Power Electronics Interface for PV Systems

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Abstract- **Photovoltaic generate electric power when illuminated by sunlight or artificial light. It directly convert the sun's energy into electricity which can be easily transported and converted to other forms for the benefit of society. The role of power electronics converter is very important in the PV systems. The electricity generated by a PV module is in the form of direct current (DC). Transformation of direct current to alternating current (AC) required by many common appliances and for grid-connection is achieved with inverter system. There are two stages where power electronics converter are used, first DC-DC converter stage in which lower level PV voltage is stepped-up at the required higher level; and second DC-AC inverter stage in which boosted DC link voltage is converted into AC. The inductor of traditional buck boost converter is replaced by switched inductor circuit consists of two inductor and three diodes. Buck Boost converter is used to boost the photovoltaic voltage at the required high level also act as a MPPT (Maximum Power Point Tracking) controller together with MPPT algorithm to extract the maximum power from the photovoltaic module.**

Keywords- **buck-boost converter, switched inductor, H bridge inverter, unipolar switching scheme.**

I. INTRODUCTION

The role of power electronics converter is very important in the PV systems. There are two stage where power electronics converter are used first DC-DC converter stage in which lower level PV voltage is stepped-up at the required higher level; and second DC-AC inverter stage in which boosted DC link voltage is converted into AC.

II. DC - DC CONVERTER STAGE

The heart of MPPT hardware is a switched mode DC-DC converter. That converts a dc input voltage into dc output of lower and higher amplitude. It is widely used in DC power supplies and DC motor drives for the purpose of converting unregulated DC input into a controlled DC output at a desired voltage level. MPPT uses the same converter for a different purpose: regulating the input voltage at the PV MPP and providing load matching for the maximum power transfer [1].

Many topologies are available for DC-DC converters; the most important topologies used for PV systems are, Buck converter, Boost converter and Buck – Boost converter.

A. Buck DC-DC Converter

The output voltage of this converter is lower than the input voltage provided. Figure 1 shows a typical buck converter circuit. This circuit configuration consists of four main components: switch, diode, inductor and an output capacitor for filtering. A switching control circuit is usually need to monitors the output voltage and can be maintains within the desired voltage level by switching alternately high or low at a fixed operating frequency with an adjustable duty cycle. Therefore when the switch turns on, the current from the input source will flows through the switch and inductor, and into the capacitance and the load resistor. During this period, the magnetic field in any drop in current and at the inductor builds up the stored energy. When the switch is off, the inductor opposes same time reverses the EMF which induced current towards the load from the diode [2] [7] [11].

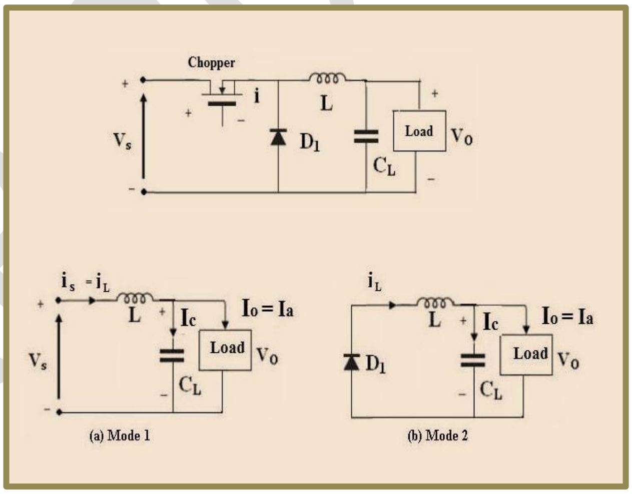

Fig. 1 Circuit diagrams of Buck Converter, (a) Mode 1 and (b) Mode 2

$$V_o = D\ V_s \qquad (1)$$

Where

V_o = average output voltage
V_s = the input voltage, PV voltage
D = duty cycle of converter switch

