High Gain DC-DC Step-Up Converter with Multilevel Output Voltage

Abstract— **In this paper a very high gain step up DC-DC converter of multilevel output voltage is proposed. Maximum voltage gain in conventional Boost converter like, switched inductor converter, cascaded Boost converter, switched capacitor converter etc. are limited due to extreme duty cycle (i.e. duty cycle near to unity). Operation at extreme duty cycle leads to, serious reverse recovery problem at the switches, high conduction losses, high electromagnetic interference etc. Isolated converter such as fly-back converter, push-pull converter, forward converter, bridge converters etc. overcomes the above issues, where basically a transformer or coupled inductor is used to Boost the voltage. But, inclusion of transformer or coupled inductor introduces voltage spike at the main switch and power loss due to leakage inductance. Recently, DC micro-grid gets major importance because of the significant increase in DC loads and demand of high quality power. These DC loads require different voltage levels based on their power ratings. Photo voltaic source (PV) is one of the prime source of energy in DC micro-grid. A very high voltage gain converter is the need for DC micro-grid because of low PV source voltage. In this regard, here a step up DC-DC converter topology is proposed, which possess a very high voltage gain characteristic. The proposed converter operates in continuous conduction mode.**

Keywords- DC-DC step-up converter; duty cycle; higher order converter.

I. INTRODUCTION

In recent years energy demand as well as concern towards the green energy has been increased quite significantly. This motivates the researchers towards distributed generation system (DG) which uses renewable energy source for power generation [1]. Renewable energy sources like photovoltaic source, fuel cells etc. generate DC power [2]. Energy storages like Li-ion secondary battery, super capacitor etc. also supply DC power. So, these days DC micro-grid are used in the DG system for optimal control of power flow from the sources to loads as well as supplying a high quality power to consumers [2][3]. Another important aspect is take lighting and 'gadgets' for example. Lighting is widely considered to account for around 20% of global electricity consumption, and a recent report from the International Energy Agency estimates that up to 15% of domestic energy is consumed through 'gadgets' - *i.e.* computers and consumer electronics.

LEDs are emerging as a preferred option for high efficiency lighting, and they run on DC power. Similarly, most gadgets operate on DC power, so these two sectors alone add significant and increasing global consumption of electricity by DC devices. But these are presently powered by AC mains via multitudinous individual transformers.

In DG system one of the major source of energy is Photovoltaic (PV) generation system. Photovoltaic panel has the limitation of low single cell voltage, at the same time, those cannot be connected in series to achieve higher voltage level because of the reliability issues [4]. To overcome this issue, a Boost converter is used in between the PV source and DC bus.

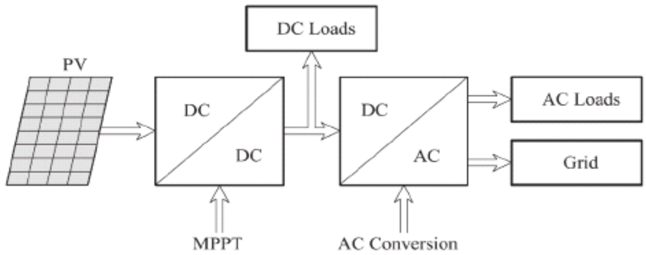


Fig. 1. Schematic of DC micro-grid

In conventional Boost converter, cascaded Boost converter, switched inductor converter, switched capacitor converter etc. experience the issues like reverse recovery problem and electromagnetic interference problem, when it is operated with extreme duty cycle, to get higher voltage gain [5][6]. Isolated converter such as fly-back converter, push-pull converter, forward converter, bridge converters etc. overcome the above issues, where high voltage gain can be achieved by adjusting the transformer turns ratio [7]. But the principal controlled switch of these converters, suffer from high voltage spike and power loss due to leakage inductance of the transformers [15]. Self lift converters may overcome the above issues, which use more number of inductors and capacitors to Boost the voltage [16]. In this model combination of this obtaining the multilevel voltages across the capacitors.

II. CONVENTIONAL TOPOLOGIES OF HIGH VOLATAGE GAIN DC DC CONVERTERS

Though researchers have worked extensively on high-gain DC–DC converter configurations, the dynamic modeling, and control of these converters has not been addressed adequately in the reported literature. However, modeling technique of higher order DC–DC converters is available in the literature which helps proposed modeling method for high-gain DC–DC converter.

