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A High Gain Bidirectional SEPIC Converter

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ABSTRACT
With increase in energy demand, the utilization of renewable energy sources like solar and wind energies become important. Energy storage systems with bidirectional converters are essential to overcome the intermittent nature of these renewable sources. In this a non-coupled inductor based SEPIC bidirectional converter having reduced ripple in output voltage and low voltage stress on switches are presented. The converter is simple and some auxiliary components are added to the conventional SEPIC topology to have a higher gain. The non- coupled SEPIC converter is modified into bidirectional SEPIC converter by replacing diodes with switches. The converter has many advantages such as high voltage gain, non-inverting output, continuous input current, high efficiency and lower voltage stress on the switches. Moreover, high voltage gain is achieved without using any transformer and coupled inductor, so there is no voltage over shoot for switches during the turn-off process. The number of components of introduced converter is comparatively lesser than other non-coupled inductor converter. The bidirectional converters are mainly used in applications such as battery charger/dischargers, renewable power systems, electric vehicles, uninterrupted power supplies and micro grid to improve dynamic response and stability of the system. The performance study of the converter is carried out with MATLAB/SIMULINK R2017a. Using FPGA controller pulses for the switches are obtained.
Keywords - SEPIC Converter, MOSFET, Non-Coupled Inductor, FPGA

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I. INTRODUCTION

Due to the rapid depletion of fossil fuels, effective utilization of alternate resources to meet the rising energy demand becomes important. The renewable energy resources, such as photovoltaic and wind power, are the best options for clean electric power generation. However, the intermittent nature of these resources introduces issues related to system stability, reliability, and power quality. Energy storage systems (ESSs) are required to deal with such issues. These ESSs should have bidirectional power flow capability to store the excess energy generated by renewable resources, and release it when the energy is not sufficient. The energy storage system play an important role in applications like renewable power systems, electric vehicles, uninterrupted power supplies and micro grid to improve dynamic response and stability of the system. For that a converter is necessary to transfer the energy in both ways. Bidirectional DC-DC converters allow transfer of power between two dc sources, in either direction. Due to their ability to reverse the direction of flow of power, they are being increasingly used in many applications such as battery charger/dischargers, dc uninterruptible power supplies, electrical vehicle motor drives, aerospace power systems, tele- com power supplies, etc. The single-ended primary inductor converter (SEPIC) and buck-boost converter have the ability to step up and step down the output voltage according to its duty cycle. A high gain converter with continuous input current is more ideal to track the maximum power point of PV panels. Therefore, the DC-DC converters which are used in renewable energy must benefit from high step-up voltage gain as well as continuous input current.

In [1] introduces a novel non-coupled inductor high voltage gain SEPIC converter. The converter is simple and modification of the SEPIC converter is accomplished by adding only four components. The converter has various advantages such as lower voltage stress on the switches, non-inverting output voltage, high efficiency, and high voltage gain. Also, the introduced converter has a continuous input current which makes it suitable for renewable energy and fuel cell applications. A novel switched-coupled inductor DC-DC step-up converter with high conversion ratio is presented in [2]. A coupled inductor is used to charge a switched capacitor, thus voltage gain can be effectively increased, and the turns ratio of the coupled inductor can be also reduced. The converter is simply composed of six components. A high step-up DC-DC converter based on the modified SEPIC converter is discussed in [3]. The converter has low switch voltage and high efficiency for low input voltage and high output voltage applications. The magnetic coupling allows to increase the static gain with a reduced switch voltage. The commutation losses of the proposed converter with magnetic coupling are reduced due to the presence of the transformer leakage inductance and the secondary voltage multiplier that operates as a non dissipative clamping circuit to the output diode voltage. In [4] presented a high step-up DC-DC converter with active switched-inductor and passive switched-capacitor networks. The main advantages of the proposed converter are the high voltage gain, reduced voltage stresses across the switches and reduced number of components when compared to topologies that provide the same voltage gain using similar principles. The main drawback of this converter is structure employs two isolated gate drivers, which suggests an additional cost.

