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High Gain Switched Capacitor Converter with Alternate Sources

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ABSTRACT

The High gain DC to DC converters are commonly anecessary circuit in solar power applications and other intermediate converters of power supplies equipments like laptops, computers etc.. The conventional converters like boost and buckboostprovide low voltage gain. Due to the uncertainty of solar power, where sources are tapping, continuous power with high quality reduced ripple is also a redundant need. In this paper a high gain DC to DC converter with alternate power sources is proposed to address the above significant concerns. The switched capacitor and inductor combination improves the voltage gain of the converter when compared to other similar converters. The alternate switching of the sources is made by the addition of a switching logic sequence. A bidirectional converter in the circuit allows the flow of power for battery charging and discharging. The power from the solar panel is fed to the switched capacitor converter or it can be stored in battery for further use. The theoretical analysis of the converter is carried out and validation is performed using MATLAB/Simulink. The results yield that the gain of the converter is improved and switching of the sources are adequate. The load transient and line transient waveforms suggest that the settling time is too fast with low over shoot.

KEYWORDS:Alternate sources, bidirectional converter; high gain; switched capacitor, buck and boost mode

1. INTRODUCTION

The usage of nonconventional energy sources has been promoted to make the environment pollution free. The increase in availability of solar energy makes it more widely used even in domestic applications. In a grid tied system it is necessary to meet grid voltage. It can be achieved with the use of multiple converters along with a stage of DC-DC converter. The storage of energy is also an adequate requirement nowadaysdue to the increase of the energy consumptions in daily life. Bidirectional converters can be used to interface the solar energy and battery with DC to DC converters. Isolated as well as non-isolated converters are commonly used with solar energy systems. Isolated converters can be widely used in tremendous power applications in other domains also.

Non-isolated converters has more advantages like simple structure, low cost and size. Non-isolated based boost converters are preferred in solar systems. The two boost converters are compared [1] on the basis of their performance found that their characteristics are not adequate with low duty ratios. These converters provide low voltage gain even at moderate duty ratios.The high voltage gain classic boost converters with transformers and coupled inductors presented in [2] - [4] are suitable for renewable and solar power conversion applications. But they have very low efficiency in high power applications due to highly inductive components and more numbers of switches. In boost type converters several structures were reported to provide high gain but converteroperate in low duty ratio region and performance is poor in transient conditions. The two stages of AC/DC and DC/AC converters made the operation analysis difficult even though it provide high voltage gain. In [5]converters with ultra-high gain is reported but the gain obtained is far from DC link voltage. The converters which consists of magnetic elements are presented in [6] are very bulky and hence the control becomes complex. In [7], [8] various converters based on dual coupled inductors are presented but they produce high magnetic interference and large number of devices. Also the overall efficiency of the converters are less due to isolation magnetic components. The galvanically isolated converters are presentedin [9], [10] to improve the output side performance, yet they are bulky, stress on the switches are high and produce EMI issues. A high performance DC-DC converter with soft switching [11] improves the voltage gain. The voltage across the switch is reduced to zero using a capacitor connected and zero current turn on is achieved. The more number of inductor windings and resonant cell makes the modelling complex and closed loop trouble shooting is difficult. Hence, switched capacitor converters are the best choice for high gain.

The switched capacitor converters when integrated with boost type converters will improve the voltage gain. The switched capacitor with dual switches [12] improves the voltage gain to 1/(1-2D) by using the front end converter. This topology provides high transformation ratio with low duty ratios. The voltage multiplier stack is active when operating with the upstream side of the discussed converter which further improves the voltage gain. The switched inductor converters and active network converters based on switched capacitor are reported in [13],a practical realizable approach is adopted to improve the voltage gain moderately. In order to improve gain further a voltage lift approach is described in [14], but still the gain is not adequate. Hence a high voltage gain switched capacitor converter along with diodes is proposed in this paper. The operating principle of the proposed converter are discussed section II. MATLAB simulation validation is carried out and the waveforms are analyzed in section III. The results are concluded in section IV.