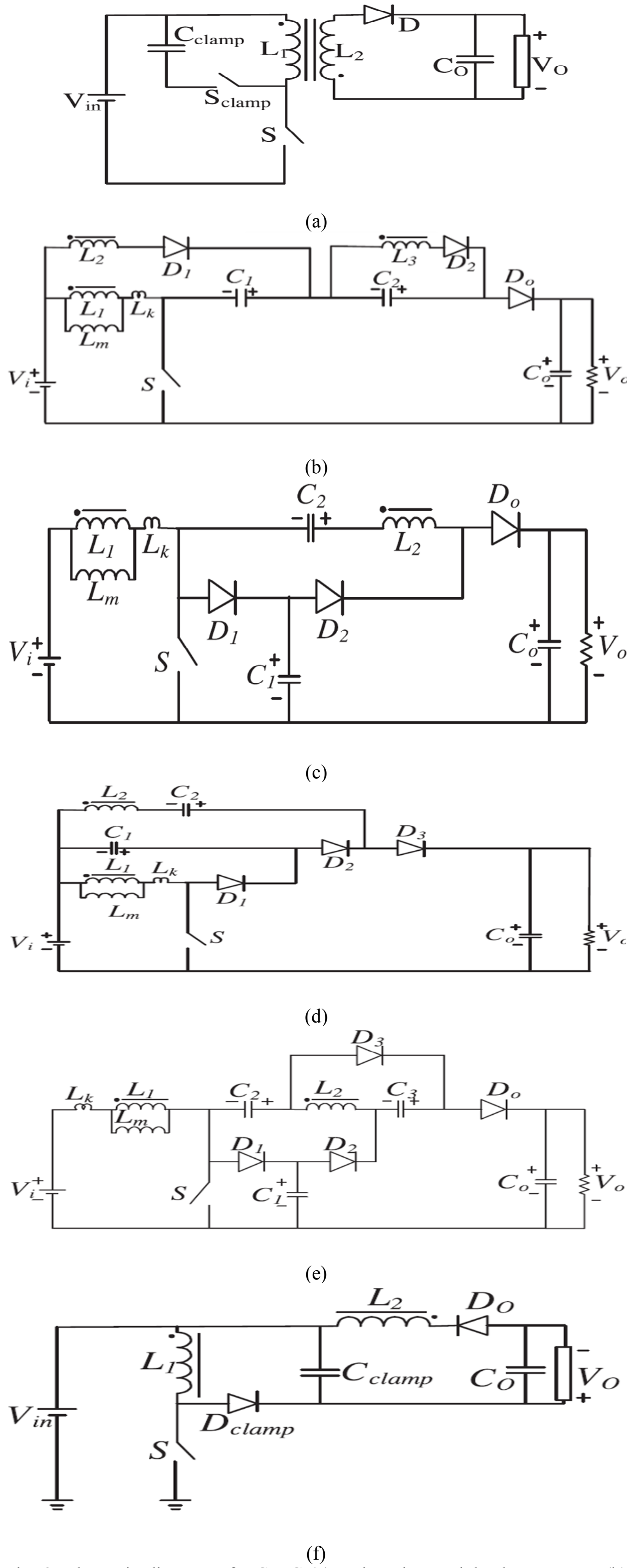


Fig. 2 schematic diagram of DC-DC (a) active clamp Flyback converter, (b) high voltage gain and reduced switch stress converter, (c) high step-up with coupled inductor converter, (d) high efficiency and soft switched converter, (e) ultra high voltage gain converter, (f) high efficiency and high step-up converter.

A. Proposed topology

In this paper a high gain step up DC-DC converter is proposed, which overcomes the above issues. It is able to maintain two DC voltage level (one of very high voltage level for high power DC bus and another of relatively less high voltage level for low power DC bus), which makes it more suitable for DC micro-grid application as shown in Fig. 1. It uses lower number of high voltage capacitors in comparison to the transformer less self-lift Boost converter for the same voltage gain, which in turn reduces the system size. A relatively lower duty ratio is used to maintain the high voltage level because of the higher voltage gain. The switches of the proposed converter are controlled by a single control signal; as a result control complexity of the converter is reduced. As the voltage gain at two buses depends on single duty cycle, the voltage can be maintained within a range at one bus and as desired at another bus. Rest of the paper is organized as follows: Section II- Operation of the proposed converter with different operating modes and mathematical validation, Section III- Simulation results are discussed and Section IV- paper is ended with conclusion.

