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Non Isolated Bidirectional DC-DC Converter With High Voltage Gain

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Abstract: **Dependence of the extracted power of the photovoltaic (PV) and wind energies on environmental specifications and low dynamic response of Fuel cells cause a battery to be required in these systems. In order to charge and discharge the battery, a bidirectional converter is needed. In this paper, a non-isolated bidirectional DC-DC converter is presented. The converter consists of two boost converters to enhance the voltage gain. Four power switches are employed in the converter with their body diodes. Two inductors and a capacitor are also employed as passive components. The input current is divided to the inductor which causes the efficiency to be high and the size of them to become smaller. The voltage gain of the converter is higher than the Conventional Cascaded Bidirectional buck/boost Converter (CCBC) in step-up mode. Besides, the voltage gain in step-down mode is lower than CCBC. Circuit is simulated with 25/250V input voltage and 250/25V DC output voltage is verified. Performance parameters such as voltage stress and output ripples are also analyzed. The efficiency of the converter is more than CCBC while the total stress on active switches are same. The simulation is done in MATLAB R2014a.**

Keywords: **DC-DC converter, High voltage gain converter, Non-isolated bidirectional converter, Voltage Stress.**

I. INTRODUCTION

In recent years, renewable energies comprising fuel cell, wind energy, photovoltaic and so on, have been widely applied to obtain environment-friendly purposes. Besides, the development of bidirectional DC-DC converters has become urgent for clean-energy vehicle applications because battery-based energy storage systems are in need of cold starting and battery recharging. Bidirectional converters are used as transferor converters between two DC sources in both directions. Back-up power from the battery is supplied using a bidirectional converter because the battery should be charged and discharged. Therefore a bidirectional converter to charge and discharge battery is needed[1]. The bidirectional DC-DC converters are widely used for renewable energy systems, hybrid electric vehicle energy systems, uninterrupted power supplies (UPS), fuel-cell hybrid power systems, photovoltaic hybrid power systems, battery chargers aerospace power systems and many other industrial applications[2]. Dependence of the extracted power of the photovoltaic (PV) and wind energies on environmental specifications and low dynamic response of Fuel cells (F.C) cause a storage element (battery) to be required in these systems. In order to charge and discharge the battery, a bidirectional converter is needed. Bidirectional converters transfer energy between two sources in both directions [3]. Depending on the application, isolated and non-isolated bidirectional converters are applied. Some of the isolated types of the bidirectional DC-DC converters are the fly back converters [4], forward-fly back converters , half-bridge converters and full-bridge converters. Having large voltage gain in both step-up and step-down operation by adjusting the turn ratio of the transformers is one of the advantages of these converters. The fly back converters have simple structure and can be controlled easily. While the leakage-inductor energy cannot be recycled and the power switches of these converters suffer high-voltage stresses and the diodes at the secondary side of the converters have reverse recovery problem. In order to increase efficiency of these

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converters, the voltage clamp technique is applied to reduce voltage stresses on the switches and recycle the leakage-inductor energy in order to increase efficiency[5]. Non-isolated types of bidirectional converters comprise conventional boost-buck type, multilevel type, three-level type, switched capacitor type, Sepic-Zeta type and coupled inductor types. The multilevel type of converter has many switches. Also in the three-level type, voltage gain is low in both of step-up and step-down modes. The non-isolated types of these converters have been researched[6], which include the conventional boost/buck type, multilevel type, three-level type, sepic/zeta type, switched capacitor type and coupled inductor types. The multilevel types are magnetic less converters, but more switches are used in this converter. If voltage gain is needed to be higher in step-up mode and lower in step-down mode, more switches are required and also the control circuit of this converter would be more complicated. In the three-level type, step-up and step-down voltage gains are low. The converters with coupled inductors have also complicated configuration.

II. NON ISOLATED BIDIRECTIONAL DC-DC CONVERTER

A non-isolated bidirectional DC-DC converter is studied, which has simple structure and large voltage gain. It consists of two conventional boost converters. Four power switches are employed with their body diodes. In each direction, two of the switches are used as power switches and the others are used as the synchronous rectifiers. The input current is divided to the inductors which cause the size of them to become smaller. Consists of two conventional boost converters. The operation principle of the converter is also discussed.