2. Proposed High Gain Switched Capacitor Converter

The circuit schematic of proposed high gain switched capacitor converteris depicted in Fig.1.A bidirectional converter with alternate sources such as solar PV energy and battery is integrated with a high gain switching capacitor converter. Voltage gain can be greatly increased using switched capacitor networks. Bidirectional converters can be employed for transferring power in both direction between two sources. These converters can be used to step-up and step-down voltage depending on the duty cycle of the switches. It uses solar PV energy to feed the converter and also to charge the battery. If the solar PV energy is insufficient then battery is used to power the converter.

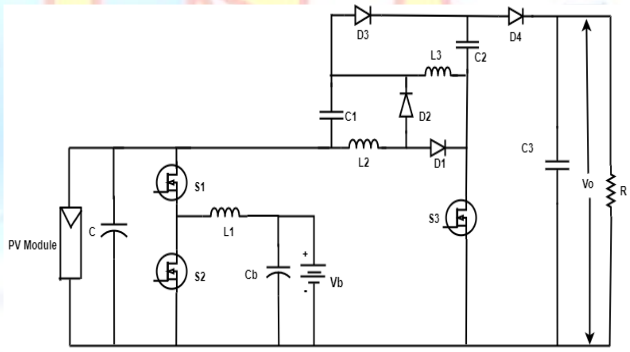

Fig. 1 Proposed high gain switched capacitor converter

The bidirectional converter has two modes of operation. The proposed converter has sources of solar power and battery DC voltage. The battery is charged from the solar power by using the combination of control logic using the switches S_1 and S_2. The proposed converter operation is carried out in buck (forward) and boost (backward) modes.

Both the power sources are turned in buck mode and the energy is stored in the inductor. And in the boost the stored energy is used to charge the battery. The operation of the proposed high gain switched capacitor converter is discussed in detail as follows.

Forward Mode: switch S_1 is turned on and the switch S_2 is turned off and buck operation is carried out (forward mode). The input current increases when the switch S_1 is turned on, charging the inductor L. The inductor delivers the stored energy to charge the battery when switch S_1 is turned off. In this mode the PV panel charges the battery and also supply power to converter.The converter operation is analyzedin detail in theoretical and simulation mode.

Backward Mode: The switch S_2 is turned on and boost operation is carried out (backward mode), whereas S_1 remains off. When S_2 is turned on, the current rises, charging the inductor L. When S2 is turned off, the inductor discharges and through the body diode of S_1 power is delivered to the converter. In boost mode the converter is fed by the battery.

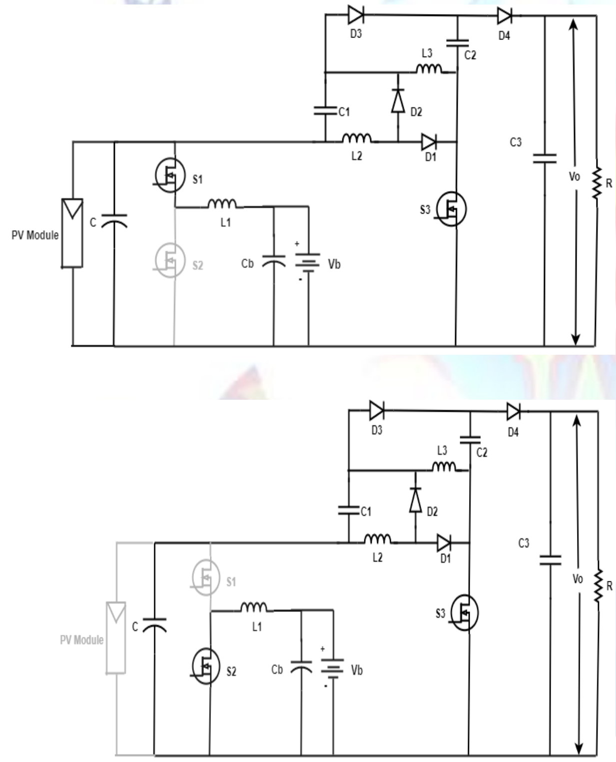

Fig.2 Proposed converter in (a)forward mode buckoperation (b) backward mode boost operation

In the switched capacitor converter the inductor L_2 stores energy and later it discharges to capacitor C_1.The input side voltage charges C_1, L_3 and C_2. Afterwards L2, L_3 and C_2 delivers the energy through load. Hence the high voltage is obtained at the output side. There are two sub modes of operation with S_1 turned ON.