B. Boost DC-DC Converter

The output voltage of this circuit configuration will always be greater than the input sources. Figure 2 shows the typical boost converter circuit configuration. It had the same component as the buck converter but is arranged in a different configuration so as to boost or step-up the voltage. The switch is selected for high speed operation and switching duty cycle are used to control the voltage output. In the switch on state, the current pass through inductor and switch, and energy is stored in the inductor magnetic field. No current can pass through the diode and the charge in capacitance supplied the current to the load. When the

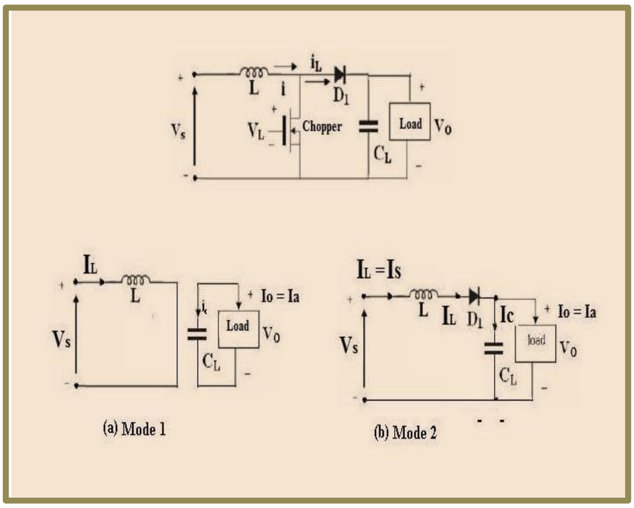

Fig. 2 Circuit diagrams of Boost converter, (a) Mode 1 and (b) Mode 2

switch is off, the inductor output voltage will be added with the input voltage and the current from the boosted voltage will flow from the source to the load, recharging the capacitance. Large ripple occur in this kind of situation and required a large input bypass capacitor to reduce the source impedance. [2]

$$V_O = \frac{1}{1-D} V_3 \qquad (2)$$

Where

V_o = average output voltage
V_i = the input voltage, PV voltage
D = duty cycle of converter switch

C. *Buck-Boost DC-DC Converter*

This converter is modified like a combination of a buck and boost converter. It can be an inverting topology where the output voltage is of opposite polarity as the input. It can also act as a buck converter follow by the boost converter function. From figure 4.3, when the switch is in the "on state", the inductor stored the energy in the magnetic field as it is connected with the source voltage where currents will flow through the diode is reversed biased and hence no current can flow to the load through the diode. The capacitance will provide current in this "Ton" situation. When the switch is off, inductance is disconnected from the source and there will be no current drop which the inductance will reverse it EMF. A voltage is generated as the diode at this time is forward biased; current will flow in the load and charged up the capacitance. The buck boost is a simple converter with good response speed and the controlling method is flexible. The overall efficacy of the photovoltaic with buck boost is improved. The output voltage function of the duty cycle is given by the equation 3 [2] [9].

$$V_O = -V_{in} \frac{1}{1-D} \qquad (3)$$

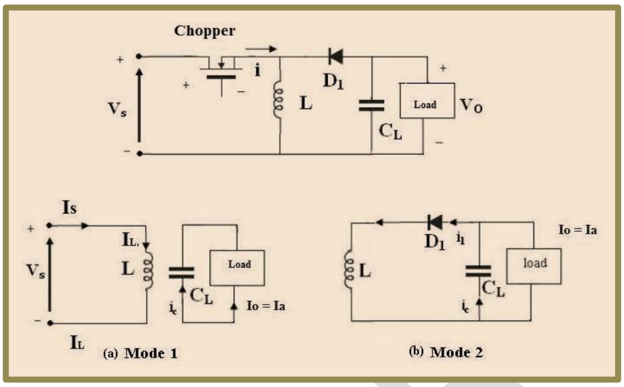

Fig. 3 Circuit diagrams of Buck Boost converter, Mode 1 and Mode 2

III. OPERATING MODE OF DC-DC CONVERTER

DC - DC converters can operate and function into the continuous mode and discontinuous mode. During the continuous mode, the current does not fall to zero during the whole cycle. In the discontinuous mode, the current value is unstable and fluctuates during the cycle and reaches zero during the end of cycle. This is due to the incapability of the stored energy to sustain the current flow of the next cycle of the input voltage frequency. The energy stored is depended and usually affected due to the size of inductor, duty cycle value, input voltage and the output voltage.