This paper presents a new high voltage gain non-coupled inductor bidirectional SEPIC converter with simple topology and control strategy. The non-coupled SEPIC converter is modified into bidirectional SEPIC converter by replacing diodes with switches. High efficiency, low voltage stress, simple structure, non-inverting output voltage and high voltage gain are the features of the converter. The suggested converter is analyzed in continuous conduction mode. The low switch voltage stress offered by the converter allows the use of lower voltage rating MOSFETs to reduce both switching and conduction losses, thereby improving the overall efficiency. The output voltage ripple also can be reduced. In this converter capacitors are charged during the switch-off period using the energy stored in the inductors which increases the voltage transfer gain. The gating pulses for both of the switches are the same and a wide output voltage range can be achieved by changing the duty cycle. The number of the components and the voltage stress across the switches of the converter are less than the other non-coupled inductor SEPIC-based converters.

II. OPERATING PRINCIPLE OF PROPOSED CONVERTER

A. Configuration of proposed converter

A non-coupled inductor high voltage gain bidirectional SEPIC converter consists of dc voltage source V_{in}, four switches $S1$, $S2$, $S3$ and $S4$, three inductors $L1$, $L2$ and $L3$, two capacitors C_s and C_a, and output capacitor $C0$. Fig.1 shows a circuit of typical arrangement of non-coupled inductor high voltage gain bidirectional SEPIC converter. The two inductors $L1$ and $L2$ are connected in parallel during charging mode and are connected in series during discharging mode. The converter operates in continuous conduction mode (CCM) with the duty cycle of 0.74.

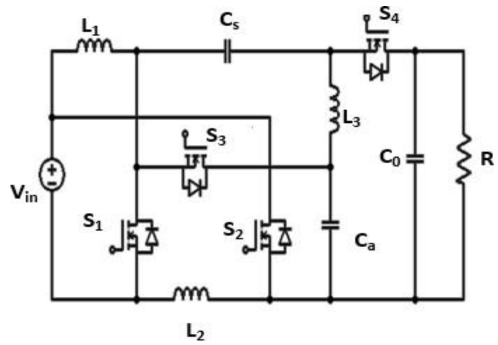

Fig.1. High Voltage Gain Bidirectional SEPIC Converter

B. Operating modes of the proposed converter

Bidirectional SEPIC converter operates in both boost and buck mode at a switching frequency of 40kHz.

Boost Mode

During boost mode, the input voltage is 20V and output voltage is 250V. The switches $S1$ and $S2$ are operating in this mode. The gate pulse given to the both the switches are same with duty cycle of 0.74.

Mode 1

In this mode, switches $S1$ and $S2$ are turned on simultaneously and switches $S3$ and $S4$ are turned off. During this mode input current is flowing through inductors $L1$ and $L2$ and they are in parallel. The energy is being stored in inductors $L1$, $L2$ and $L3$. The output load gets energy from the discharge of output capacitor $C0$. Fig. 2 shows the equivalent circuit diagram of the converter for mode 1 and current paths for this mode is also shown.

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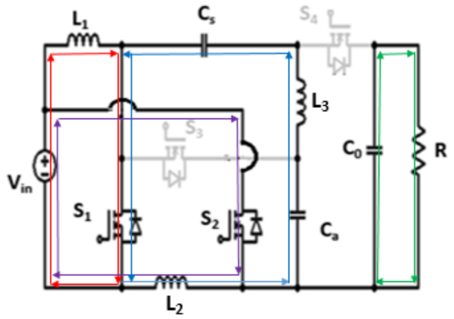

Fig. 2. Operating Circuit of Mode 1

Mode 2

In this mode, the switches $S1$ and $S2$ are turned off and the body diodes of the switches $S3$ and $S4$ are in forward biased condition. During this mode input voltage source V_{in} and the input inductors $L1$ and $L2$ are in series. The energy stored inductors are transferred to the load. The output capacitor $C0$ and load R are getting charged through the body diode of $S4$. This mode of operation ends when the switches $S1$ and $S2$ are turned on. Fig. 3 shows the equivalent circuit diagram of the converter for mode 2 and current paths for this mode is also shown.