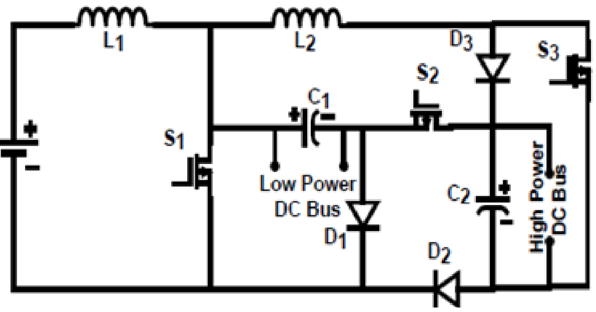


Fig. 3 Schematic of DC micro-grid with two DC buses

II. PROPOSED HIGH GAIN STEP UP DC-DC CONVERTER

The proposed high gain step up DC-DC converter is able to maintain two different higher level voltages at low and high power DC buses. The high power loads which require higher voltage input are connected to high power DC bus, whereas low power loads, which need comparatively less voltage input are connected to low power bus. The proposed converter uses two inductors (L_1, L_2), two capacitors (C_1, C_2), three diodes (D_1, D_2 and D_3) and three controlled switches (S_1, S_2 and S_3) to maintain two higher DC voltage levels as shown in Fig.2. Here in the Fig. 2 the high frequency switches S_1, S_2, S_3 can be taken as IGBT or MOSFET and V_i represents the low voltage PV source. The controlled switches are operated based on the duty cycle to control the voltages at two DC buses. It requires only one controlling signal to operate all the controlled switches, as a result control complexity and sensor requirement are reduced. Voltage gain at two buses is dependent on single duty cycle, so voltage at one bus can be maintained within a range, keeping other bus voltage as desired.

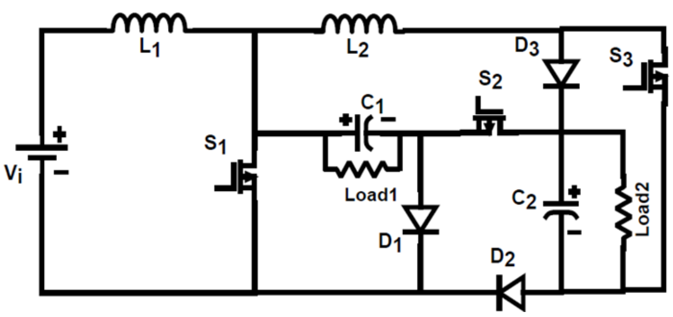


Fig. 4. Equivalent circuit of high gain step up DC-DC converter when DC buses are replaced by loads.

The operation and steady state analysis of the proposed converter are discussed as follows. For easy understanding the DC buses are replaced by loads as shown in Fig. 3. From this equivalent circuit, it is realized that the voltage at low power DC bus is same as the voltage across capacitor C_1. Similarly the voltage at high power DC bus is same as the voltage across capacitor C_2.

Let,
V_i =Low voltage PV source
V_{L1} = Voltage across inductor L_1
V_{L2} = Voltage across inductor L_2
V_{C1} = Voltage across capacitor C_1
V_{C2} = Voltage across capacitor C_2
T_s = Switching time period of controlled switches
T_{on} = Switch ON time period of controlled switches
D = duty cycle of controlled switches (ratio of T_{on} to T_s)

A. When switches S_1, S_2, S_3 are Turned off

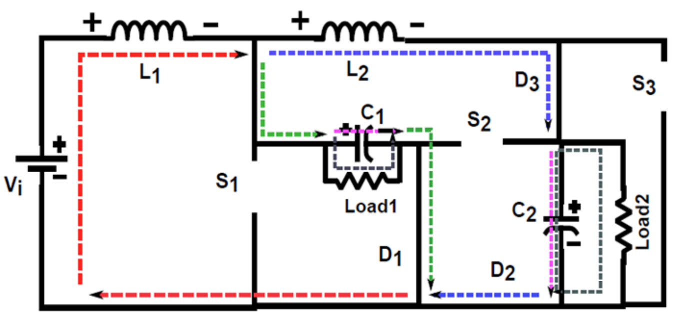


Fig. 5. The equivalent circuit of high gain step up DC-DC converter when all the controlled switches are turned OFF