A. *Buck Boost Converter in Continuous Mode*

The current through the inductor never drop to zero during the cycle in fig 3 (b). Hence, the polarity of the output voltage is always in negative side. [3]

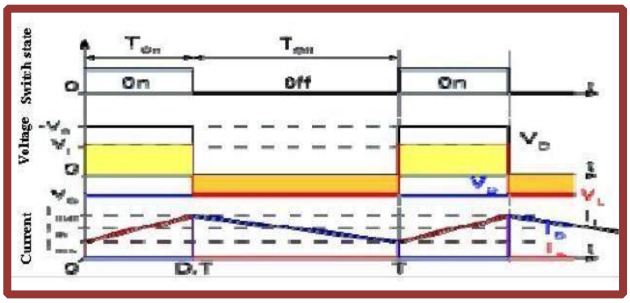

Fig. 4 Current and voltage waveforms in continuous mode

B. *Buck Boost Converter in Discontinuous Mode*

In some situation, there exists a small amount of energy to be transferred to the load in a time lower than the cycle period. This occurrence causes the current passing through the inductor dropping to zero during part of the period cycle. The difference as compared with continuous mode is that the inductor is completely discharge at the end of the whole cycle as seen in fig. 5. This mode is complicated as the output voltage gain depends not solely on the duty cycle, but on the input voltage, inductor, frequency and output current. [3]

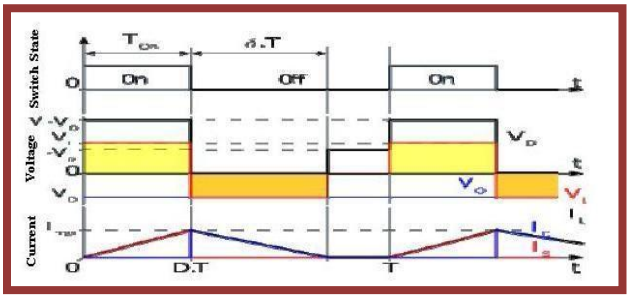

Fig. 5 Current and voltage waveforms in discontinuous mode

IV. SWITCHED INDUCTOR BUCK BOOST CONVERTER

Here inductor is replaced by switched inductor as compared to Traditional Buck-Boost converter. It comprises of two inductor and three diodes as shown in fig. 6. Introducing this switched inductor we get the advantage of high voltage gain with keeping the efficiency almost no change. The proposed converter operates in discontinuous conduction mode**.** It has three modes of operations. [4]

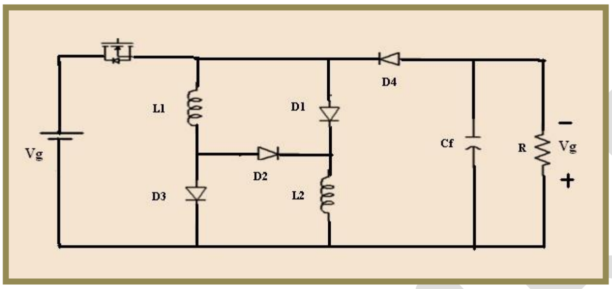

Fig. 6 Switched Inductor Buck Boost Converter

1) Mode-1

From Fig. 6 (a), mode-1 takes place when SW_1, diodes D_1 and D_3 are on. When switch Sw1 is on and D_2 and D_4 are off, the circuit is split into two different parts: the source chargers the two inductors on the left while the right has the capacitor, which is responsible for sustaining outgoing voltage via energy, stored previously. The current of inductor L is increased gradually. In this case, the steady state equation of the converter is given by, [4] [8]

