POWER ELECTRONICS: A SERVING TOOL TO IMPROVE THE EFFICIENCY OF SOLAR POWER SYSTEM

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Abstract: To harness the power from sunlight has become a common phenomenon to the places situated near equator globally. Photovoltaic cell is the core component of the solar system and generate electricity when sunlight bombard on it. Though efficiency of the photovoltaic cell has been claimed by the manufacturers 85% against virtual gain of 65-68%. Day after day research work is going on for improvement in efficiency on these core component by the implementation of enhanced semiconductor materials and technology. Power Electronics Engineering has also gained their achievement in the improvement of overall efficiency from harnessed energy through photovoltaic cell to utility grid. This paper describe the importance of power electronics interface which plays their role at two stages in solar power system. At DC-DC converter stage where harnessed DC voltage are boosted up to the required higher voltages and at DC-AC inverter stage where these raised voltages are converted into AC for utility grid improving current as well as power. Thus overall efficiency is improved by power electronics interface.
Keywords: photovoltaic (PV) cell, Maximum Power Point Trackink (MPPT), DC-DC converter, DC-AC inverter, unipolar switching scheme.

I. INTRODUCTION

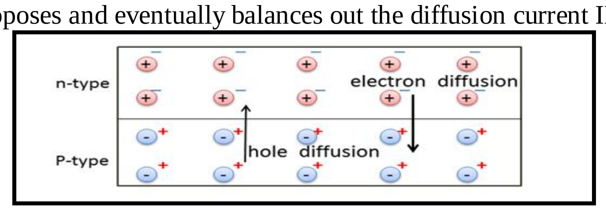
For developing countries, providing energy to its stakeholders in an efficient and cost effective manner is a highly challenging task. In spite of significant harnessing of the fossil fuel reserves, the breach between supply and demand of energy is ever growing. One of the possible options to tie this breach is by making extensive use of solar power [17]. The need for a clean surroundings and the incessant increase in energy demand makes decentralized renewable energy production more and more substantial [17]. 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 [12]. Though PV technologies use both direct and dispersed sunlight to create electricity, harnessing efficiency is 68% eventually against the claim of 85% by the various manufacturers worldwide. Power Electronics Interface are incorporated with PV System to intensify the efficiency of the PV system and undoubtedly we have reached to the goalmouth. Power Electronics is the field of engineering which deals with the use of electronics for the conversion, control and conditioning of bulk electrical power. It also plays an important role in the solar system [11], [21], [22], [30]. 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 [24]; and second DC-AC inverter stage in which boosted DC link voltage is converted into AC [4], [6]. If Maximum Power Point Tracking (MPPT) is accountable for optimizing the efficiency of the photovoltaic system, power electronics interface is the solver. The power loses incurred at the converter stage is reimbursed at inverter stage.

II. PHOTOVOLTAIC CONSTRUCTION AND WORKING

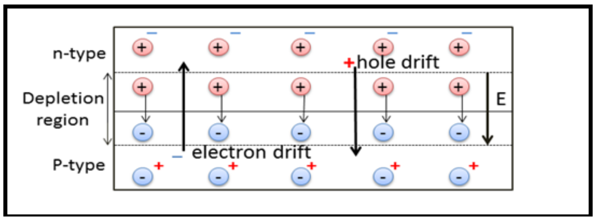
In most of solar cells, the absorption of photons takes place in semiconductor materials, resulting in the generation of the charge carriers and the subsequent separation of the photo-generated charge carries. Therefore, semiconductor layers are the most important parts of a solar cell.

A. Silicon Solar Cell

A solar cell is a device that converts the energy of sunlight directly into electricity by the photovoltaic effect [1]. Although there are many kinds of solar cells developed by using different semiconductor materials, the operating principle is identical. The most commonly known solar cell is configured as a large-area p-n junction made from silicon. When a piece of p-type silicon is placed in intimate contact with a piece of n-type silicon, a diffusion of electrons occurs from the region of high electron concentration (the n-type side) into the region of low electron concentration (p-type side). Similarly, holes flow in the opposite direction by diffusion [15]. This forms a diffusion current ID from the p side to the n side Fig. 1 (a). When the electrons diffuse across the p-n junction, they recombine with holes on the p-type side. The diffusion of carriers does not happen indefinitely because of an electric field which is created by the imbalance of charge immediately on either side of the junction which this diffusion creates. The electric field established across the p-n junction generates a diode that promotes charge flow, known as drift current IS, that opposes and eventually balances out the diffusion current ID.



