in the Boost mode State 1

SWITCHING STATE 2: (t_0-t_1)

This switching state takes place when V_{gs1} is low, and S_1 is turned off. But the current flows through the diodes of other power switches during this state. In this switching state, the three inductors are discharging, C_3 and C_4 are charging, C_1 and C_2 are discharging, and C_O is charging.

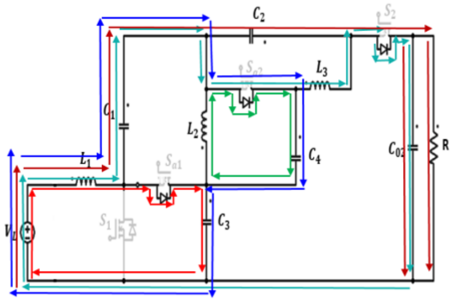

Fig. 4.Current-flow paths of the converter in the Boost mode State 2

Mode II. Buck Mode of the Proposed Converter:

In the buck operating mode, power switches S_2, S_{a1} and S_{a2} operates as the main power switches and S_{a1} act as the synchronous rectifier. The duty ratio of the gate signals D_{buck} is taken as (1- D_{boost}).This operating mode also has two different switching states. The corresponding current flow paths in each switching states are illustrated in Fig. 5 and Fig 6.

SWITCHING STATE 1 :(t_1-t_2)

This switching state takes place when V_{gs2}, V_{gsa1} and V_{gsa2} of the power switches S_2, S_{a1} and S_{a2} are high with duty ratio D =30% , and these switches are turned ON. But no pulses are given to the power switch S_1. In this switching state, the three inductors L_1, L_2 and L_3 are charging, C_3 and C_4 are discharging and C_1 and C_2 are charging.

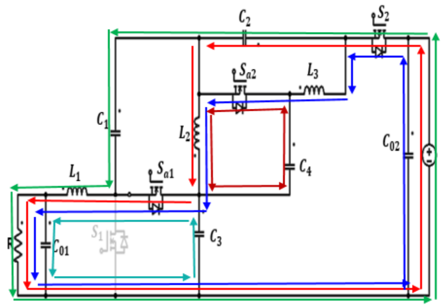

Fig. 5.Current-flow paths of the converter in the Buck mode State 1

SWITCHING STATE 2: (t_0-t_1)

This switching state takes place when V_{gs2}, V_{gsa1} and V_{gsa2} of the power switches S_2, S_{a1} and S_{a2} are low and these switches are turned OFF.

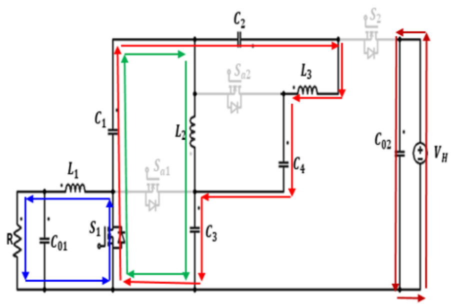

Fig. 6.Current-flow paths of the converter in the Buck mode State 2

III. DESIGN OF THE COMPONENTS

The bidirectional Buck and Boost converter is designed at 50V (low voltage) V_L and 400V (high voltage) V_H . The converter operates at 100kHz and an output power of 1.6kW.

A. Duty Ratio D in Buck and Boost Modes

The duty ratio D_{boost} in boost mode is calculated as follows [2];

$$V_H = \frac{1+2D_{boost}}{1-D_{boost}} * V_L \quad ; \quad D_{boost} = 0.70 \quad \text{….(1)}$$

and the duty ratio D_{buck} in Buck mode is obtained as below[2];

$$D_{buck} = 1 - D_{boost} = 0.30 \quad \text{….(2)}$$

B. Load Resistor R

Taking P_o as 1.6kW and output voltage as 400 V, for boost mode, load resistance is calculated as

$$R = \frac{V_0^2}{P_0} = \frac{400^2}{1.6*10^3} = 100\Omega \quad ....(3)$$

Choose R = 100 Ω for Boost mode.
Taking P_o as 1.6 kW and output voltage as 50 V, for Buck mode , load resistance is calculated as

$$R = \frac{V_0^2}{P_0} = 2\Omega \quad ....(4)$$

Choose R_0 = 2 Ω for Buck mode.