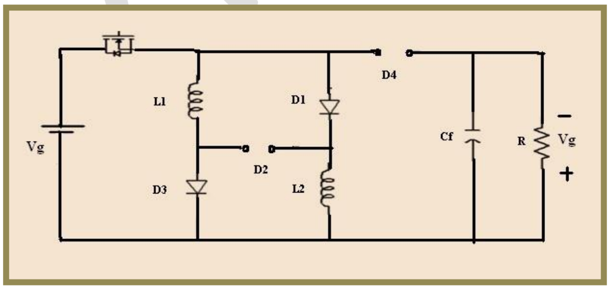

Fig. 6 (a) Mode 1

$$v_L = V_g \quad (4)$$

$$i_c = -\frac{V_o}{R} \quad (5)$$

2) Mode-2

From Fig. 6 (b), mode -2 takes place when diodes D2 and D4 are on are $SW_1$and diodes D_1 and D_3 are off. When the switch SW1 is off and D2 and D4 are on, the energy that is stored within the two inductors will help supplement power for the circuit that is on the right there by resulting in a boost for the output voltage. Then, the inductor current discharges and reduces gradually. The output voltage could be sustained at a particular wanted level if the switching sequence is controlled. The steady state equation of the converter in this mode is given by [4],

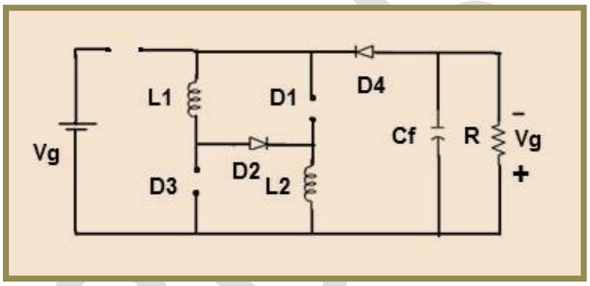

Fig. 6 (b) Mode 2

$$v_L = -\frac{V_O}{2} \quad (6)$$

$$i_c = I_L - \frac{V_O}{R} \quad (7)$$

3) Mode-3

Mode-3 takes place when SW_1 and all diodes are off as shown in fig. 6 (c). Then the inductor current becomes zero [4].

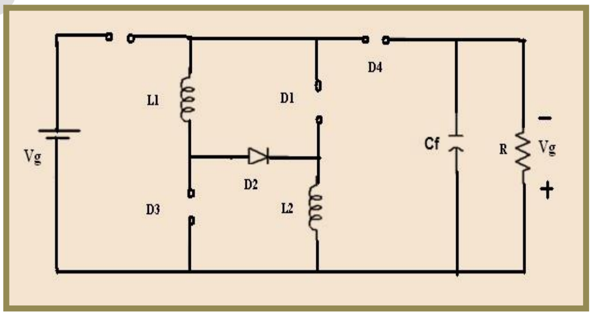

Fig. 6 (c) Mode 3

$$v_L = 0 \quad (8)$$

$$i_c = -\frac{V_O}{R} \quad (9)$$

A Inductor Volt Second Balance

Figure 7 shows inductor current waveform which is discontinuous in nature. From the steady state analysis and balance theory the average value of inductor voltage is zero.

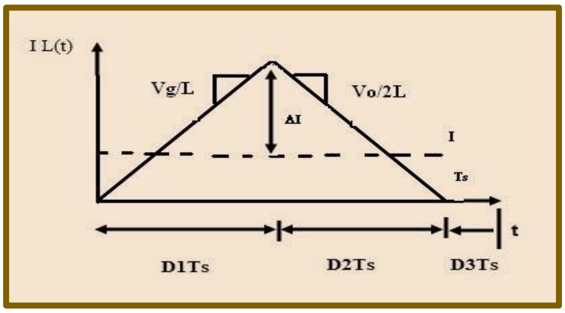

Fig. 7 Inductor current

$< v_l \geq = 0$

$D_1 v_g + D_2\left(-\frac{V_O}{2}\right) + D_3(0) = 0$

Solve for V_O

$V_O = 2\,\frac{D_1}{D_2} v_g$ (10)