(a) Diffusion current I_D from the p side to the n side



(b) Drift current I_S from n side to the p side and the depletion zone

Fig. 1. I_D, I_S, and depletion zone of a p-n junction

The region where electrons and holes have diffused across the junction is called the depletion zone Fig. 1 (b).

B. Photo-generated Current and Voltage

When a visible light photon with energy above the band-gap energy strikes a solar cell and is absorbed by the solar cell, it excites an electron from the valence band. With this newfound energy transferred from the photon, the electron escapes from its normal position associated with its atom, leaving a localized "hole" behind [1].

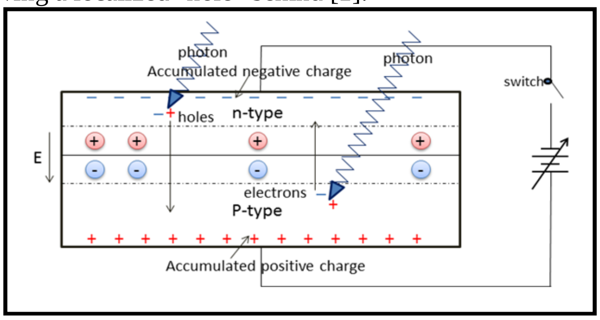


Fig. 2. Illustration of drift current as well as photo-generated current and voltage

When those mobile charge carriers reach the vicinity of the depletion zone, the electric field sweeps the holes into the p-side and pushes the electrons into the n-side, creating a photo-generated drift current. Thus, the p-side accumulates holes and the n-side accumulates electrons Fig. 2 which creates a voltage that can be used to deliver the photo-generated current to a load. At the same time, the voltage built up through the photovoltaic effect shrinks the size of the depletion region of the p-n junction diode resulting in an increased diffusion current through the depletion zone.

Hence, if the solar cell is not connected to an external circuit (switch in the open position in Fig. 2), the rise of the photo-generated voltage eventually causes the diffusion current ID balancing out the drift current IS until a new equilibrium state is reached inside a solar cell [1].

C. PV Cell Constructions

A photovoltaic cell is basically a semiconductor diode whose p-n junction is exposed to light [2]. Photovoltaic cells is made of several types of semiconductors using different Manufacturing processes. The mono-crystalline and polycrystalline silicon cells are the only found at commercial scale at present era.

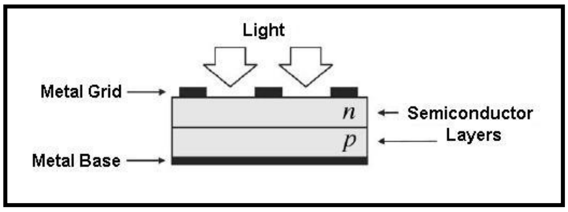


Fig. 3. Photovoltaic Cell Constructions

Silicon PV cells are composed of a thin layer of bulk Si or a thin Si film connected to electric terminals. One of the sides of the Si layer is doped to form the P–n junction. A thin metallic grid is placed on the Sun-facing surface of the semiconductor. Fig. 3 illustrates the physical structure of PV cell [2], [3].

D. P V Cell Working

Photons of light with energy higher than the band-gap energy of PV material can make electrons in the material break free from atoms that hold them and create hole-electron pairs, as shown in Fig. 2.

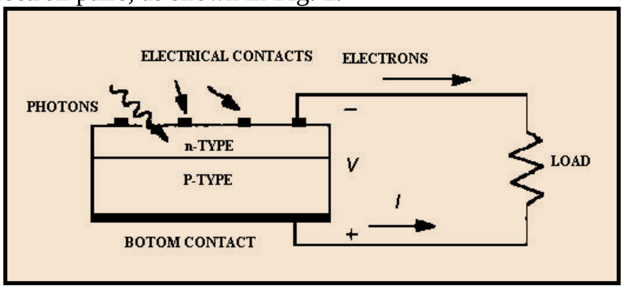


Fig. 4. Working Principle of PV Cell

These electrons, however, will soon fall back into holes causing charge carriers to disappear. If a nearby electric field is provided, those in the conduction band can be continuously swept away from holes toward a metallic contact where they will emerge as an electric current. The PV cell has electrical contacts on its top and bottom to capture the electrons, as shown in Fig. 4. When the PV cell delivers power to the load, the electrons flow out of the n-side into the connecting wire, through the load, and back to the p-side where they recombine with holes [2]. Note that conventional current flows in the opposite direction from electrons [4], [14].