In this interval of switching period all the controlled switches are turned OFF, which in turn forward biases the diodes D_1, D_2, D_3 as shown in Fig. 4. As a result, input V_i and inductors (L_1 and L_2) energize the capacitors (C_1 and C_2) as well as supply power to the loads as shown in above figure. Now from the Fig. 4 applying Kirchhoff's voltage low, voltage across inductors L_1 and L_2 are found to be as follows.

$$V_{L1} = V_i - V_{C1} \tag{1}$$

$$V_{L2} = V_{C1} - V_{C2} \tag{2}$$

B. When switches S_1, S_2, S_3 are Turned on

In this interval of switching period all the controlled switches are turned ON, which in turn reverse biases the diodes D_1, D_2, D_3 as shown in Fig. 5. As a result both the capacitors (C_1 and C_2) along with the input V_i energize the inductors (L_1 and L_2) and supply power to loads as shown in Fig. 5. Now from the Fig. 5 applying Kirchhoff's voltage low, voltage across inductors L_1 and L_2 are found to be as follows.

$$V_{L1} = V_i \tag{3}$$

$$V_{L2} = V_{C1} + V_{C2} \tag{4}$$

Applying Volt-second balance across inductor L_1, using equation (1) and equation (3),

$$\left(V_i - V_{C1}\right)\left(1-D\right)T_S + V_i D T_S = 0 \tag{5}$$

$$or, V_{C1} = V_i\left(1-D\right) \tag{6}$$

Similarly, Applying Volt-second balance across inductor L_2, using equation (2) and equation (4),

$$\left(V_{C1} - V_{C2}\right)\left(1-D\right)T_S + \left(V_{C1} + V_{C2}\right)DT_S = 0 \tag{7}$$

$$or, V_{C2} = V_{C1}\left(1-2D\right) \tag{8}$$

Now, using the value of V_{C1} from equation (6),

$$V_{C2} = V_i\left(1-D\right)\left(1-2D\right) \tag{9}$$

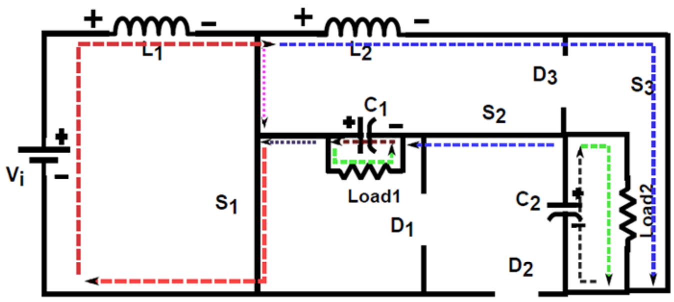


Fig. 6. The equivalent circuit of high gain step up DC-DC converter when all the controlled switches are turned ON

Now from the equation (9), it is observed that, voltage gain at capacitor C_2 (same as the high power DC bus), is significantly high. The voltage gain versus duty cycle plot is shown in Fig.6. It is observed that, with the help of small duty cycle D, a higher Boost voltage can be achieved. Similarly from equation (5), it is observed that voltage at low power DC bus (same as the voltage at capacitor C_1), can be Boosted with the help of suitable duty cycle D. From the voltage gain versus duty cycle plot as shown in Fig. 7, it is also observed that, the voltage gain at low power DC bus is less than the voltage gain at high power DC bus for the same duty cycle D. So, by choosing a suitable duty cycle D the voltage at two DC buses can be maintained for high power and low power loads application simultaneously. The switches S_1, S_2, S_3 of the proposed converter are controlled by using traditional simple PWM technique as shown in Fig. 8. Here reference voltage signal V_{ref} is compared with high frequency triangular carrier signal V_{tri}. The switching frequency of the proposed converter is same as the carrier frequency. The reference signal's amplitude is determined based on the duty ratio. Here all the controlled switches are operated based on single control signal. So, the control complexity and sensors requirement are reduced as a result cost of the system is also reduced.