Fig.1 shows the system configuration of the bidirectional converter, which has a capacitor, two inductors and four switch-diodes. Two of the switches work as power switches and the remainders are applied for the synchronous rectifiers. The steady-state analysis of the bidirectional converter in step-up and step-down modes is discussed as follows. In order to analyze the steady-state characteristics of the bidirectional converter, the ON-state resistance R_{DS}(ON) of the switches and the equivalent series resistances of the inductors and capacitors are ignored and the voltages of the capacitors are constant.

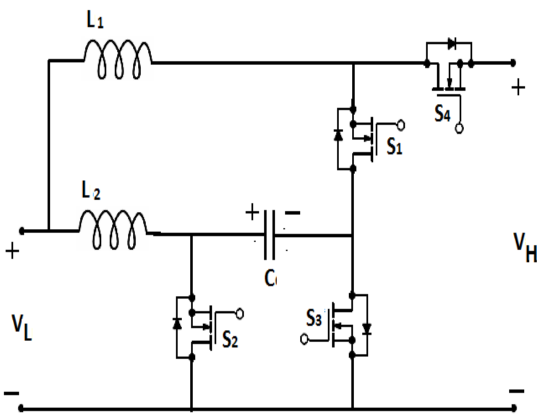

Fig.1. Circuit diagram

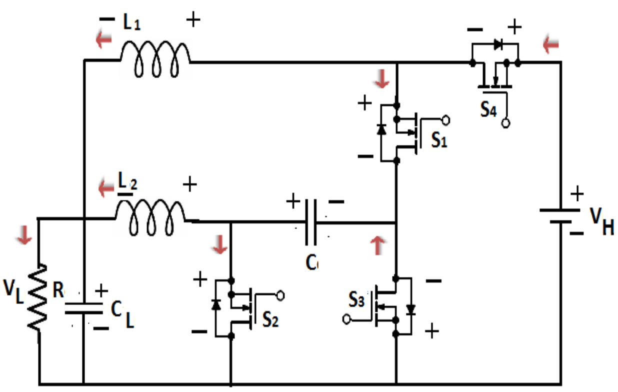

Fig.2. Equivalent circuit in the step-down mode

A. Step-Down Mode Of The Converter:

The non-isolated bidirectional DC-DC converter in step-down mode is shown in fig.2. In this operation mode, S_3 and S_4 work as power switches and switches S_1 and S_2 are the synchronous rectifiers.

(a). Mode 1[t_0 −t_1]

During this time interval $[t_0, t_1]$, S_3 and S_4 are turned on and S_1 and S_2 are turned off. The current-flow paths of the proposed converter are shown in fig.3. As seen in this figure, the energy of the DC source V_H is transferred to inductor L_1. Capacitor C is discharged to inductor L_2 and capacitor C_L. The characteristic waveforms of the proposed converter in continuous conduction mode (CCM) are depicted in fig.4. The following equations can be written in this mode:

$$V_{L1} = V_H - V_L \quad (1)$$

$$V_{L2} = V_C - V_L \quad (2)$$

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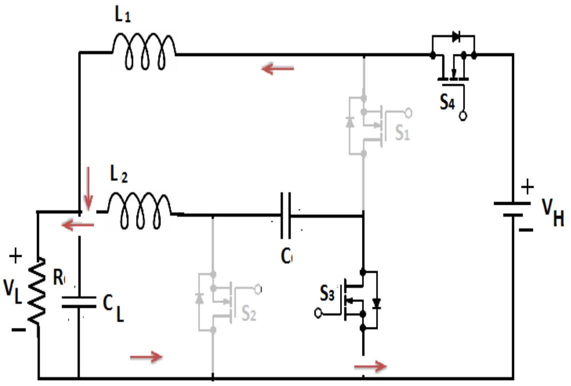

Fig. 3. Mode 1 operation in step-down mode

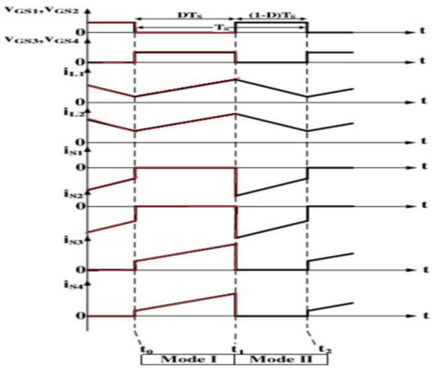

Fig. 4. Theoretical waveforms

(b). Mode 2[$t_1 - t_2$]