Peak Inductor current is

$$i_{pk} = \frac{v_g}{L} D_1 T_S \quad (11)$$

$$i_d(t) = i_c(t) + \frac{V_O}{R}$$

From the capacitor charge

Balance theory $< i_C > = 0$ (12)

Therefore, $< i_d > = \frac{V_O}{R}$

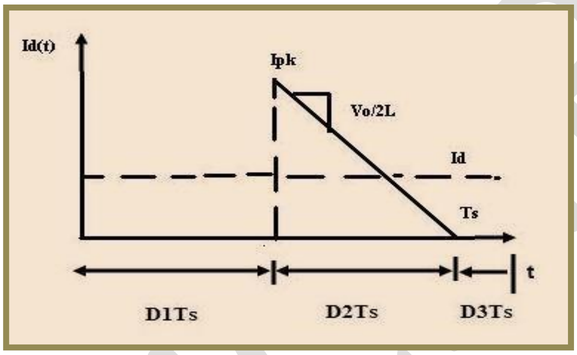

Fig. 8 Diode D_4 Current

B. *Capacitor Charge Balance*

Figure 8 shows diode D4 current. Taking node equation in Fig. 9

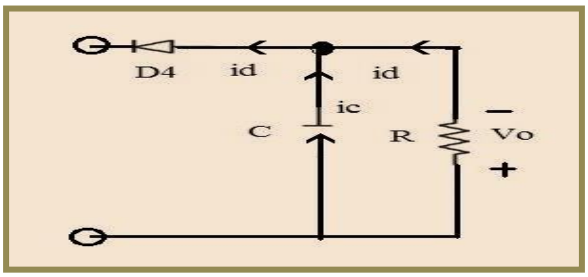

Fig. 9 Current flows through Diode D_4

Average diode current

$$< i_d > = \frac{1}{T_S}\int_0^{T_S} i_d(t)\,dt$$

From the triangle area formulae

$$\int_0^{T_S} i_d(t)\,dt = \frac{1}{2} i_{pk} D_2 T_s$$

Therefore average diode current is

$$< i_d > = \frac{1}{T_S}\left(\frac{1}{2} i_{pk} D_2 T_s\right)$$

$$= \frac{1}{2}\,(i_{pk} D_2)$$

$$\frac{V_O}{R} = \frac{V_g D_1 D_2 T_S}{2L} \quad (13)$$

C. *Gain of the Converter*

From the equation (13)

$$\frac{V_O}{v_g} = \frac{R\,D_1\,D_2\,T_S}{2L} \quad (14)$$

From the Volt second balance (10)

$$D_2 = \frac{2 D_1 v_g}{V_O} \quad (15)$$

Substitute this equation 15 in charge balance equation 14

$$\frac{V_O}{vg} = RD_1\left(\frac{2\,D_1 v_g}{V_O}\right)\frac{T_s}{2L}$$

Hence

$$\frac{V_O}{v_g} = \sqrt{2K} \quad (16)$$

Where

$$K = {D_1}^2 \frac{R}{2L} T_S$$

From the equation 16 gain of switched inductor buck boost converter is higher by √2 than the traditional buck boost converter.

V. DC-AC INVERTER STAGE

The electricity generated by a PV module is in the form of direct current (D.C). Transformation of direct current to alternating current (A.C) required by many common appliances and for grid-connection is achieved with an inverter. Power inverters produce one of three different types of wave output [5] [8] [10].

- Square Wave

- Modified Square Wave or Modified Sine Wave
- Pure Sine Wave or True Sine Wave

Based on their operation the inverters can be broadly classified into

- Voltage source inverter (VSI)
- Current source inverter (CSI)

The type of inverter where the independently controlled ac output is a voltage waveform mostly remaining unaffected by the load. Due to this property, the VSI have many industrial applications such as adjustable speed drives (ASD) and also in Power system for FACTS (Flexible AC Transmission System).The voltage source inverters have a capacitor in parallel with the DC input [5] [12].
The type of inverter where the independently controlled ac output is a current waveform mostly remaining unaffected by the load. These are widely used in medium voltage industrial applications, where high quality waveform is required. The current source inverters have an inductor in series with the DC input. The simplify converter topology are shown in fig. 10 (a) and (b).