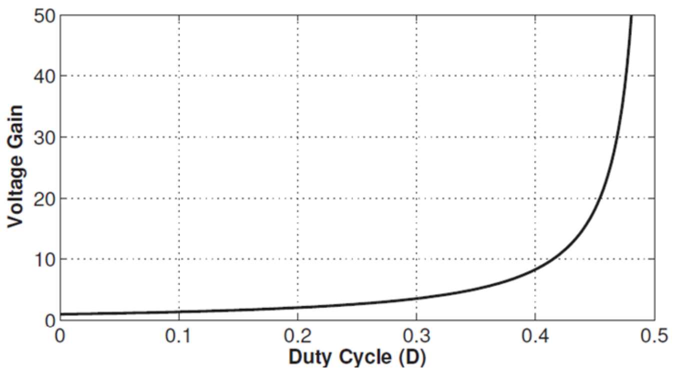


Fig. 7. Voltage gain at high power DC bus versus duty cycle plot

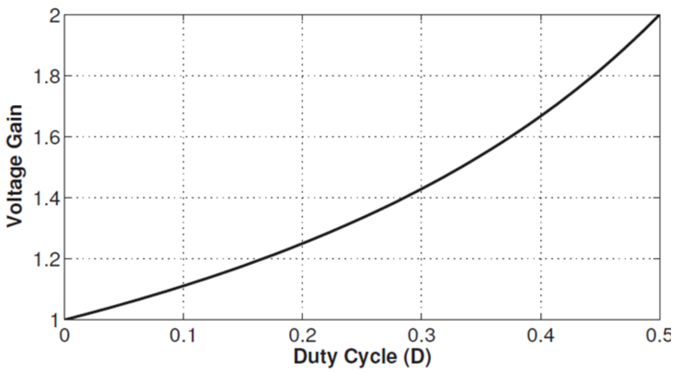


Fig. 8. Voltage gain at low power DC bus versus duty cycle plot

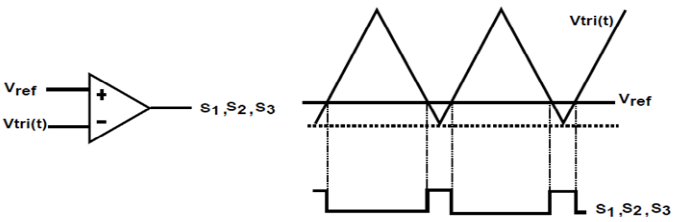


Fig. 9. PWM control of proposed high gain step up DC-DC converter

TABLE I

SL. No	Parameters	Values
1	Switching Frequency	10kHz
2	Duty ratio	0.368
3	Inductor L_1, L_2	350µH, 600µH
4	Capacitor C_1, C_2	470 µF
5	Resistor R_1, R_2	180 Ω, 170 Ω
6	Supply Voltage	12V

III. SIMULATION RESULTS

The circuit has been designed and implemented using MATLAB Simulink. The circuit parameter has been taken for simulation is as given in TABLE I. Using equation (6) and equation (9), mathematically the high power and low power DC bus voltages for the given source voltage is found to be V_{C2} =380 Volts, V_{C1} = 80 Volts respectively. After simulation the voltage at low power DC bus (V_{C1}) has been found to be very near to 80 Volts with negligible ripple content as shown in Fig. 9.

Similarly, after simulation the voltage at high power DC bus (V_{C2}) has been found to be nearly 380 Volts with negligible ripple content as shown in Fig. 11. It has been observed that ripple content of the DC bus voltage can be minimized with appropriate value of capacitors C_1 and C_2. From the voltage plot versus time across inductor L_1 it is found that volt second balance is happening as shown in Fig. 17. Similarly current through this inductor is found to be well within the tolerable limit as shown in Fig. 18. The inductor current through the inductor L_1 also indicates that, input current is continuous. From the voltage plot versus time across inductor L_2 it is found that volt second balance is happening as shown in Fig. 19. Current through the inductor L_2 is found to be well within the limit as shown in Fig. 20, where the ripple current can be minimized by choosing appropriate inductor L_2. The voltage stress across the switch S_1 and diode D_1 is same as the voltage across C_1 which is relatively low as compared to voltage across capacitor C_2. As a result a lower voltage rating diode and switch can be used in the place of diode D_1 and switch S_1 respectively. The voltage stress across the switch S_3 and diode D_3 is found to be same as the voltage across the capacitor C_2 as shown in Fig. 21 and Fig. 22 respectively.