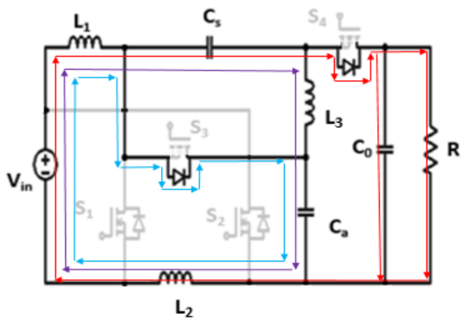

Fig. 3. Operating Circuit of Mode 2

The theoretical waveform of converter in boost mode is shown in Fig. 4.

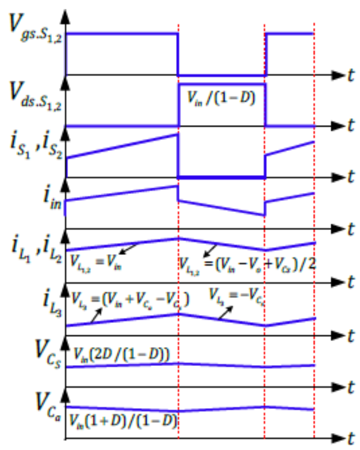

Fig.4. Theoretical wave form of converter in boost mode

Buck mode

In buck mode of operation the switches $S3$ and $S4$ act as the main switches with duty ratio of 0.26 and switches $S1$ and $S2$ are turned off with no pulse providing to them.

Mode 1

In this mode, switches $S3$ and $S4$ are turned on simultaneously and the body diodes of switches $S1$ and $S2$ are in reverse biased condition. During this mode input current is flowing through inductors $L1$, $L2$ and $L3$. The energy is being stored in inductors $L1$, $L2$ and $L3$. The output load gets energy from the discharge of output capacitor $C0$. Fig. 5 shows the equivalent circuit diagram of the converter for mode 1 and current paths for this mode is also shown.

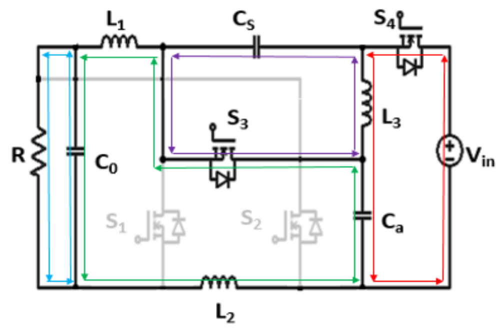

Fig. 5. Operating Circuit of Mode 1

Mode 2

In this mode, the switches $S3$ and $S4$ are turned off and the body diodes of switches $S1$ and $S2$ are in forward biased condition. During this mode, the energy stored inductors are transferred to the load by the body diodes of the switches $S1$ and $S2$. The output capacitor $C0$ and load R are getting charged through body diode of switch $S1$.This mode of operation ends when the switches $S3$ and $S4$ are turned on. Fig. 6 shows the equivalent circuit diagram of the converter for mode 2 and current paths for this mode is also shown. The theoretical waveforms of different modes during buck mode are shown in Fig. 7.