During this time interval $[t_1, t_2]$, S_1 and S_2 are turned on and S_3 and S_4 are turned off. The current-flow paths of the suggested converter are shown in fig.5. Inductor L_1 is demagnetized in this mode to capacitors C and C_L. Inductor L_2 is discharged to capacitor C_L and provides energy to the load. The characteristic waveforms of the proposed converter in continuous conduction mode (CCM) are depicted in fig.4. Therefore, the voltages of inductors L_1 and L_2 can be written as:

$$V_{L1} = -V_L - V_C \quad (3)$$

$$V_{L2} = -V_L \quad (4)$$

By applying volt-second balance principle on the inductor L_1 and L_2, and then simplifying we get the following equations:

$$\frac{V_C}{V_L} = \frac{1}{D} \quad (5)$$

$$\frac{V_H}{V_C} = \frac{1}{D} \quad (6)$$

Substituting Eqn(5) into Eqn(6), the voltage gain of the proposed converter in step-down mode can be obtained as:

$$G_{VCCMstp-down} = D^2 \quad (7)$$

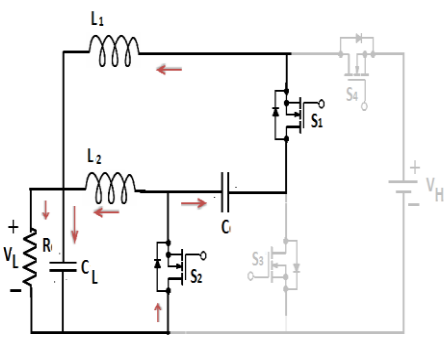

Fig. 5: Mode 2 operation in step-down mode

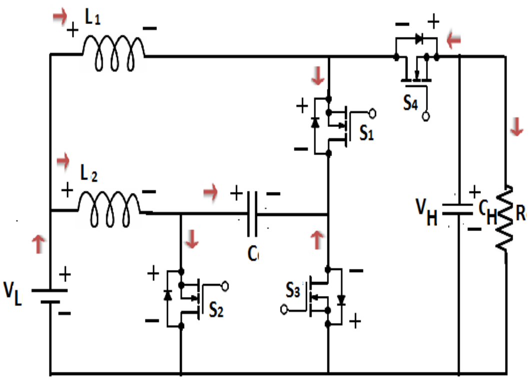

Fig. 6: Equivalent circuit in the step-up mode

B. Step-Up Mode Of The Converter:

The non-isolated bidirectional DC-DC converter in step-up mode is shown in fig.6. In this operation mode, S_1 and S_2 work as power switches and switches S_3 and S_4 are the synchronous rectifiers.

(a). Mode 1[$t_0 - t_1$]

During the interval $[t_0, t_1]$, S_1 and S_2 are turned on and S_3 and S_4 are turned off. As shown in fig.7, in this interval the energy of the DC source V_L is transferred to inductor L_2. Inductor L_1 is magnetized by the DC source V_L and the energy

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stored in capacitor C. Capacitor C_H is also discharged to the load. The following equations can be obtained in this mode. The characteristic waveforms of the proposed converter in continuous conduction mode (CCM) are depicted in fig.8. The following equations can be written in this mode.

$$V_{L1} = V_L + V_C \tag{8}$$

$$V_{L2} = V_L \tag{9}$$

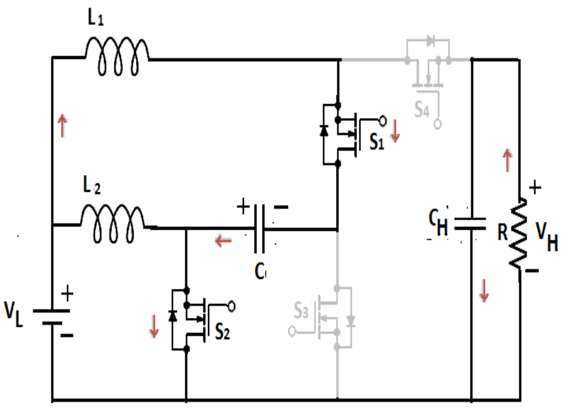

Fig. 7. Mode1 operation in step-up mode

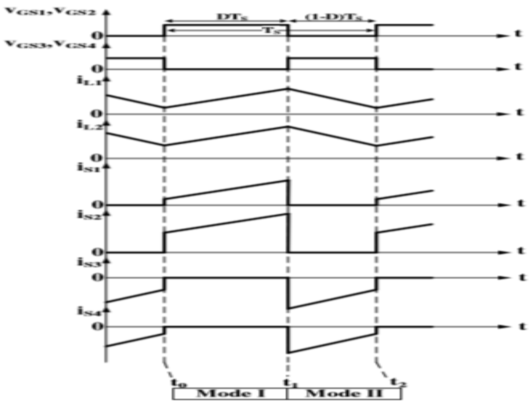

Fig. 8. Theoretical waveforms

(b). Mode 2[$t_1 - t_2$]