III. MAXIMUM POWER POINT TRACKING PROCESS

Fig. 5 shows I-V characteristics of the PV under a given irradiation condition. The internal impedance of the PV array is low on the right side of the curve and high on the left side of the curve. The maximum power point of the PV array is located at the knee of the curve. According to the maximum power transfer theorem the power delivered to the load is maximum when the source internal impedance matches with the load impedance. Thus the impedance seen from the converter side needs to match with the internal impedance of the PV array to operate the system near to MPP of PV [5].

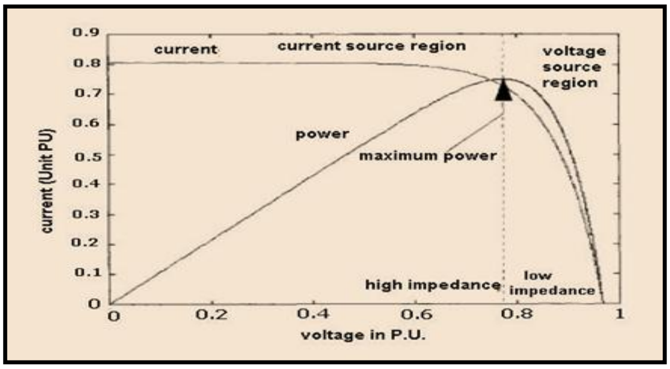


Fig. 5. Photovoltaic I-V characteristics

Generally most of DC-DC converter has a negative impedance characteristic that means its current increases when voltage decreases. This is due to the constant input power and adjustable output voltage of the power supply. To perform the tracking process, PV array required to operate on the right side of the curve. If the system operates on the high impedance side (low voltage) of PV array curve, the PV array terminal voltage will collapse [5].When PV module is directly coupled to a load, the PV module's operating point will be at the intersection of the I-V curve and the load line. Load line is the I-V relationship of the load.

In Fig. 6 (a) resistive load is connected to the photovoltaic system, which has straight line with slope of 1/Rload as shown in Fig. 6 (b). This operating point is seldom at the PV module's MPP. Thus it will not producing the maximum power. Hence a direct coupled system utilizes approximately 31% of the PV capacity [6], [7].

To increase the efficiency of the PV system a DC-DC converter is used as an interface between PV module and the load to perform the MPPT process and at the load matching (Rload = Ropt) where Rload is the impedance load. Ropt is the optimal load for PV. By varying the duty cycle of the converter the peak power point is obtained.

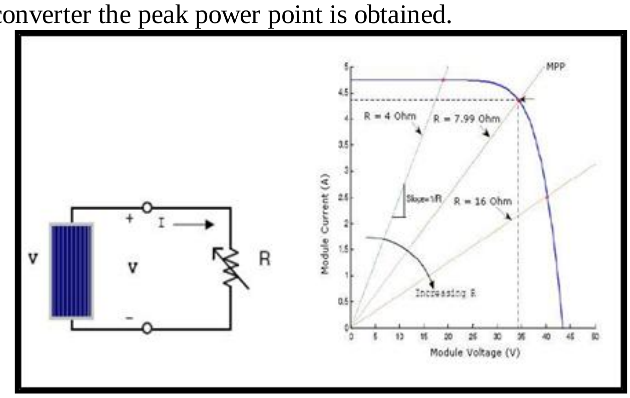


Fig. 6. Photovoltaic module directly connected to the Resistive load (a), and I-V curve of directly connected module at various resistive loads (b)

For boost converter average output voltage is given by

$$V_O = \frac{1}{1-D} V_S \tag{1}$$

Where
D = Duty cycle of converter
V_o = Output voltage of converter
V_i = Input voltage of converter

Assuming power constancy we can write
Input power = output power

$$V_S I_S = V_O I_O \tag{2}$$

$$\frac{V_S}{V_O} = \frac{I_O}{I_S} = 1 - D \tag{3}$$

From Equation 1 and Equation 3 input impedance of the converter is

$$R_{in} = \frac{V_S}{I_S} = (1-\mathrm{D})^2 \frac{V_O}{I_O} = (1-D)^2 R_{load} \tag{4}$$

The impedance seen by the PV is the input impedance of the converter. By changing the duty cycle of the converter the value of Rin can be matched with Ropt. Therefore the impedance of the load can be taken any value as long as the duty cycle is adjusted accordingly [5], [6], [10].