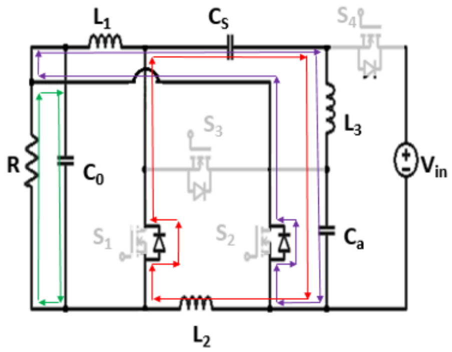

Fig. 6. Operating Circuit of Mode 2

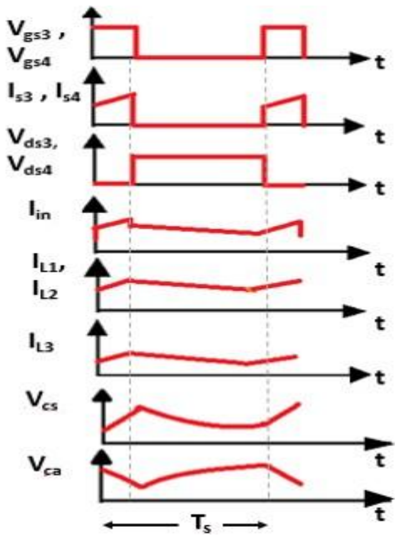

Fig.7. Theoretical wave form of converter in buck mode

III. DESIGN OF THE COMPONENTS

The bidirectional SEPIC converter is designed at 20V (low voltage) V_L and 250V (high voltage) V_H with an output power of 200W. The converter operates at 40 kHz

A. *Duty Ratio*

In boost mode, converter input voltage is 20V and the output voltage is 250V and vice versa in buck mode. The switching frequency is 40 kHz. For boost mode, the duty ratio is obtained as

$$D_{boost} = \frac{V_0 - V_{in}}{V_0 + 3V_{in}} \qquad (1)$$

For buck mode, the duty ratio is

$$D_{buck} = (1 - D_{boost}) \qquad (2)$$

B. *Inductors L_1 , L_2 and L_3*

Let the inductor ripple current be 20 % to 40 % of output
current. The rated output current is 0.8A.

$$L_1 = L_2 = \frac{V_{in} * D}{\Delta i_l f_s} \qquad (3)$$

$$L_3 = \frac{2 * V_{in} * D}{\Delta i_l f_s} \qquad (4)$$

C. *Capacitors C_s and C_a*

Let the capacitor voltage ripple is assumed as 10 % of nominal voltage capacitor C_S.

$$C_s = C_a = \frac{I_0}{\Delta V_C f_s} \qquad (5)$$

D. *Output Capacitor C_o*

Let the peak -peak output voltage ripple equal to (0.6 % to 1 %) of the output voltage.

$$C_o = \frac{I_0 * D}{\Delta V_C f_s}$$
(6)

IV. SIMULATION RESULTS AND ANALYSIS OF THE PROPOSED CONVERTER

A. *Simulation Results*

The high voltage gain non-coupled inductor bidirectional SEPIC converter is simulated in MATLAB/SIMULINK by choosing the parameters listed in TABLE I.

TABLE I
SIMULATION PARAMETERS

Parameters	**Specifications**
Low voltage (V_L)	20V
High voltage (V_H)	250V
Output power (P)	200W
Switching Frequency (F_s)	40kHz
Inductance (L_1, L_2)	123µH
Inductance (L_3)	246µH
Capacitor (C_s and C_a)	4µF
Output Capacitor (C_0)	15µF
Load Resistance (R) in boost mode	330Ω
Load Resistance (R) in buck mode	2Ω

Simulation results of the converter in boost mode is shown in the following figures. Fig. 8 shows the gate pulse and voltage stress across the switches $S1$ and $S2$ of the converter. The pulses given to both the switches are same with duty ratio of 0.74. The maximum voltage stress is 78V across the switches $S1$ and $S2$.

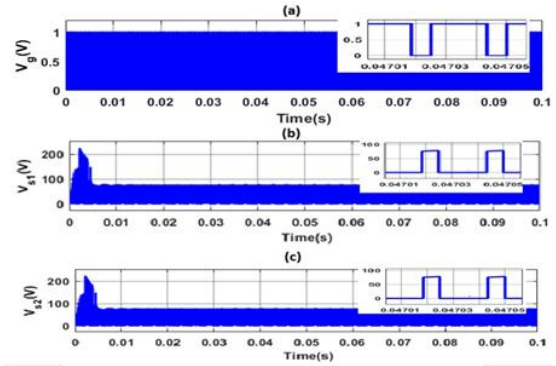

Fig. 8. Simulink result: (a) Gate pulse of S_1 and S_2, (b) Voltage stress across S_1 and (c) Voltage stress across S_2

Fig. 9 shows the input voltage V_{in} and the output voltage V_o. The input voltage is 20V and output voltage is 249.5V.
This verifies the high step up voltage gain of 12.5. The output voltage ripple is about 0.9V.