During the interval $[t_1, t_2]$, $S_1$and $S_2$are turned off and $S_3$and $S_4$are turned on. As shown in fig.9, capacitor C is charged by the input source V_L and the energy stored in inductor L_2. Capacitor C_H is also charged by the input source V_L. and the energy stored in inductor L_1. Therefore, the voltages across the inductors can be written as:

$$V_{L1} = V_L - V_H \tag{10}$$

$$V_{L2} = V_L - V_C \tag{11}$$

By applying volt-second balance principle on the inductor $L_1$and L_2, and then simplifying we get the following equations:

$$\frac{V_C}{V_L} = \frac{1}{1-D} \tag{12}$$

$$\frac{V_H}{V_C} = \frac{1}{1-D} \tag{13}$$

Substituting Eqn(12) into Eqn(13), the voltage gain of the proposed converter in step-down mode can be obtained as:

$$G_{VCCMstp-up} = \frac{1}{1-D^2} \tag{14}$$

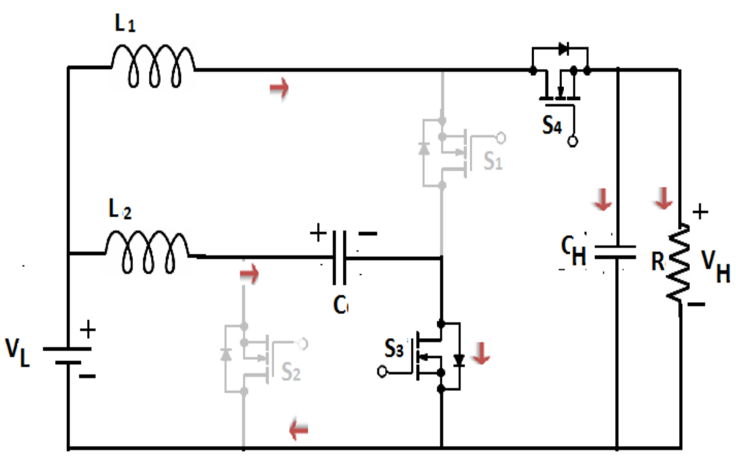

Fig. 9: Mode 2 operation in step-up mode

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III. SIMULATION MODEL AND RESULTS

In order to verify the operation principle and the theoretical analysis, a converter is simulated with MATLAB/SIMULINK simulation software and the simulation parameters are listed in Table.1. The simulation results of both step-up and step-down modes are presented in this section All switches using in simulation are ideal switches.

Table I: Simulation parameters

Parameters	Specifications
V_L	25 V
V_H	250 V
Switching Frequency	30 KHz
L_1	1.3 mH
L_2	500 mH
C_L, C_H, C	47µF, 220µF, 220µF
$P_{step-down}, P_{step-up}$	160 W,160 W

A. Simulink Model:

Fig.10 and fig.11 shows the simulink model of the converter in step-down mode and step-up mode respectively. In the step-down mode duty ratio, D is obtained as 0.316 and in step-up it is 0.6837.