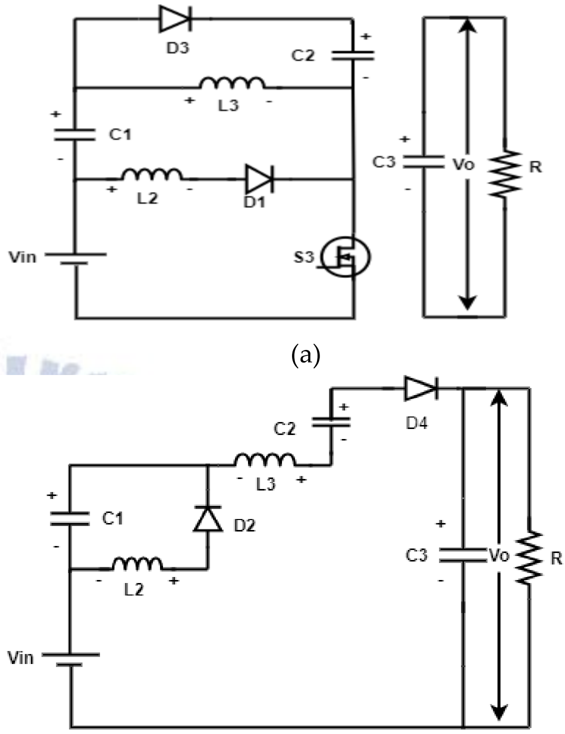

Fig.3 Equivalent circuit with S_1 in ON stage (a) Turn ON Mode (S_3) operation (b) Turn OFF Mode (S_3)operation

Turn ON Mode: The switch S_3 is triggered on in Turn ON Mode operation, and the inductor begins to charge. C_2 and L_3 are connected in parallel. C_1 energizes both C_2 and L_3. Fig. 3 (a) depicts the Turn ON Mode equivalent circuit. The voltage across the inductor L_2 is equal to the input voltage given in equation (1).

$$V_{L2} = V_{in} \quad (1)$$

The voltage across L_3 and C_3 are given by equation (2)

$$V_{L3} = V_{C2} = \frac{V_{in}}{(1-D)} \quad (2)$$

Turn OFF Mode: The gate pulse to switch S_3 is removed in Turn OFF Mode operation. The total stored energy in L_2, L_3, and C_2 is given to the load. This results in a massive increase in voltage gain. The inductor L_2 charges the capacitor C_1 as well as the inductor L_3. Figure 3 (b) depicts the analogous circuit for Turn OFF Mode.

The analyzed theoretical waveforms for current through diodes and inductors are plotted in Fig. 4 with reference to the gate pulse to the switch S_3.

The voltage across C_1 and L_2 is deduced from the basic KVL equations and derived as follows in equation (3):

$$V_{C1} = V_{L2} = \frac{V_{in}\ D}{(1-D)} \quad (3)$$

The voltage across L3 and C2 are given by equations (4) and (5)

$$V_{L3} = \frac{2\ V_{in}}{(1-D)} \quad (4)$$

$$V_{C2} = \frac{V_{in}}{(1-D)} \quad (5)$$

The voltage gain can be achieved by using the Volt-second balance method. The average voltage across the inductor is zero in the steady state. Hence

$$\frac{V_{in}}{(1-D)} D + \left[\frac{2\ V_{in}}{(1-D)} - V_O\right](1-D) = 0 \qquad (6)$$

The dc voltage gain K is derived by simplifying equation (6) as shown in equation (7).

$$K = \frac{V_O}{V_{in}} = \frac{(2-D)}{(1-D)^2} \quad (7)$$

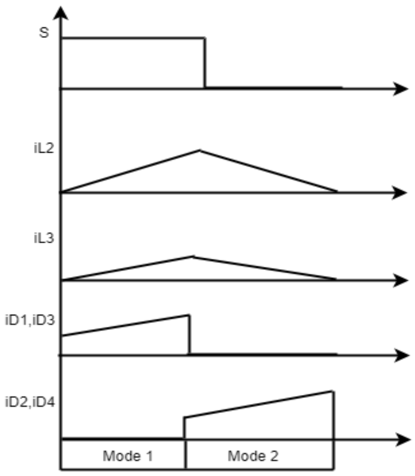

Fig. 4 Waveforms of Turn ON Mode and Turn OFF Mode operation

Design:

The inductors and capacitors are designed with respective ripple values. Also the switches and diodes are selected with its rating and switching frequency. The converter can be used for single phase as well as three phase inverter applications with adequate designed values. The inductors can be selected from the ripple current equations given below. The current ripple is assumed as 10% and the switching frequency is 20kHz. In forward operation of bidirectional converter inductor L1 is obtained by the equation (8).

$$L_1 = \frac{D\ T_s(V_d - V_O)}{\Delta\ I_{in}} \quad (8)$$

In the similar way for backward operation L1 is obtained by the equation (9).

$$L_1 = \frac{D\ T_s V_d}{\Delta\ I_{in}} \quad (9)$$

The inductors L2 and L3 are given by the equations as shown in (10) and (11) respectively.

$$L_2 = \frac{(1-2D+D^2)D\ V_{in}}{f_s\ (1-D)^2 \Delta I_{in}} \quad (10)$$

$$L_3 = \frac{D\ V_{in}}{f_s\ (1-D)\ \Delta I_{in}} \quad (11)$$

The voltage ripple of the capacitors are assumed to be 1%. The voltage across the capacitors are obtained from the equations (2) and (3). The capacitors can be selected from the equations given by (12) to (15) with the load resistance R and the switching frequency f.

$$C_b = \frac{(1-D)V_O\ T_s{}^2}{8\ L_1\ \Delta V_O} \qquad (12)$$

$$C_1 = \frac{D\ V_O}{R\ f\ \ \Delta V_{C1}} \qquad (13)$$

$$C_2 = \frac{(1-D)V_O}{R\ f\ \ \Delta V_{C2}} \qquad (14)$$

$$C_3 = \frac{D\ V_O}{R\ f\ \ \Delta V_{C3}} \qquad (15)$$

The voltage stress on diodes and switches is expressed in terms of duty ratio and input voltage by the equations (16) to (18).

$$\frac{V_{D1}}{V_{in}} = \frac{D}{(1-D)^2} \qquad (16)$$

$$\frac{V_{D3}}{V_{in}} = \frac{V_{D4}}{V_{in}} = \frac{\left[\frac{V_O}{V_{in}}(1-D)\right] - 1}{(1-D)} \qquad (17)$$

$$\frac{V_{SW}}{V_{in}} == \frac{1}{(1-D)^2} \quad (18)$$

II. Simulation and Discussions

The closed loop circuit diagram is shown in Fig. 5 for a high voltage gain switched capacitor DC-DC converter using alternate sources. The switching logic pulses to the switches S1 and S2 are generated using MPPT and a PWM generator. The converter's output voltage is compared to the reference voltage and the resulting error is sent to a PI controller. The output of controller is fed into a PWM generator. The switch S3 receives the PWM pulses obtained from thislogic for closed loop control. According to the reference value the switch S3 operates with a required duty ratio. The capacitor inductor circuit along with switch control generate the required output voltage.

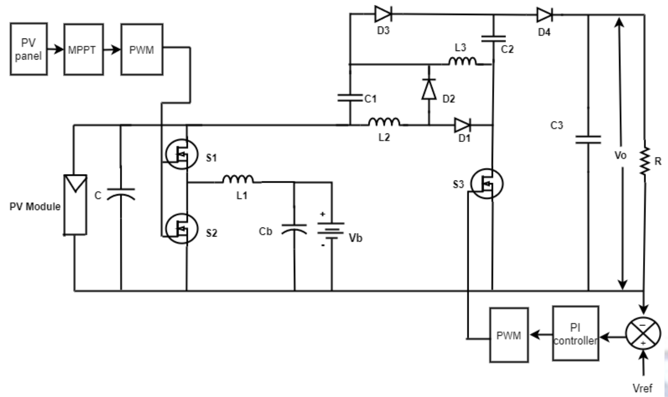

Fig. 5 closed loop circuit diagram of Proposedhigh voltage gain switched capacitor DC-DC converter

Table 1 lists the simulation parameters evaluated based on the defined equations of inductors and capacitors. MATLAB/Simulink is used to conduct a closed loop simulation of the proposed converter. The converter is simulated for a 100W power rating, input voltage as 20V and output voltage as 325V.The switching frequency of the converter is set as 20 kHz.