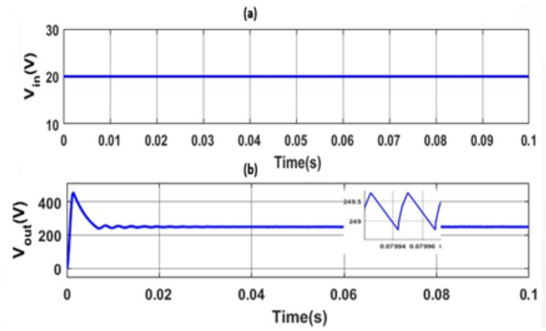

Fig. 9. Simulink result: (a) Input voltage (V_{in}) and (b) Output Voltage (V_o)

Fig. 10 shows the input current of 10A, an output current of 0.82A. The output ripple current is about 0.0032A. Fig. 10. Simulink result: (a) Input current (I_{in}) and (b) Output current (I_o)

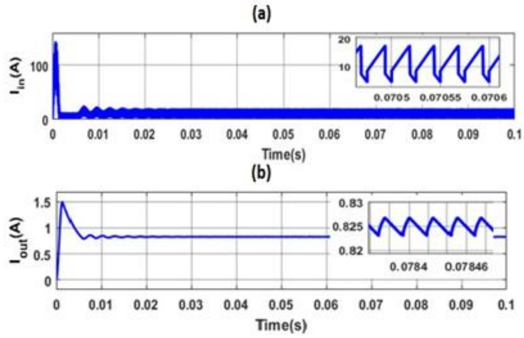

Fig. 10. Simulink result: (a) Input current (I_{in}) and (b) Output current (I_o)

Fig. 11 shows the currents I_{L1}, I_{L2} and I_{L3} through inductors $L1$, $L2$ and $L3$ respectively. The current through inductors $L1$ and $L2$ are same. The average currents of the inductors $L1$, $L2$ and $L3$ are 6A, 6A and 1.5A respectively. The inductor current ripple is about 3A.

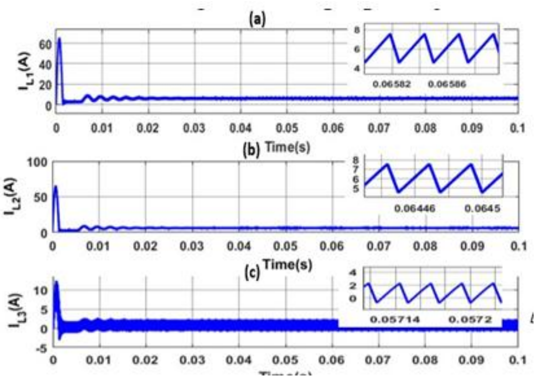

Fig. 11. Simulink result: Inductor current (a) I_{L1}, (b) I_{L3} and (c) I_{L2}

Simulation results of the converter in buck mode is shown in the following figures. Fig. 12 shows the gate pulse and voltage stress across the switches $S3$ and $S4$ of the converter. The pulses given to both the switches are same with duty ratio of 0.26. The maximum voltage stress is 150V across the switches $S3$ and $S4$.

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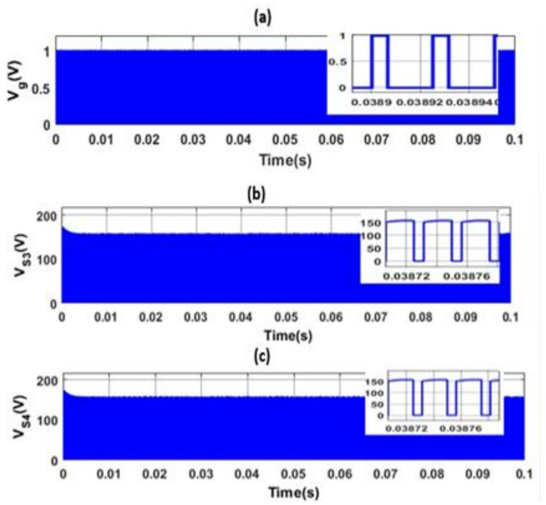

Fig. 12. Simulink result: (a) Gate pulse of S_3 and S_4, (b) Voltage stress across S_3 and (c) Voltage stress across S_4

Fig. 13 shows the input voltage V_{in} and the output voltage V_o. The input voltage is 250V and output voltage is 19.6V. This verifies the high step down voltage gain of 0.079.