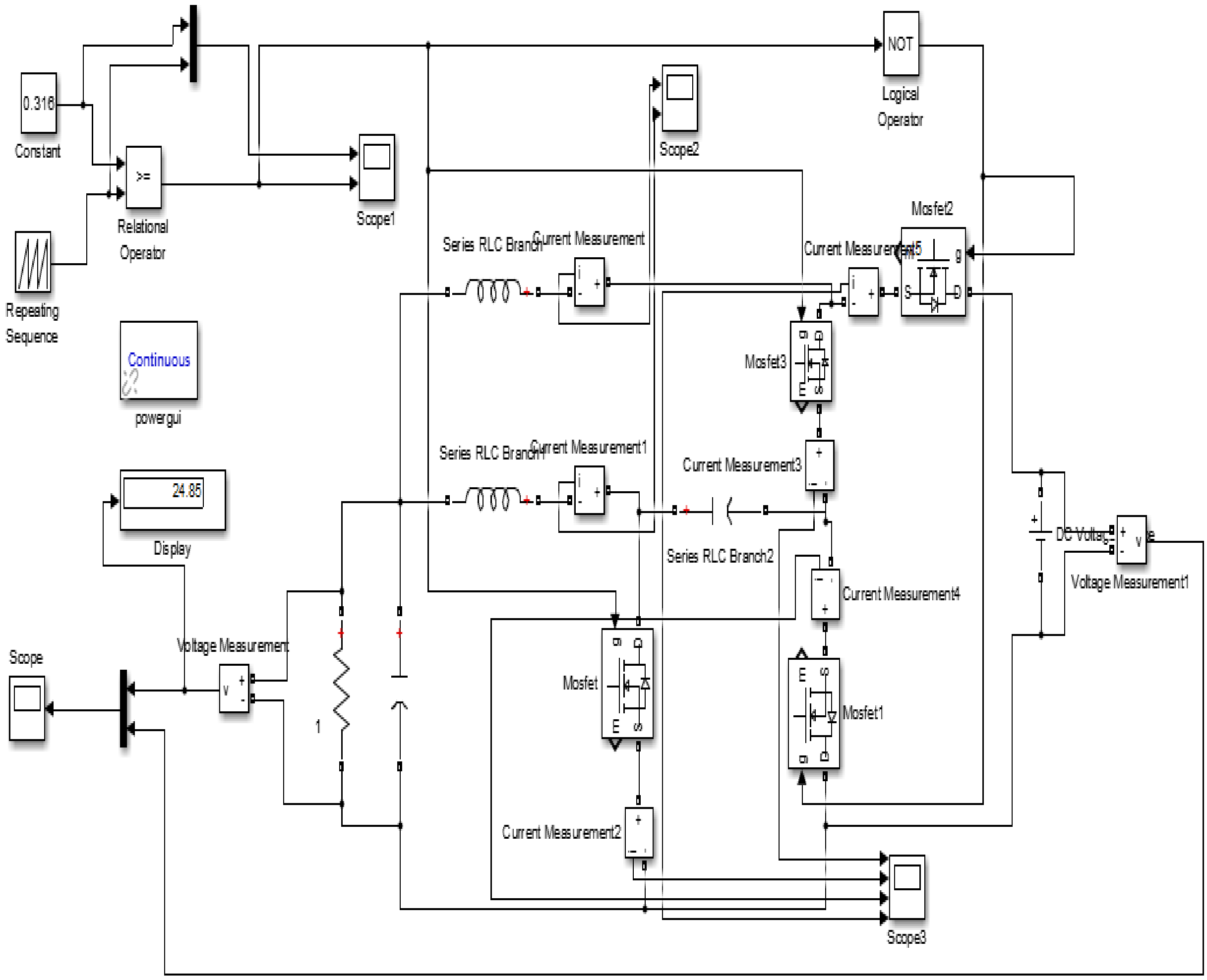

Fig. 10: Simulink model of converter in step-down mode

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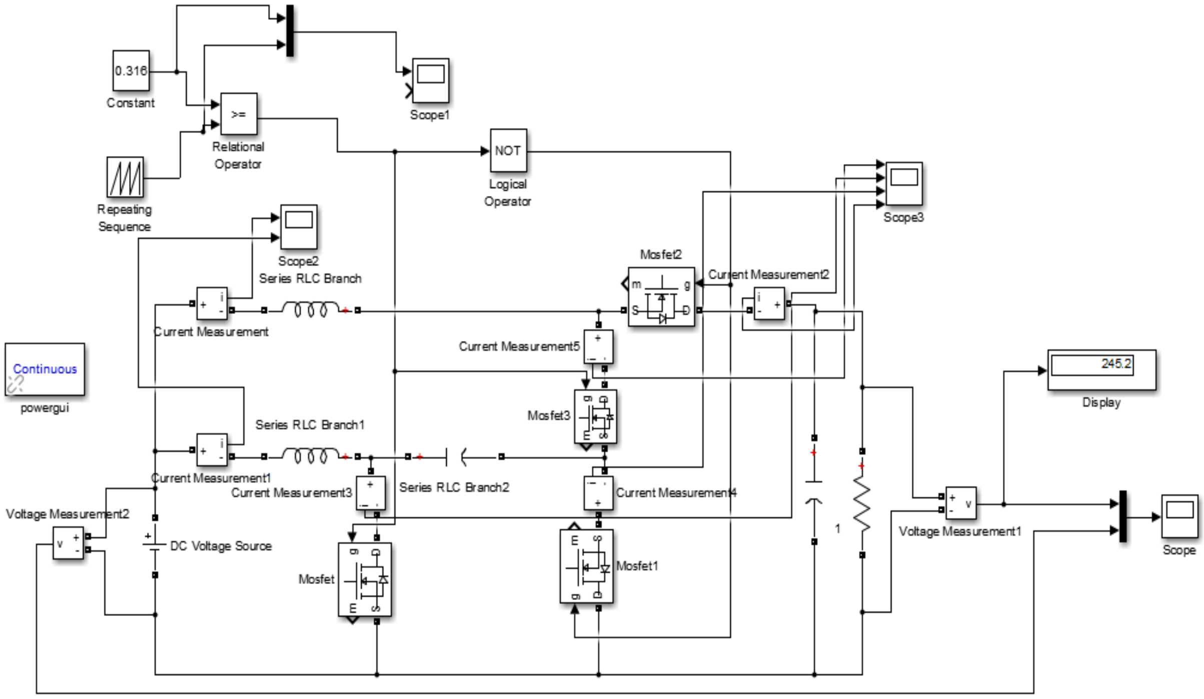

Fig. 11: Simulink model of converter in step-up mode

B. *Simulation Results:*

The voltage and current waveforms of electrical components of the proposed converter in step-down operation mode is shown in figures. Fig.12 shows the gate pulse for the switches. The input voltage and output voltage are shown in fig.13 and fig.14 respectively. For an input voltage of 250V we obtain output voltage as 25V. Fig.15 shows the current