Different Converter Topologies for Solar Photovoltaic System with methods for Maximum Power Point Tracking Algorithms

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Abstract: Renewable energy sources are becoming important for the production of electricity used in residential, commercial and industrial applications. These resources include non-conventional sources like solar, wind, hydro, biogas, tidal and biomass. All these are contributing in the production of electrical energy and also help in reducing the pollution by reducing the green gas emissions which were one of the reasons to reduce the use of conventional sources. Out of all of the above, the source which is gaining an importance and maximum usage is a solar energy. The reason behind its extensive use is it is freely available, abundant, non-polluting nature and its conversion without involving any rotating device. Combining the two systems increases the performance and efficiency of a particular system. Hence to improve its performance and use by two-fold, a solar system can be integrated with thermal, hydro or wind power system. Also, a suitable converter topology will be used along with an appropriate control algorithm. Solar energy changes as per irradiance and temperature in a day also one factor which reduces the power output is the partial shading in cells. This will alleviate the conversion efficiency of solar system (About 20%). Many conventional and advanced algorithms are used for getting the optimum output from a solar system. Now days to get optimum energy from a solar system, soft computing algorithms are used in a system which are called as operating point tracking algorithms. This paper intended to emphasize on converter topologies and a brief introduction of MPPT algorithms.

Keywords: Distributed generation, Converter topology, MPPT algorithms, Perturb and Observe, Global maxima

I. INTRODUCTION

An energy source which will be inexpensive and has a ability to sustain is today’s need due to the rapid changes in environmental conditions and global warming. Also, the fast increase in demand of the electricity should be accomplished with the continuity and less interruption. By taking into account the noise, pollution, environmentally friendly factor and availability, solar photovoltaic system plays a vital and prominent role among other notable renewable energy sources. Its few remarkable advantages are, it has flexible characteristics, lower maintenance cost, longevity as well as abundance. PV systems are classified into 2 categories, stand alone and grid connected. Places where electrical installation is not feasible due to the locations which are away from utility grid, a stand-alone PV system is used. While the PV systems, which are connected to utility grids are in turn useful to the grids as they supply electricity and also help in reducing the pollution by reducing the green gas emissions which were one of the reasons to reduce the use of conventional sources. Out of all of the above, the source which is gaining an importance and maximum usage is a solar energy. The reason behind its extensive use is it is freely available, abundant, non-polluting nature and its conversion without involving any rotating device. Combining the two systems increases the performance and efficiency of a particular system. Hence to improve its performance and use by two-fold, a solar system can be integrated with thermal, hydro or wind power system. Also, a suitable converter topology will be used along with an appropriate control algorithm. Solar energy changes as per irradiance and temperature in a day also one factor which reduces the power output is the partial shading in cells. This will alleviate the conversion efficiency of solar system (About 20%). Many conventional and advanced algorithms are used for getting the optimum output from a solar system. Now days to get optimum energy from a solar system, soft computing algorithms are used in a system which are called as operating point tracking algorithms. This paper intended to emphasize on converter topologies and a brief introduction of MPPT algorithms.

Keywords: Distributed generation, Converter topology, MPPT algorithms, Perturb and Observe, Global maxima

II. PV CELL EQUIVALENT CIRCUIT AND MATHEMATICAL MODELLING

Diode current is given by,
\[ I_d = I_l(\exp(q(V + I_r s)/(kT)) - 1) \] ..........................(1)
Output current of a solar cell I,
\[ I = I_L - I_d - I_{sh} \] ..........................(2)
Putting the value of I_l and I_{sh}, I will be
$$I = I_{ph} - I_{sat} \left[ \exp \left( \frac{q(V + IR)}{ATk} \right) - 1 \right] - \frac{V + IR}{R_P}$$

Where,
I- load side current (A)
I_{ph} photon current
I_{sat} saturation current of a diode (A)
$q$- charge of an electron-1.6*10^{-19} \, \text{C}$
A- Diode ideality factor
$k$- Boltzmann’s constant -1.38*10^{-23} \, \text{J/K}$
T- Temperature of a cell (°K)
Rs- Resistance in series (Ω)
$R_P$- Resistance in parallel (Ω)
V- Output voltage of a solar Cell