C. Inductors L_1, L_2 and L_3

Let the current through inductor $L1$ be,

$$I_{L1} = I_{in} = 32A \quad ...(5)$$

Also,

$$I_{L2} = I_{L3} = I_o = 4A \quad ...(6)$$

Assume ripple current Δi_L = 25% of I_L
Therefore,
ΔI_{L1} =8A and $\Delta I_{L2} = \Delta I_{L3}$ = 1A

Now, according to [1]

$$L_1 \geq \frac{DV_{in}}{f_s \Delta i_{L1}} \geq 43.75\mu H \quad ...(7)$$

Similarly,

$$L_2 = L_3 \geq \frac{DV_{in}}{f_s \Delta i_{L2}} = 350\mu H \quad ...(8)$$

Choose L_1=50 µH and L_2= L_3= 350µH

D. Capacitors C_1, C_2, C_3 and C_4

Let

$$V_{C1} = V_{C2} = V_{C4} = \frac{D}{1-D} * V_{in} = 116.6\ V \quad ...(9)$$

and

$$V_{C3} = \frac{1}{1-D} * V_{in} = 166.6\ V \quad ...(10)$$

Assume $\Delta V_{C1} = \Delta V_{C2}$ = 2% of ΔV_C,
Therefore, $\Delta V_{C1} = \Delta V_{C2}$ = 2.4V

$$C_1 = C_2 \geq \frac{2I_0 d}{f_s \Delta V_C} \geq 24.34\mu F \quad ...(11)$$

Choose $C_1 = C_2 = 40\ \mu$ F
Assume, $\Delta V_{C3} = \Delta V_{C4}$ = 0.5% of ΔV_C
Therefore,

$$C_3 = C_4 \geq \frac{2I_0 d}{f_s \Delta V_C} \geq 214\ \mu F \quad ....(12)$$

Therefore, choose $C_3 = C_4 = 220\mu$ F

IV. SIMULATION RESULTS AND ANALYSIS

A. Simulation Results of the Converter

Simulation parameters for the proposed bidirectional transformerless DC-DC converter are given in Table 1. A low voltage V_L of 50 V and high voltage V_H of 400 V for an output power P_0 of 1.6 kW is chosen. The switches are MOSFETs with constant switching frequency of 100 kHz.

TABLE I
SIMULATION PARAMETERS OF THE BIDIRECTIONAL CONVERTER

Parameters	Specifications
Rated Power (P_o)	1.6kW
Switching frequency (f_s)	100kHz
Low voltage(V_L)	50V
High voltage	400V
Inductor (L_1)	50µH
Inductors (L_2,L_3)	350µH
Capacitors(C_1,C_2)	40µF
Capacitors(C_3,C_4)	220µF
Capacitor(C_o)	240µF
Load(R) in Boost mode	100Ω
Load(R) in Buck mode	2Ω

Fig 7.shows the input voltage V_{in} and input current I_{in} and its zoom version for the BDC on Boost mode of operation. Input voltage V_{in} is 50V and input current I_{in} is about 28.59A. Input current has a ripple of 6.15A.

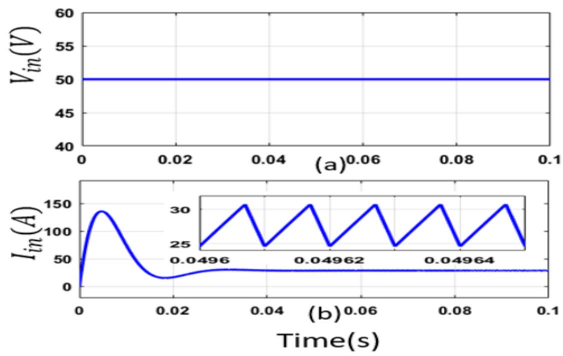

Fig 7. (a) Input Voltage (V_{in}) (b) Input current (I_{in})

Fig8. shows the output voltage(V_{out}) and output current(I_{out}) and its zoom version for the BDC on Boost mode of operation. Output voltage (V_{out}) is about 352.3V and has a ripple of 0.102V. Output current I_{out} is about 3.523A and output current ripple is in the range of 0.001A.