IV. DC-DC CONVERTER STAGE

The heart of MPPT hardware is a switched mode DC-DC converter. It 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 [6]. 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. Fig. 7 shows a typical buck converter circuit. This circuit configuration consists of four main components: switch, diode, inductor and an output capacitor for filtering.

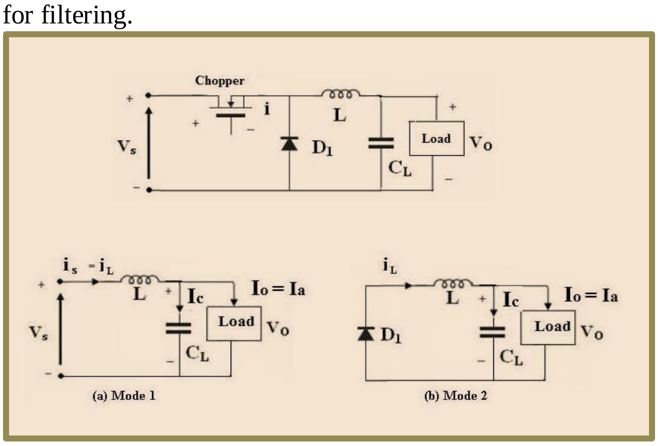


Fig. 7. Circuit diagrams of Buck Converter, (a) Mode 1 and (b) Mode 2

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 [4], [9], [11].

$$V_o = D\,V_s \quad (5)$$

Where

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

B. DC-DC Boost Converter

The output voltage of this circuit configuration will always be greater than the input sources. Fig. 8 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.

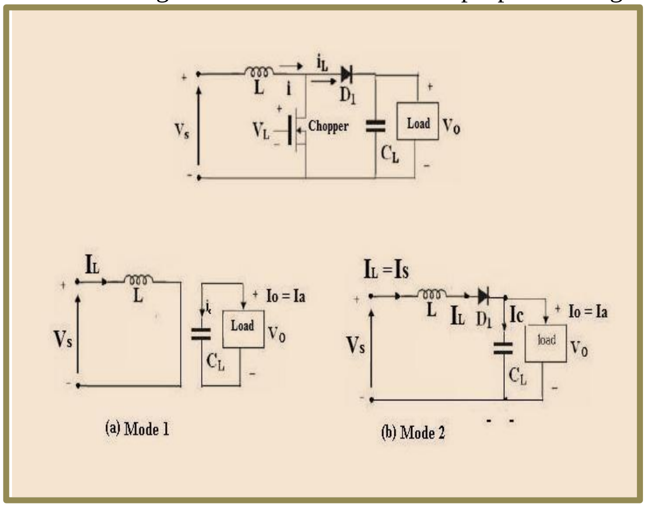


Fig. 8. Circuit diagrams of Boost converter, (a) Mode 1 and (b) Mode 2

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 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 [9].

$$V_o = \frac{1}{1-D}\,V_3 \quad (6)$$

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 Fig. 9, 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.

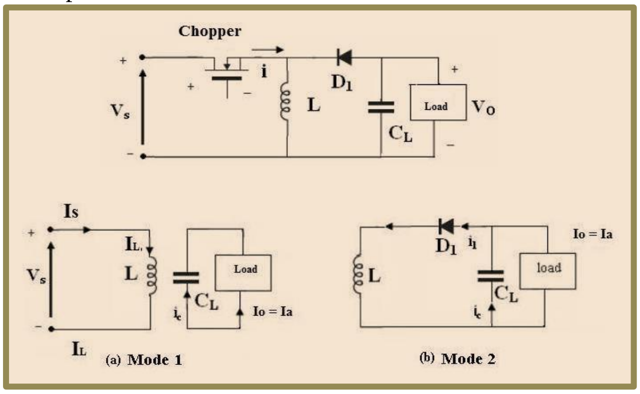


Fig. 9. Circuit diagrams of Buck Boost converter, Mode 1 and Mode 2

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 7 [9], [12].

$$V_o = -V_{in}\,\frac{1}{1-D} \quad (7)$$

V. 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. 9 (b). Hence, the polarity of the output voltage is always in negative side [13].

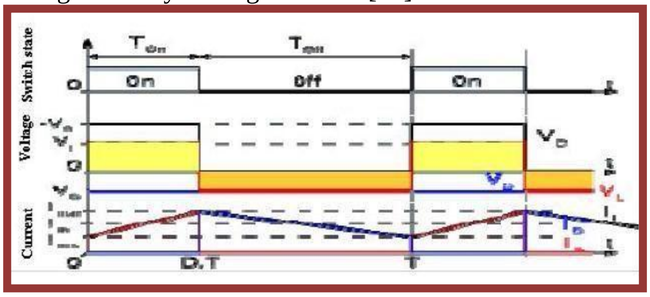


Fig. 10. Current and voltage waveforms in continuous mode

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.