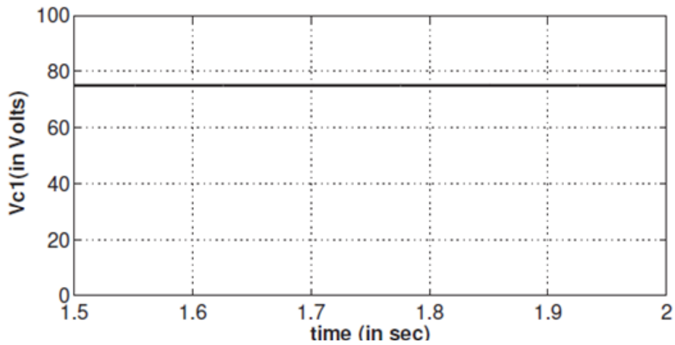


Fig. 10. Voltage at low power DC bus (in Volts) versus time (in sec)

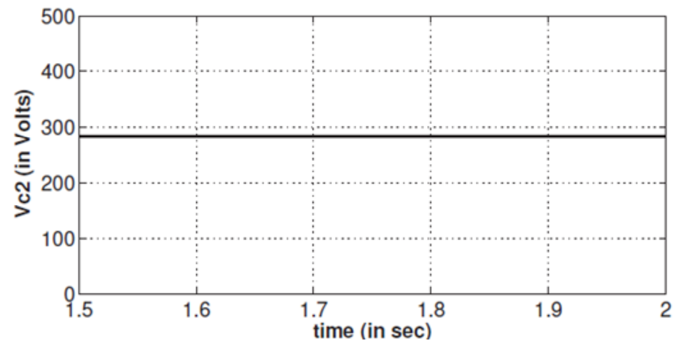


Fig. 11. Voltage at high power DC bus (in Volts) versus time (in sec)

It can be observed from the above plot that, a higher voltage rating switch S_3 and diode D_3 is used based on the voltage rating of high voltage DC bus. Similarly, it can be analyzed that the voltage stress across Switch S_2 is same as the voltage across capacitor C_2 and voltage stress across capacitor D_2 is the sum of voltage across capacitor C_1 and C_2.