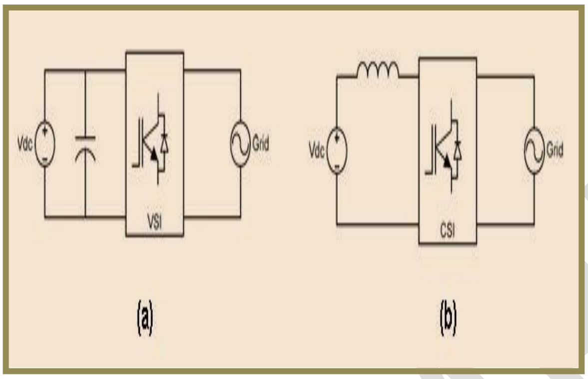

Fig. 10 Voltage source inverter (a), Current source inverter (b)

The full-bridge inverter is the most used in PV system. Therefore here we discuss the full bridge Voltage source inverter and its switching schemes are explained here.

A. *Full bridge or H-Bridge inverter*

As can be seen in Figure 11 the full bridge or H-bridge as it is sometimes known consists of two parallel strings having two switching power devices in series with anti-paralleled diodes. The full bridge converter can be used to generate two different PWM pulse trains depending on the switching scheme implemented. The two schemes are called bipolar and unipolar switching [6].

B *Bipolar Switching Scheme*

A full bridge converter which uses a bipolar switching scheme is called a two level converter. With a bipolar switching scheme, the full bridge converter only has two switching states as the junction voltage (V_j) switches from $+V_{dc}$ to $-V_{dc}$ using PWM. When used as a two level converter the full bridge converter uses the switching scheme outlined in Table I the resulting pulsed output is displayed in Fig. 12. Figure 13 displays the carrying current paths at each switching state [6].

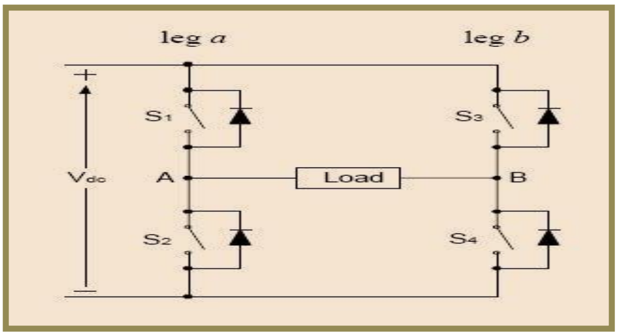

Fig. 11 H-Bridge Inverter

Table I Switching States For Bipolar Switching Scheme For A Full Bridge Converter

Switching State	Switches On	Switches Off	Pulsed Output Voltage (V_j)
1	S1, S4	S2, S3	$+V_{dc}$
2	S2, S3	S1, S4	$-V_{dc}$