Table 1: Simulation parameters

PV panel	**Battery**	**L_1**	**L_2**	**L_3**
100W, 20V	18V, 10AH	0.18mH	1mH	5mH
C_b	**C_1**	**C_2**	**C_3**	
17 μF	20 μF	10 μF	10 μF	

The duty ratio for the switched capacitor converter is kept adequately to generate 325V as output voltage.In this simulation the duty ratio for the two switches S_1 and S_2 are generated using MPPT and the pulse to the switch S_3 is generated using PI controller. Here a solar panel of 100W is considered for analysis. The obtained waveforms of voltage and current with MPPT control is shown in Fig. 6. The resulting voltage is of 20V with a current of 5A as shown. This input voltage is applied to the proposed converter in buck mode. In this mode storage inductor charges from solar panel. In the next boost mode the battery is charged with stored energy from the inductor

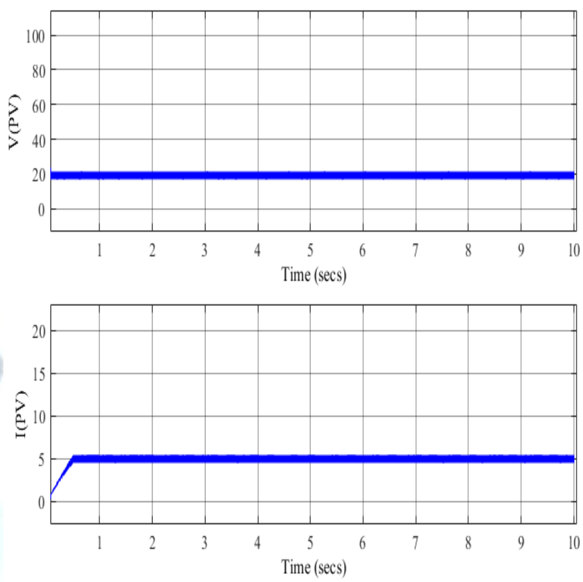

Fig. 6 Panel voltage (20V) and panel current (5A) waveforms

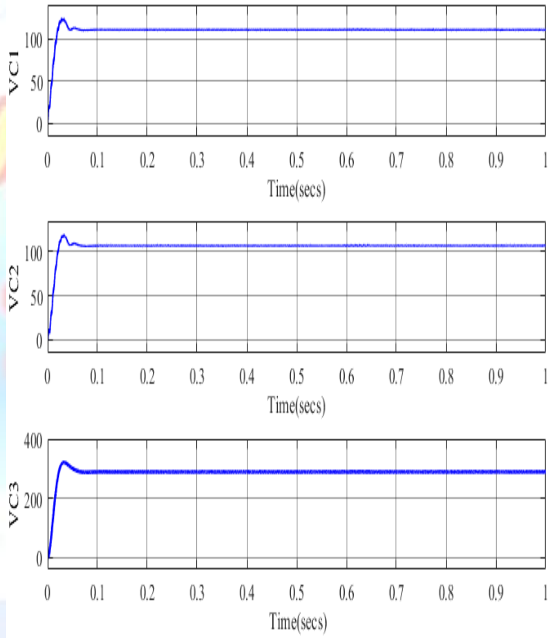

Fig. 7 Waveforms of capacitor's voltage

The output side capacitor voltages of V_{c1},V_{c2} and $V_{c3}$are shown in Fig. 7. The voltage resulted across capacitors is mathematically agree with the voltage computed using equations (2) and (3). The capacitor voltages obtained from the simulation are 55V, 75V and 325V. So the voltage gain of the converter is evaluated as 16 which is quite high in comparison with existing converters reported.TheFig. 8 depicts the current flowing through the storage inductors$L_2$and L_3. The currents in the inductors $L_2$and $L_3$are 6A and 2.7A respectively. Also the ripple currents are obtained as 10% as in agreement with designed inductor equations.

The waveforms of the converter's output voltage and output current are shown in Fig. 9. The output voltage and current obtained are 325V and 0.3aA. The DC output power is evaluated as 98W.

The Fig. 10 shows the voltage stress across the switches. When the switch S_3 is OFF the average voltage stress is 20V and also the on state voltage drop in Switch S_1 is low. The voltage stress across switch S_1 is 8V peak when it is OFF state.