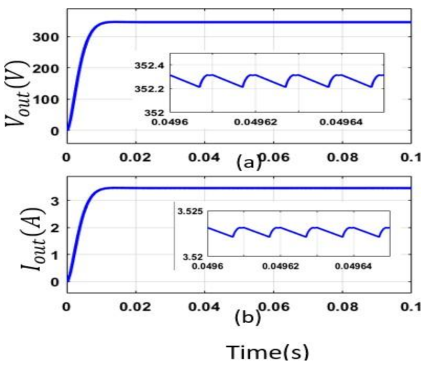

Fig 8. (a) Output Voltage (V_{out}) (b) Output current (I_{out})

The duty ratio of switch S_1 is equal to 0.70 as per the design. Fig 9.shows the gate pulse and voltage across the switch S_1. Comparing with the conventional Boost converter, the voltage stress of the main switch S_1 decreased about 57V.

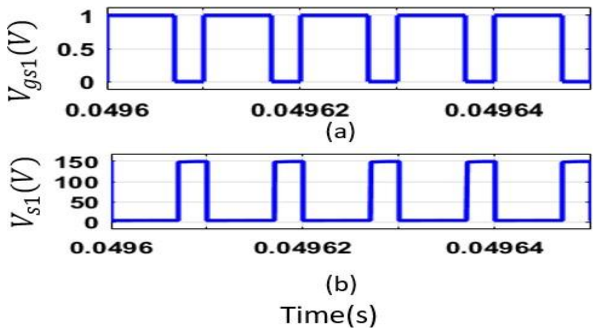

Fig. 9. (a)Gate pulse (V_{gS1}) (b) Voltage across switch (V_{S1})

Fig 10. shows the voltage stresses across the other main switches, i.e., S_{a1}, S_{a2} and S_2. All these three switches have a voltage stress of 146V.

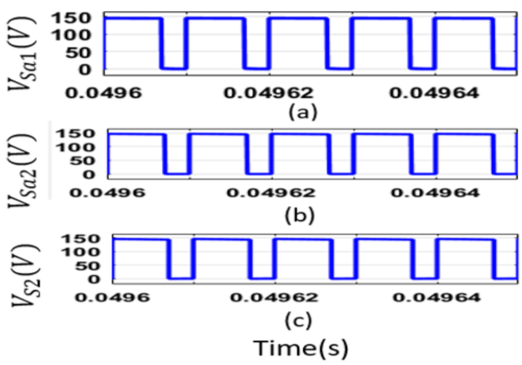

Fig. 10. (a) Voltage across (S_{a1}) (b) Voltage across (S_{a2}) and (c)Voltage across (S_2)

In buck mode of operation the switches Sa1, Sa2 and S_2 acts as the main switches and no pulse is given to S_1. The duty ratios of the main switches are 0.30.

Fig 11.shows the input voltage (V_{in}) and input current (I_{in}) and its zoom version for the BDC on Buck mode of operation. Input voltage V_{in} is 400V and input current I_{in} is about 3.5A. Input current has a ripple of 2.075A.

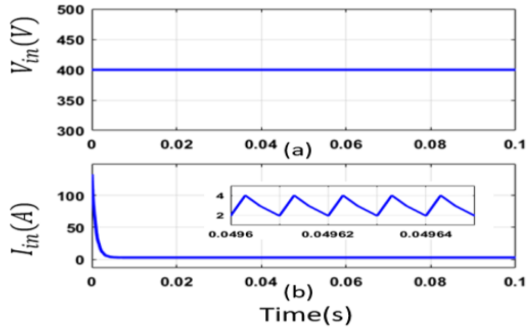

Fig. 11. (a) Input Voltage (V_{in}), (b) Input Current (I_{in})

Fig 12.shows the output voltage (V_{out}) and output current (I_{out}) and its zoom version for the BDC on Buck mode of operation. Output voltage (V_{out}) is about 47V and has a ripple of 0.004V. Output current I_{out} is about 23.5A and output current ripple is in the range of 0.0024A.