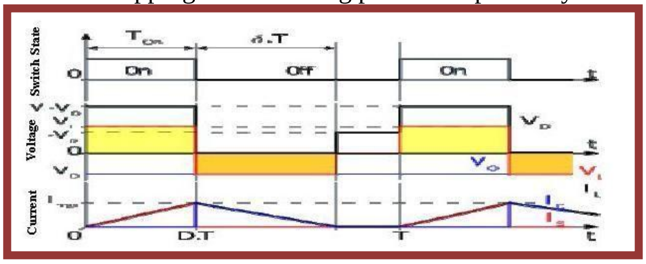


Fig. 11. Current and voltage waveforms in discontinuous mode

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. 11. 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 [8], [13].

VI. DC-AC Inverter Stage

The power produced by a PV module is in the form of direct current. Conversion of direct current to alternating current required by many common appliances and for grid-connection is realized with an inverter. Inverter is basically an interface between photovoltaic cell and AC grids. There are several inverter topologies but output current distortion and efficiency are the two key parameters for the selection of inverters. Power inverters produce one of three different types of wave output [15] [16] [7] [17].

- Square Wave
- Modified Sine Wave
- Pure Sine Wave

Based on their operation the inverters can be broadly classified into

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

The output voltage waveform of Voltage Source Inverter are independently controlled and mostly remain unaffected by the load. Due to this phenomenal behavior, the VSI have many industrial applications such as adjustable speed drives and also in Power system for FACTS (Flexible AC Transmission System) [25]. The voltage source inverter possesses a capacitor in parallel with the DC input [16], [18].

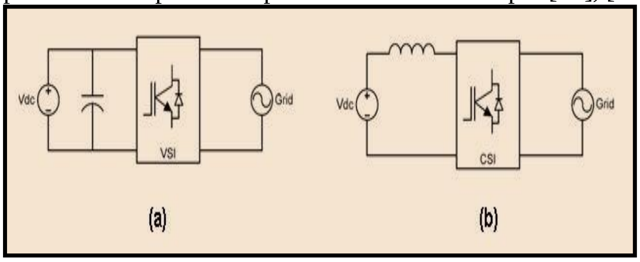


Fig. 12. VSI (a), CSI (b)

The output current waveform of Current Source Inverter are independently controlled and mostly remain unaffected by the load. Such Inverters are broadly used in medium voltage industrial applications where high quality waveform is mandatory. The current source inverters possess an inductor in series with the input. The converter topology are shown in Fig 12 (a) and (b). Full - Bridge inverters are widely used in Photovoltaic system [29]. Therefore here we will discuss the full bridge voltage source inverter and its switching schemes.

A. Full Bridge Inverter

Fig. 13 the Full bridge inverter consists of two parallel strings contributing two switching power devices in series with anti-paralleled diodes. Variation of duty cycle of the PWM signal offers a voltages across the load in a specific pattern which appear to the load as AC signal. A pure sin wave is attained after passing the signal through a low pass filter [28]. The pattern at which the duty cycle of a PWM signal varies can be realized using simple analogue components or a digital microcontroller [24]. Either of the two basic topologies generate sinusoidal PWM that controls the output of the inverter [15]. 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 [19], [20], [21], [22], [26].

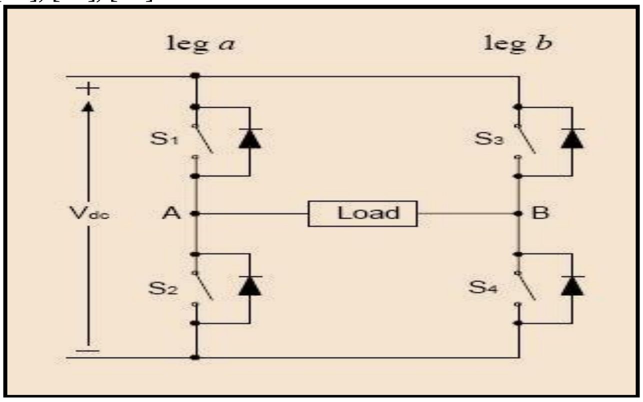


Fig. 13. Full - Bridge Inverter

B. 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. 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 [19], [23].