waveforms of the inductors L_1 and L_2 in step-down mode. The voltage stress of switches in step-down mode are shown in fig.16.

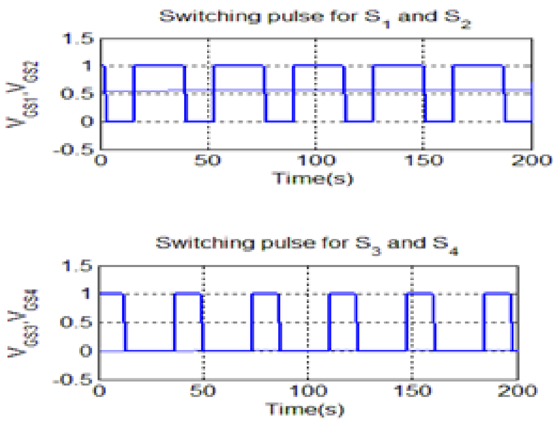

Fig. 12: Switching pulses

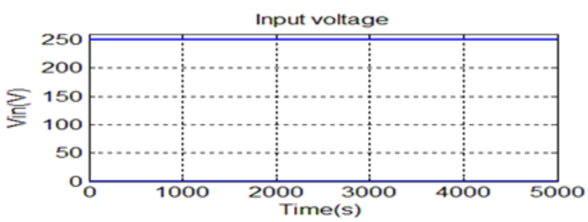

Fig.13:Input voltage of converter in step-down mode

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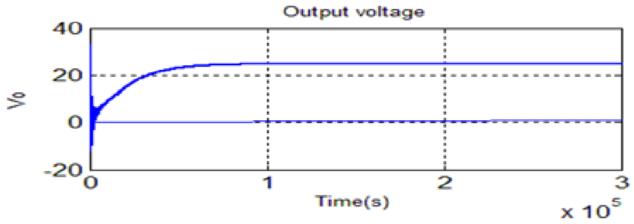


Fig.14:Output voltage of converter in step-down mode

As shown in the fig.15, the current of inductors L_1 and L_2 are about 2A and 4.5A, respectively, in step-down mode. Therefore, the input power in step-down mode is about 160W.