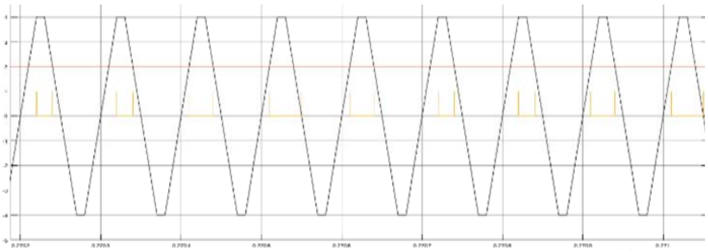


Fig. 12. Gate pulses at duty ratio 0.369

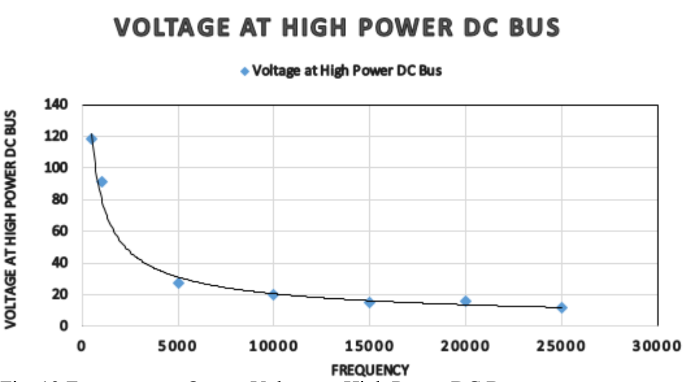


Fig. 13 Frequency vs Output Voltage at High Power DC Bus

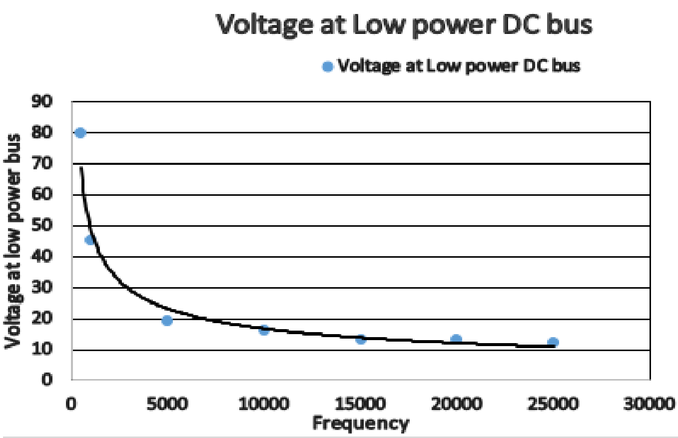


Fig. 14. Frequency vs Output Voltage at Low Power DC Bus

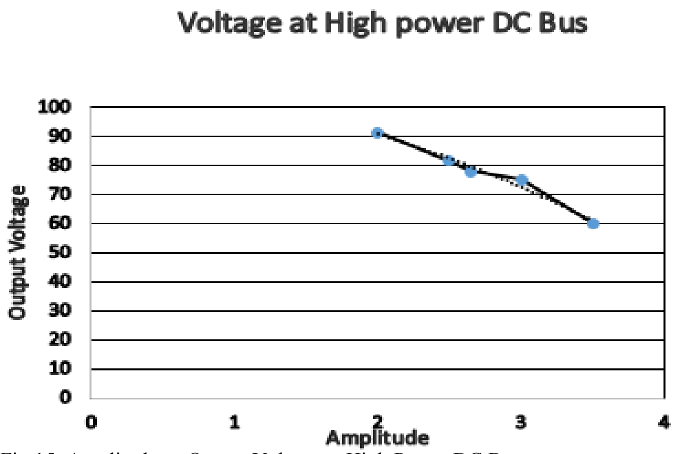


Fig 15. Amplitude vs Output Voltage at High Power DC Bus

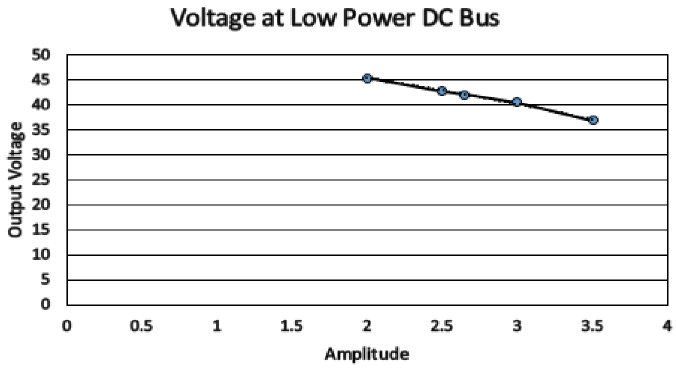


Fig.16. Amplitude vs Output Voltage at Low Power DC Bus

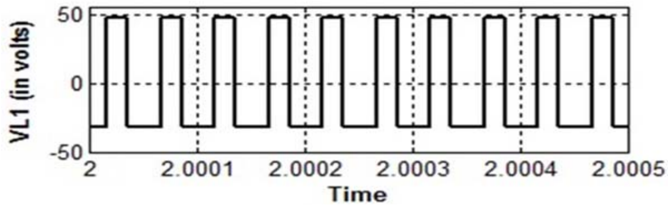


Fig. 17. Voltage across inductor L_1 versus time (in sec)

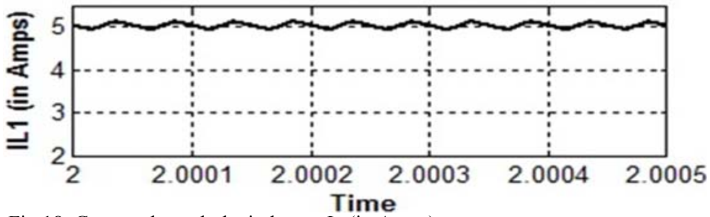


Fig.18. Current through the inductor L_1 (in Amps)