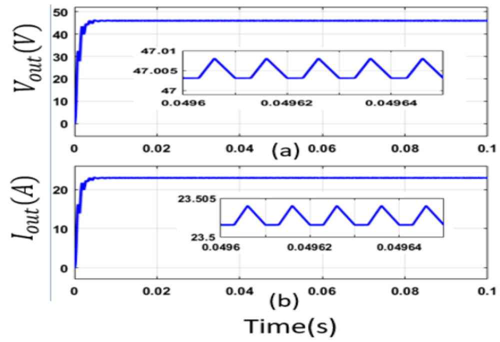

Fig. 12. (a) Output Voltage (V_{out}) and (b) Output Current (I_{out})

The duty ratio of main switch S_2 is equal to 0.30 as per the design. Fig 13.shows the gate pulse and voltage across the switch S_2. The voltage stress of the main switch S_2 is about 167V. Similarly, the gate pulses and voltage stresses of the switches S_{a2} and S_{a1} are shown in Fig 14.and Fig 15. respectively. Both these switches have the same duty ratio as the main switch S_1, i.e., 0.30.

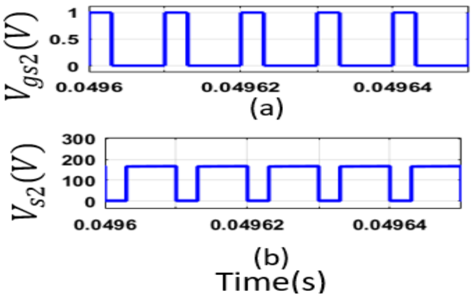

Fig. 13. (a)Gate pulse (V_{gS2}) and (b) Voltage across switch (V_{S2})

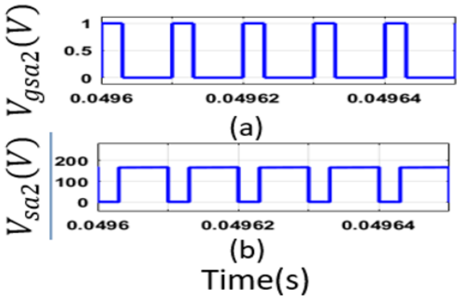

Fig. 14. (a)Gate pulse (V_{gSa2}) and (b) Voltage across switch (V_{Sa2})

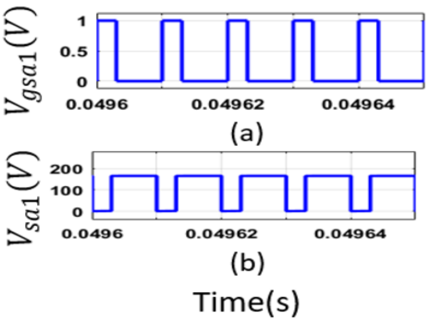

Fig. 15.(a)Gate pulse (V_{gSa1}) and (b) Voltage across switch (V_{Sa1})

B. Analysis of the Converter

The efficiency is the fraction of the input power delivered to the load. A typical curve for the variation of efficiency as a function of input voltage for 3 different output powers are shown in Fig 16.

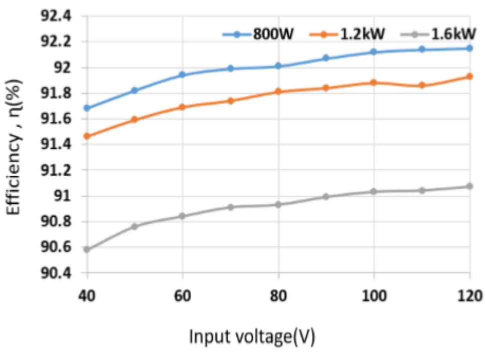

Fig. 16. Efficiency of the converter

The converter efficiency is around 90.76% for the designed output power of 1.6kW for R load.