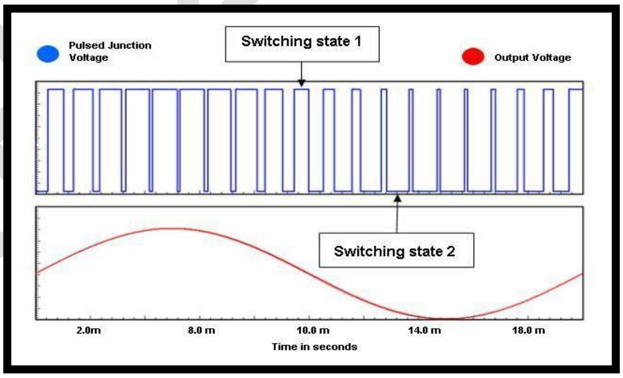

Fig. 12 Unipolar (Two Level) Switching Scheme

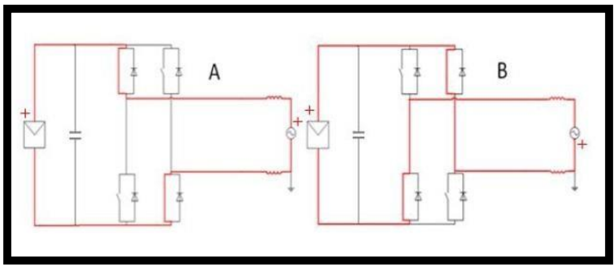

Fig. 13 **A**-Current Path for Full Bridge Converter implementing Bipolar Switching Scheme during Switching State-1, **B**-Current Path for Full Bridge Converter implementing Bipolar Switching Scheme during Switching State-2

C. *Unipolar Switching Scheme*

A full bridge converter which uses unipolar switching is called a three level converter. A unipolar switching scheme is where the output of the converter (V_j) switches between

$+V_{dc}$ and zero during the positive half wave and between and $-V_{dc}$ and zero during the negative half wave.

Unlike bipolar switching, unipolar switching requires at least three different switching states as the junction voltage (V_j) can be either $+V_{dc}$, $-V_{dc}$ or zero although most inverters implement four switching states by having a different switching combination to create the zero junction voltage for each half wave. This to evenly distribute the use of switches making heating symmetrical and thereby reducing losses. [6]

A number of different unipolar switching schemes exist for full bridge topologies with associated advantages and disadvantages regarding PV array voltage, switching losses and complexity of control signal generation.

Table II Switching States For Standard Unipolar Switching Scheme For A Full Bridge Converter

Switching state	Switch on	Switch off	Junction voltage	Half wave
1	S1, S4	S2, S3	+Vdc	Positive
2	S1, S3	S1, S4	0	Positive
3	S1, S4	S2, S3	-Vdc	Positive
4	S2, S4	S1, S3	0	Positive
5	S2, S3	S1, S4	+Vdc	Negative
6	S1, S3	S2, S4	0	Negative
7	S2, S3	S1, S4	-Vdc	Negative
8	S2, S4	S1, S3	0	Negative

Table III Switching States For One Phase Chopping Unipolar Switching Scheme (Type –A) For A Full Bridge Converter

Switching state	Switch on	Switch off	Junction voltage
1	S1, S4	S2, S3	$+V_{dc}$
2	S2, S4	S1, S3	0
3	S2, S3	S1, S4	$-V_{dc}$
4	S2, S4	S1, S3	0

Table IV Switching States For One Phase Chopping Unipolar Switching Scheme For A Full Bridge Converter (Type B)

Switching state	Switch on	Switch off	Junction voltage
1	S1, S4	S2, S3	$+V_{dc}$
2	S2, S4	S1, S3	0
3	S2, S3	S1, S4	$-V_{dc}$
4	S3, S1	S2, S4	0

The three unipolar switching schemes implemented by full bridge topologies that schemes and associated switching states and orders are presented in Table II, III & Table IV.

The main difference between the three presented unipolar switching schemes is the implementation of different free-wheeling states during each half wave. While both one phase chopping methods operate similarly with the only difference being that type B implements a different switching state for the freewheeling state of each half wave, the standard method is subtly different because both freewheeling states occur in the same half wave [6].

The resulting pulsed output of the one phase chopping scheme (type B) is displayed in Figure. The associated current paths are displayed in Fig. 14 [6].

A-During Switching State 1, **B**-Current Path for Full Bridge Converter implementing Unipolar Switching Scheme during Switching State 2, **C**-Current Path for Full Bridge Converter implementing Unipolar Switching Scheme during Switching State 3 D- Current Path for Full Bridge Converter implementing Unipolar Switching Scheme during Switching State 4.