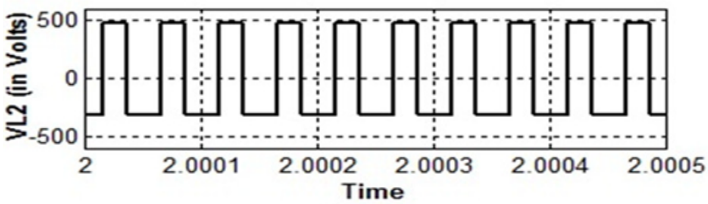


Fig. 19. Voltage across inductor L_2 (in Volts) versus time (in sec)

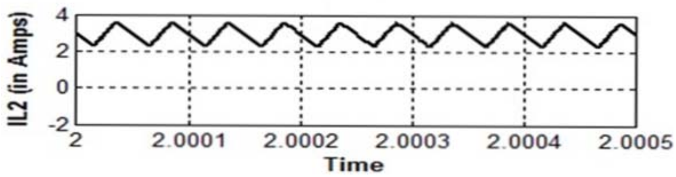


Fig. 20. Current through inductor L_2 (in Amps) versus time (in sec)

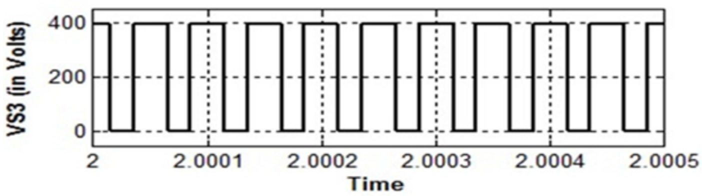


Fig. 21. Voltage stress across switch S_3 (in Volts) versus time (in sec)

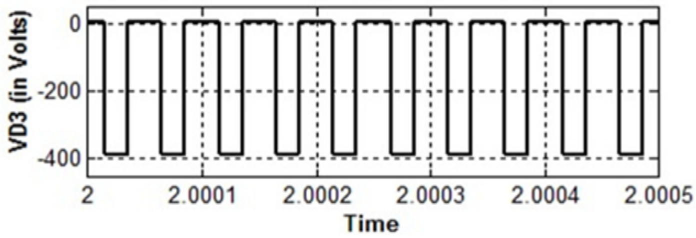
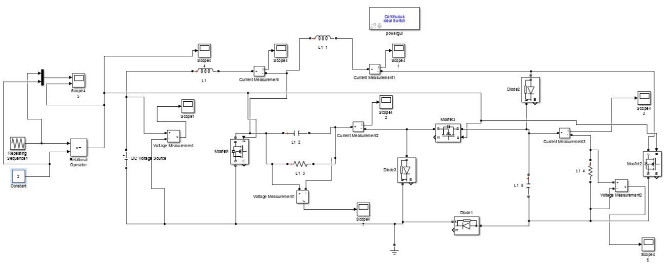
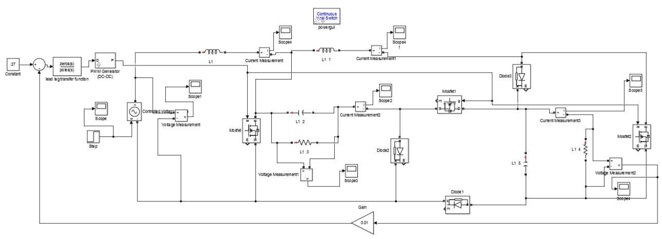


Fig.22. Voltage stress across diode D_3 (in Volts) versus time (in sec)

A. Open loop MATLAB



B. Closed-loop MATLAB



IV. CONCLUSION

A high gain DC-DC step up converter is presented in this paper, which is able to maintain a high voltage with smaller duty cycle. It overcomes the limitation due to extreme duty cycle (*i.e.* duty cycle near to unity) for getting higher voltage gain as in case of conventional Boost converter like, cascaded converter, switched inductor converter, switched capacitor connected etc. It retains all the advantages of self- Boost converter along with; added advantage is it uses lower number of passive components for the same voltage gain. It is able to maintain two DC bus voltages *i.e.* one for high power application and another for low power application. These advantages make the proposed converter more suitable for DC micro-grid application. The voltage gain at two different buses depends on single control signal, as a result control complexity and sensor requirement is reduced. The PWM switching strategy adapted for controlling the switches is discussed. Steady state analysis is done to formulate the voltage gain at the two DC buses. The converter operation is analyzed and verified by simulation by using MATLAB/ Simulink.

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