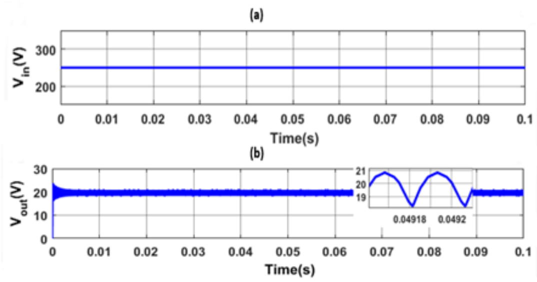

Fig. 13. Simulink result: (a) Input voltage (V_{in}) and (b) Output voltage (V_o)

Fig. 14 shows the input current of 0.79A, and output current of 9.5A.

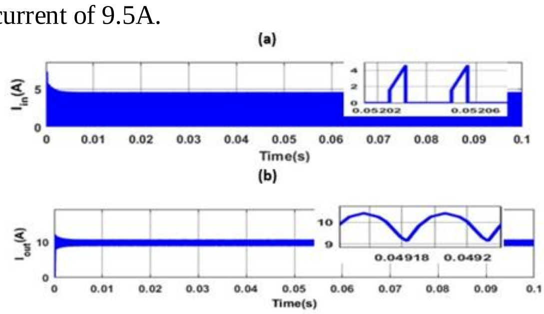

Fig. 14. Simulink result: (a) Input current (I_{in}) and (b) Output current (I_o)

Fig. 15 shows the currents I_{L1}, I_{L2} and I_{L3} through inductors $L1$, $L2$ and $L3$ respectively. The current through inductors $L1$ and $L2$ are same. The average currents of the inductors $L1$, $L2$ and $L3$ are 5A, 5A and 1.5A respectively. The inductor current ripple is about 3A.

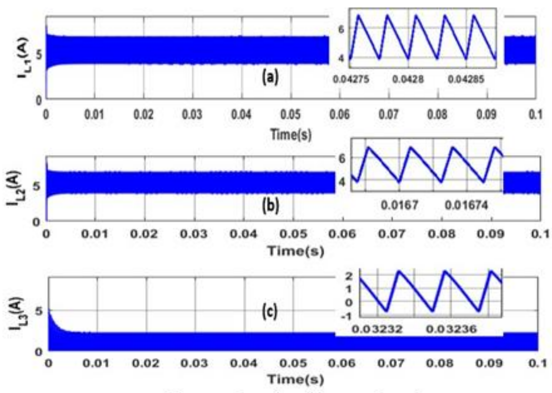

Fig. 15. Simulink result: Inductor current (a) I_{L1}, (b) I_{L3} and (c) I_{L2}

B. *Analysis*

The analysis of high voltage gain non-coupled inductor bidirectional SEPIC converter is carrried out by considering parameters like voltage gain, efficiency, voltage stress and duty cycle etc.

Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. The efficiency tells us the fraction of the input power delivered to the load. A typical curve for the variation of efficiency as a function of output power is shown in Fig. 16. The converter efficiency in boost mode is around 93.2% for 200 W output power for R load and in buck mode is around 93% for 200 W output power for R load.

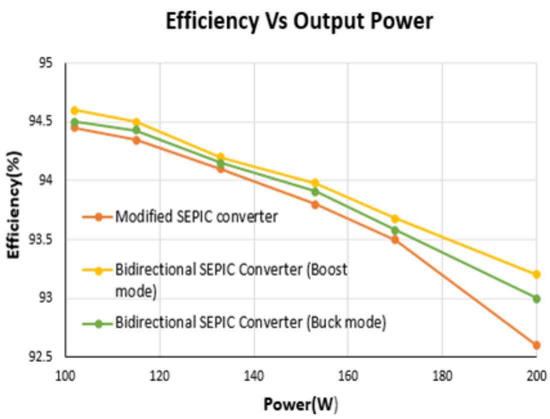

Fig. 16. Efficiency Vs Output Power

The plot of voltage gain as a function of duty cycle is shown in Fig. 17. According to figure, the voltage gain is 12.5 when the duty cycle is equal to 0.74.