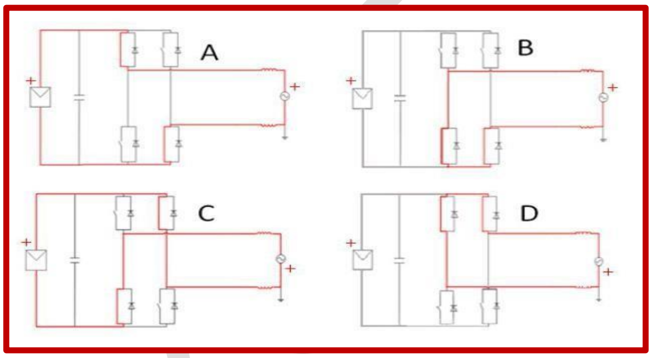

Fig. 15 A-Current Path for Full Bridge Converter implementing Unipolar Switching Scheme

One of the main associated advantages of implementing a unipolar switching scheme as opposed to a bipolar scheme is that the switching losses are significantly reduced because the associated voltage drop from switching from one state to another is halved.

One of the drawback of implementing a unipolar switching scheme however is that there are higher associated harmonic content in the output current around the zero crossing (particularly at lower power levels).

VI. CONCLUSION

At the beginning basic dc-dc converter topologies Buck, Boost, Buck Boost are presented then the switched inductor buck boost converter is presented with its different mode of operations. From the energy balance theory, gain of the switched inductor Buck Boost converter is $\sqrt{2}K$; which is higher by $\sqrt{2}$ than the traditional Buck Boost converter.

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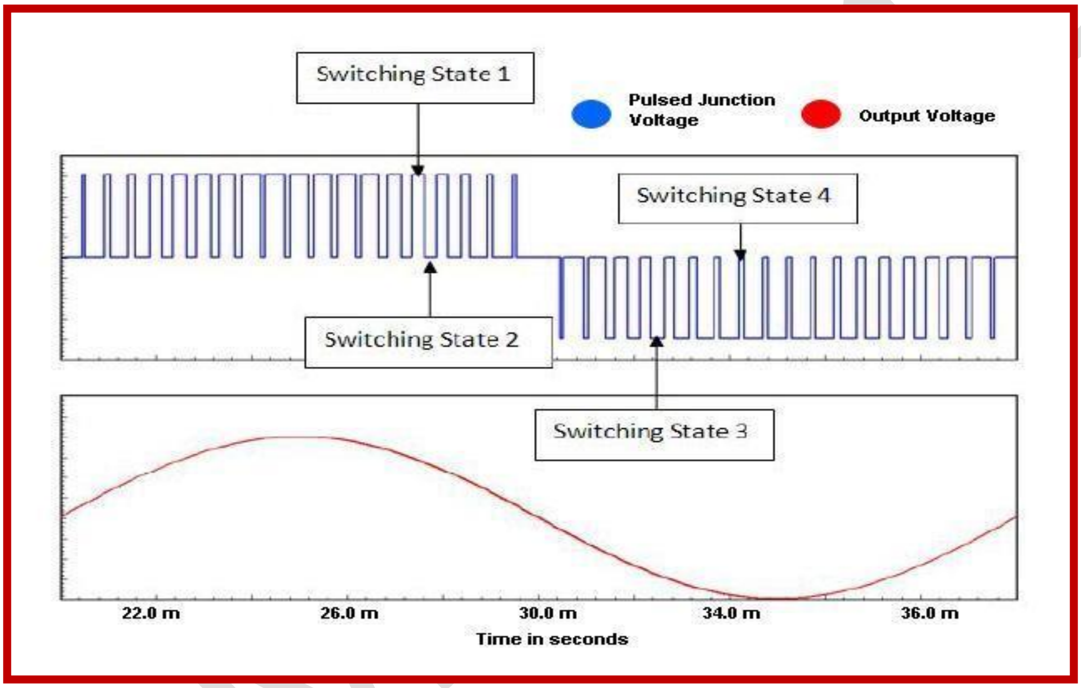

Fig. 14 Unipolar (Four Level) Switching Scheme