Table 1: Switching States for Standard Unipolar Switching Scheme for a Full Bridge Converter

Switching state	Switch on	Switch off	Junction voltage	Half wave
1	S_1, S_4	S_2, S_3	$+V_{dc}$	Positive
2	S_1, S_3	S_1, S_4	0	Positive
3	S_1, S_4	S_2, S_3	$-V_{dc}$	Positive
4	S_2, S_4	S_1, S_3	0	Positive
5	S_2, S_3	S_1, S_4	$+V_{dc}$	Negative
6	S_1, S_3	S_2, S_4	0	Negative
7	S_2, S_3	S_1, S_4	$-V_{dc}$	Negative
8	S_2, S_4	S_1, S_3	0	Negative

TABLE 2: 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	S_1, S_4	S_2, S_3	$+V_{dc}$
2	S_2, S_4	S_1, S_3	0
3	S_2, S_3	S_1, S_4	$-V_{dc}$
4	S_2, S_4	S_1, S_3	0

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

Table 3: 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	S_1, S_4	S_2, S_3	$+V_{dc}$
2	S_2, S_4	S_1, S_3	0
3	S_2, S_3	S_1, S_4	$-V_{dc}$
4	S_3, S_1	S_2, S_4	0

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 [19].

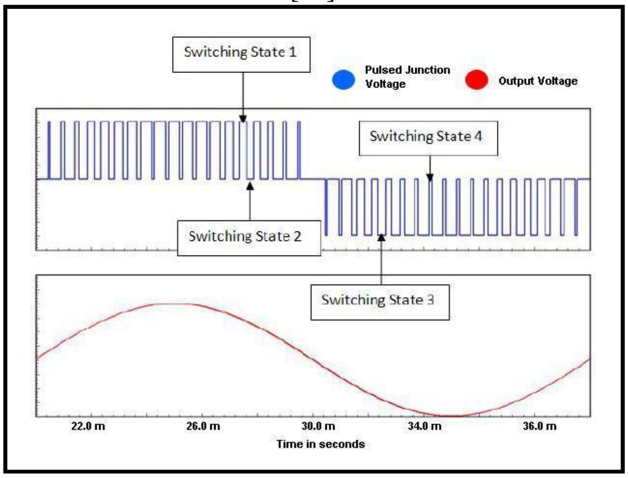


Fig. 14. Unipolar (Four Level) Switching Scheme

The resulting pulsed output of the one phase chopping scheme (type B) is displayed in Fig 14. The associated current paths are displayed in Fig. 15 [19].

One of the main advantage of executing a unipolar switching scheme compared to a bipolar scheme is that the switching losses are significantly reduced due to the allied voltage drop of switching from one state to another. Drawback of executing a unipolar switching scheme is that, there are higher associated harmonic content in the output current round the zero crossing (particularly at lower power levels)

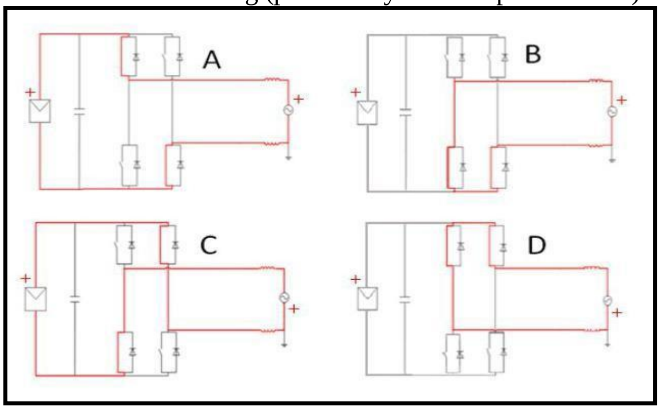


Fig. 15. A-Current Path for Full Bridge Converter implementing Unipolar Switching Scheme B-Current Path for Full Bridge Converter implementing Unipolar Switching Scheme during Switching State 2, C-Current Path for Full Bridge Converter implementing Unipolar Switching Scheme during Switching State 3 D- Current Path for Full Bridge Converter implementing Unipolar Switching Scheme during Switching State 4.

VII. CONCLUSIONS

- 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.
- The heart of MPPT hardware is a switched mode DC-DC converter. It 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.
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- One of the main advantage of executing a unipolar switching scheme compared to a bipolar scheme is that the switching losses are significantly reduced due to the allied voltage drop of switching from one state to another.

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