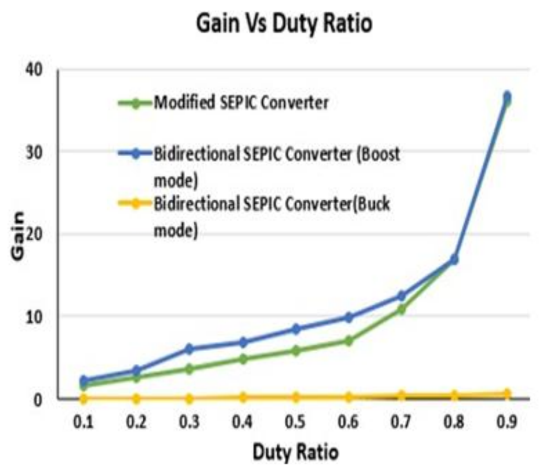

Fig. 17. Gain Vs Duty Ratio

The plot of power loss calculated across the components of high voltage gain non-coupled inductor bidirectional SEPIC converter is shown in Fig.18. The total loss of the converter is about 10W. In the modified converter, the diode losses are neglected but the diode losses are replaced by switches, the switching losses and conduction losses are increased.

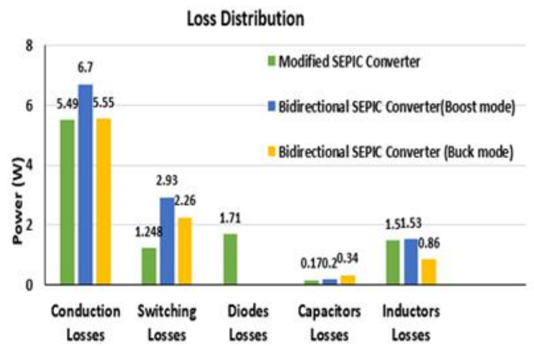

Fig.18. Power Loss Distribution Of Components

C. Comparison

The comparison of modified bidirectional SEPIC converter and other converters is given in Table II .

TABLE II COMPARISON

Parameters	**Boost Converter**	**Conventional SEPIC Converter**	**High Voltage Gain SEPIC Converter**	**Modified Bidirectional SEPIC Converter**
Voltage gain	3.84V	3.2	12.4	12.5
Voltage stress across the switch	76V	86V	78V	78V
Output voltage ripple	1V	0.8V	0.96V	0.9V
Output current ripple	0.0009A	0.0042A	0.0036A	0.0032A
Efficiency	89%	91%	92.6%	93.2%
No of switches	1	1	2	4
No of diodes	1	1	2	0

It is observed from the above discussions that in that in the modified bidirectional SEPIC converters the voltage stresses on the switches are reduced and a high step upvoltage is achieved. It can seen that converter achieves bidirectional property without changing the features of high voltage gain non- coupled inductor SEPIC converter.

V. CONCLUSION

A non-coupled inductor high voltage gain bidirectional SEPIC converter offers a high voltage gain, low switch voltage stress. This converter has many advantages such as continuous input current, high voltage gain, non-inverting output voltage and simple control system. The non-coupled SEPIC converter is modified into bidirectional SEPIC by replacing diodes with switches. It achieves an improved overall efficiency. The converter has a voltage gain of 12.5V. This converters has less no of components compared to the other converters. When the converter is in boost mode the input voltage is 20V and output voltage is 250V and similarly when the converter is in buck mode the input voltage is 250V and output voltage is 20V. The applications of bidirectional SEPIC converter include energy storage in renewable energy systems, fuel cell energy systems, hybrid electric vehicles (HEV) and uninterruptible power supplies (UPS).

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