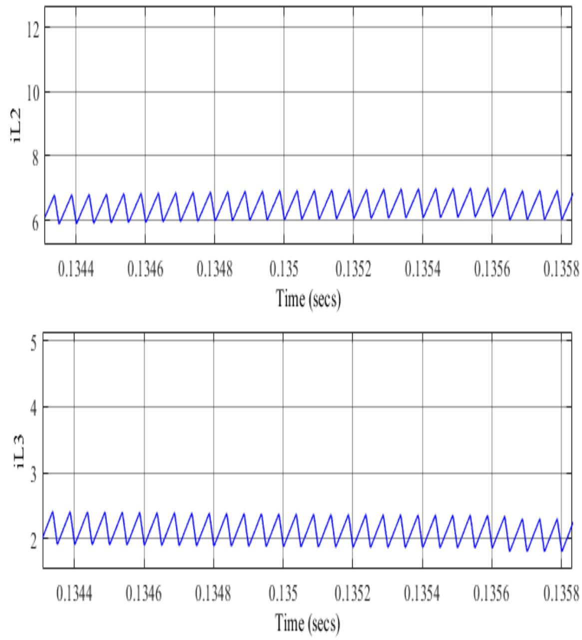

Fig. 8. Waveforms of current through inductors

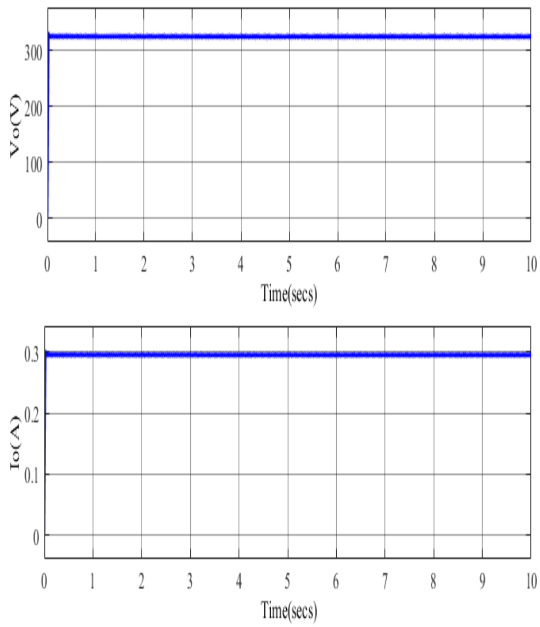

Fig. 9. Waveforms of output voltage and current

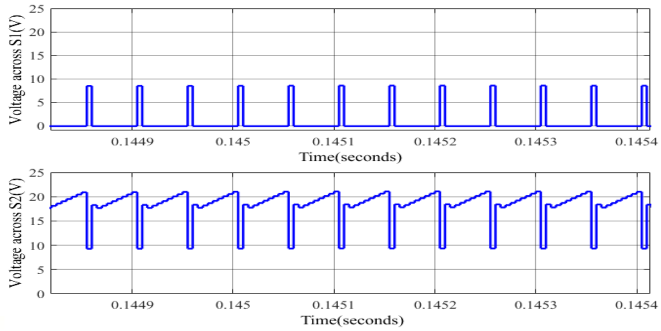

Fig. 10. Voltage stress across switches

The diode currents are shown in Fig. 11. This diagram depicts the current flowing through the diodes D_1, D_2, D_3, and D_4.The peak value of current through diode D1 is 1A. And the other diodes flow 7A current as peak current.