Fig 17.shows the graphical comparison between different converters as a function of voltage gain and duty ratio. It is clear that voltage gain increases as the duty ratio varies from 0.1 and 0.9 which indicates the high step-up/step-down capability of the converter.

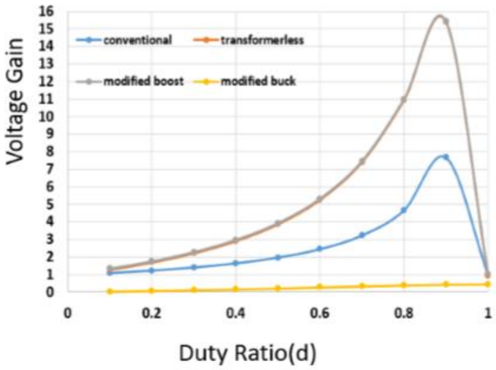

Fig. 17. Gain Vs Duty ratio of the converter

The graphical comparison between efficiency and duty ratio is shown in Fig 18. It is clear from the graph that the converter efficiency is maximum for the designed duty ratios i.e., 70% for the Boost mode and 30% for the Buck mode. The efficiency is about 91.23% for Boost operating mode and 90.6% for the Buck operating mode.

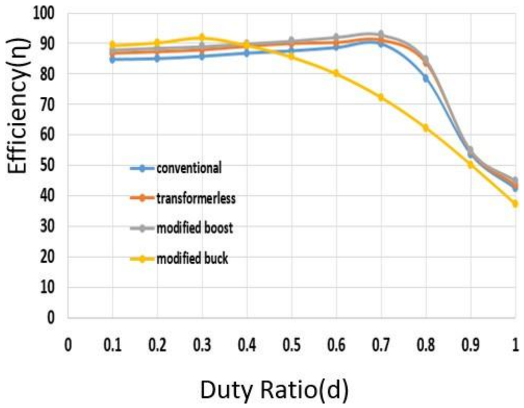

Fig. 18. Gain Vs Duty ratio of the converter

The comparison between conventional converter, Single Switch Transformerless Converter[1] and the modified Bidirectional converter is given in Table 2. Here the proposed converter is compared with other non-isolated converters. The voltage gain, the voltage stress across the semiconductor devices, component count, and the voltage gain range of these converters are summarized.

TABLE II
COMPARISON BETWEEN CONVERTERS

Parameters	Conventional boost	Single switch transformerless converter	Modified bidirectional	
			Boost	Buck
Power switches	1	1	4	4
Power diodes	1	3	0	0
Voltage gain	3.014	6.99	7.046	0.117
Efficiency	89%	90.76%	91.23%	90.6%
Voltage stress on main switch	206V	149.3V	149.5V	167.3V
Current stress on switch	24.8A	37.65A	37.1A	12.2A
Input current ripple	6.3A	6.1A	6.15A	2.075A
Output voltage ripple	0.4A	0.1A	0.102A	0.004A
Output current ripple	3.5A	0.001A	0.001A	0.0024A

It is observed from the above discussions that in the modified bidirectional DC-DC converter, the voltage stresses on the switches are reduced and the efficiency is improved to about 97%. Also, the output voltage and output current ripple is reduced to a desirable value.

V. CONCLUSION

A transformerless bidirectional DC-DC converter for electric vehicles with the hybrid energy sources is proposed. The proposed converter benefits from a wide voltage-gain range in step-up and step-down modes and an absolute common ground. In addition, the bidirectional converter has a simple structure with four active power switches, their voltage stress is lower and has an improved efficiency. Therefore, it can be applied as the power interface between the low-voltage battery pack/super capacitor bank and the high-voltage DC bus in the hybrid energy sources system for electric vehicles.

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