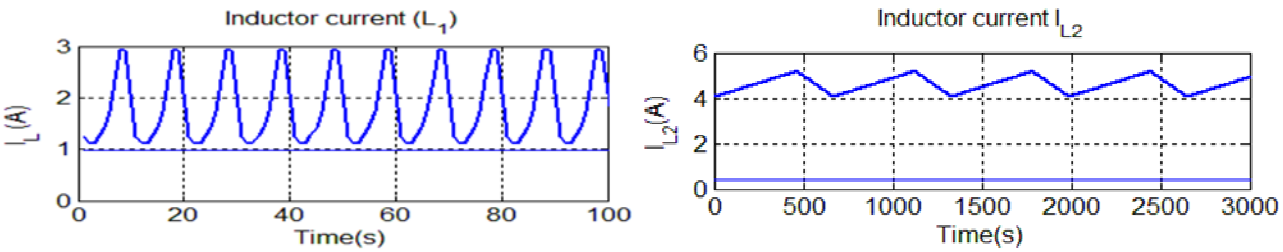
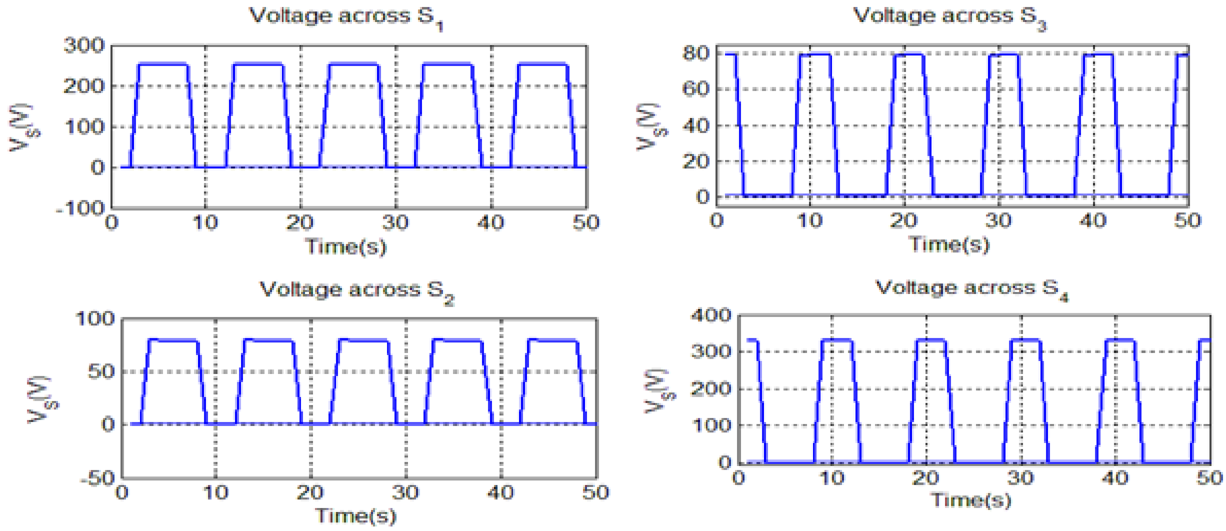


Fig. 15: Inductor currents in step-down mode



F ig. 16: Voltage across the switches

The voltage and current waveforms of electrical components of the proposed converter in step-up operation mode is shown in figures. Fig.17 shows the gate pulse for the switches. The input voltage and output voltage are shown in fig.18 and fig.19 respectively. For an input voltage of 25V we obtain output voltage as 250V. Fig.20 shows the current waveforms of the inductors L_1 and L_2 in step-down mode. The voltage stress of switches in step-up mode are shown in fig.21.