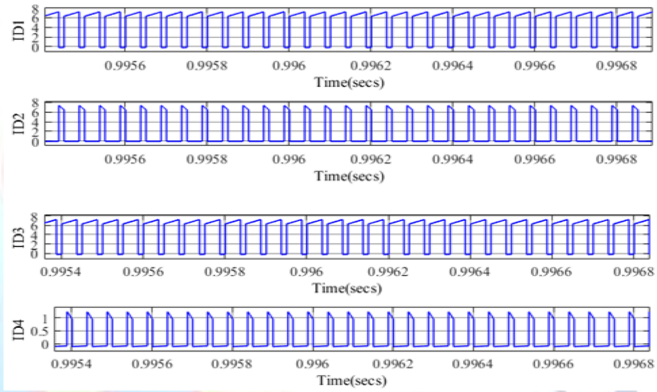

Fig. 11 Current waveforms of diodes

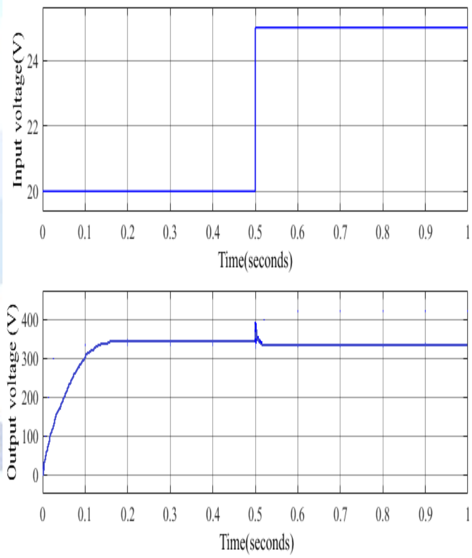

Fig. 12 Line regulation waveforms

The voltage regulation waveforms of line and load transients are plotted respectively in Fig. 12 and Fig.13 to verify the operation of the proposed converter in closed loop. The line transient is measured by applying an input voltage of 20V initially and the output voltage is corroborated as 325V. The voltage input is changed from 20V to 25V at 0.5 sec. The output voltage maintained as constant 325V as the controller regulates the output voltage against the line voltage variations.

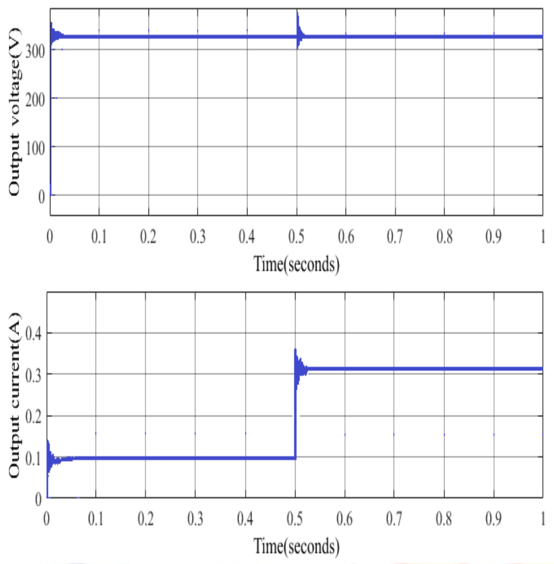

Fig. 13 Load regulation waveforms

. The load transient of the proposed converter is shown in Fig. 13. The load current is changed from half load to full load at 0.5 sec. The load voltage is maintained constant at 325V as in the diagram. So line and loadtransients of the proposed converter are verified and found to be working properly under closed loop.

The gain of the converter is evaluated based on the output voltage attained. An output voltage of 325V is achieved with respect to an input voltage of 20V. So the gain of the converter is accomplished as 325/20 =16.25 with a moderate duty ratio of 0.72. The Output power of the converter at an output voltage 325V with 0.31A load currentis evaluated to be 98W.The input power from the simulation result as in the Fig.6 with an input voltage of 20V and a current of 5A is found as100W. Hence the efficiency of the proposed converter is really high.

4. CONCLUSION

A high voltage gain switched capacitor DC-DC converter with alternate sources using bidirectional converter is proposed to improve the dc voltage gain. The high voltage gain is achieved by the combination of switched capacitors and inductors. A bidirectional converter in this topology allows the flow of power for in both directions. The redundant voltage sources and its theoretical analysis have been carried out to substantiate the simulation result. The converter is validated in closed loop to regulate constant output voltage at a designed power rating. The proposed Switched Capacitor DC-DC converter topology improves the dc voltage gain to a high value and it is evident from simulation results. The closed loop control of the proposed topology is verified by conducting line and load transient tests with the variations of input voltage and load current. The controller of the converter regulates output voltage to a constant value irrespective of line and load changes. Simulation studies prove that the converter can be employed in solar PV applications that are connected to the grid. It is evident from the validation results that the proposed converter maintains the overall efficiency to a high value in the range of 98% even at an extremely high voltage gain.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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