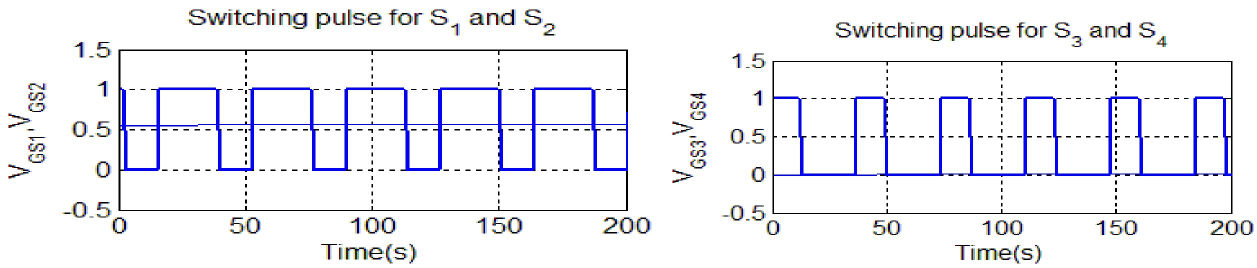


Fig. 17: Switching pulses

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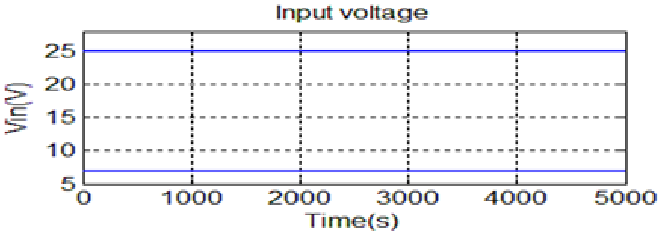


Fig.18:Input voltage of converter in step-up mode

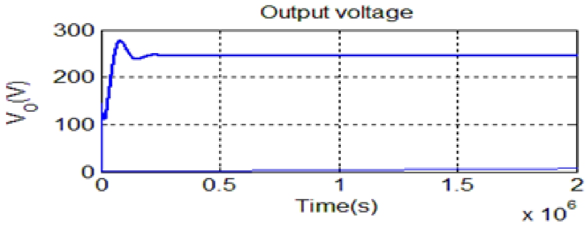


Fig.19:Output voltage of converter in step-up mode

As shown in the fig.20, the current of inductors L_1 and L_2 are about 2A and 4.5A, respectively, in step-up mode. Therefore, the input power in step-up mode is about 160W.

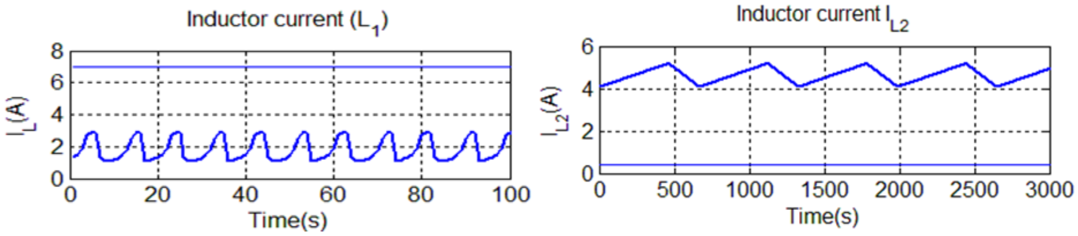
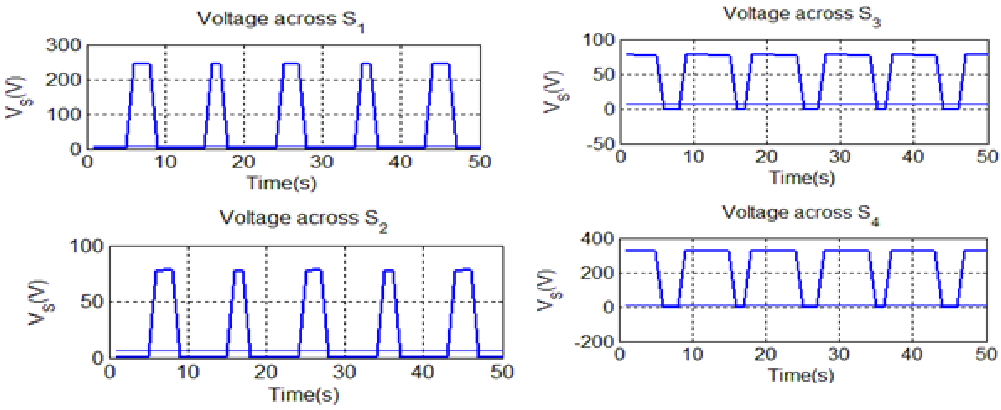


Fig. 20: Inductor currents in step-up mode



F ig. 21: Voltage across the switches in step-up mode

IV. CONCLUSIONS

The non-isolated bidirectional DC-DC converter can achieve very high step-up voltage gain(about 10 times) and very low step-down voltage gain(about 0.1). The bidirectional converter consists of four switches, two inductors and a capacitor which is same as that of conventional bidirectional buck-boost converter. But the voltage gain of the bidirectional converter in both step-down and stepup modes is more proper than the conventional bidirectional buck-boost converter. Besides, the input current is divided to the inductors which cause the size of them become smaller. In order to prove the feasibility of the converter, simulation of the converter is done with the high and low side voltages 250 and 25, respectively.

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