III. SOLAR CELL / MODULE CHARACTERISTICS UNDER STC

A. Current -Voltage Characteristics under Uniform Solar Irradiance

I-V characteristics for the Photovoltaic cell totally depend upon solar insolation (G), thermal condition and type of load. Hence the output current varies according to the different solar radiation values, but the output voltage V remains almost constant. For the temperature change voltage varies but current remain almost constant. \[13\]. The 2 main parameters of the characteristics are Isc (short circuit current) and Voc. Isc is value of current which has voltage value is zero and Voc is value of voltage which has zero cell current. Maximum values of voltage and current can be identified from the readings taken and denoted as Vmp and Imp. Location where Vmp, Imp meets is called peak operating point \[12\]. Load line will be drawn which will be the junction of current-voltage and power-voltage characteristics. To calculate this output resistance, formula used is Rmp/Rp=Vmp/Imp. Fill factor (FF) is one of the notable factor for a photovoltaic module. Given by the ratio of maximum power to product of Voc and Isc. It is useful in evaluating the performance of any panel.

$$\text{FF} = \frac{\text{Imp}}{\text{Isc}} \times \frac{\text{Vmp}}{\text{Voc}}$$

It should be always near to 1

\[\text{Fig.2 Current-voltage cell performance under uniform irradiance and STC}\] \[12\]

Solar irradiance affects the cell/module characteristics. Reduction in radiation levels droops down the curve and the standard test value for G is Kw/m². Below this value the output power generated by the cell/module reduces. Accordingly, Voc reduces.

\[\text{Fig.3 Current-voltage cell performance under Different irradiance levels}\] \[4\]

B. Power-Voltage curves a Photovoltaic Cell under Uniform Solar Irradiance (G)

For the particular insolation, growing module voltage raises panel output power, reaches peak value and reduced to zero. At a particular operating the output gain for the photovoltaic module attends its highest value, that point will be the true operating point/global operating point for solar panel. Loads at the output side are of variable nature, so the MPP is never fixed for any panel. It gets varied as load changes. For promoting PV module at its maximum efficiency, optimization algorithm will be opted. It always keeps the operating peak to work at its best and always tend to operate the panel with the maximum efficiency \[4\].

\[\text{Fig.4 P-V Performance of a PV cell under uniform insolation}\]

\[\text{Fig.5 Performance of a PV cell under diverse radiation levels}\] \[4\]

IV. PV CELL PERFORMANCE UNDER PARTIAL SHADING CONDITIONS

Among various reasons such as aging, disconnection, weather conditions and shading alleviates the output yield from a solar module, sectional/fragmentary shading is the main reason. Partial shading takes place due to tree branches, birds, neighbouring structures, ice/snow accumulation and cloud cover over the panel. Due to this in outdoor solar systems all or some of the solar cells got shadowed which results in an uneven insolation condition. If the modules joined in cascade then for the partial shading condition, few PV cells which receives uniform radiance operates at optimum efficiency, while the cells which are under partial shedding operates with the reverse voltage. This resulting reverse power effect generates an adverse effect of power consumption and in turn weakens a peak power gain from a sectionaly shadowed unit. Exposure of shadowed PV cells more and more to the excess reverse bias voltage may cause formation of ‘hot spots’ on a module. This happens due to the presence of bypass diode in parallel with a solar cell or module. Bypass diode is mainly used to alleviate the negative effects of partial shading conditions, but due the presence of bypass and blocking diodes multiple peaks got generated in the performance characteristics. These multiple peaks are called local maximum power points (LMMP’s)/Pseudo power points \[9\]. Out of number of local and one global MPP, a control algorithm works to fix up the highest operating point (MPP).
A. Current–Voltage performance for the PV Cell under Partially Shaded Condition

In partially shaded cases current-voltage curves of the shadowed and non-shadowed photovoltaic cells of a particular module or in case of array, partially shaded modules and non-shadowed modules is different. Peak power point degrades if a single cell from a module or a particular module from the array gets partially shaded. Also, if a shaded module is connected in series with the unshaded one then an additional loss will take place as the current for the serially joined arrays will get impacted by the shadowed PV cell. Cell failure is more in case of partial shading.[11]

![Fig. 6 Current-voltage performance for a Photovoltaic module in case of partial shading](image)

![Fig. 7 Current-voltage performance of cascaded modules][11]

B. Power-Voltage performance of Solar Cell for Partially Shaded Condition

In a P-V curve for a solar cell / module due to the partially shaded cells multiple peaks occurs which are nothing but the local maximum power points (pseudo points). No any local point representing the real global peak power point. Hence a control algorithm must be such that it should stick for real maximum power point. In case of practical photo voltaic applications partial shading creates more difficulty in tracking MPP.

![Fig. 8 Power-Voltage performance for a Photovoltaic module for Partially Shaded Condition](image)

![Fig. 9 P-V characteristics of a PV array under partial shading condition for series connected modules][11]

V. OPERATING POINT AND DC TO DC POWER CONVERTER

At peak operating point solar module is extracting a maximum power and supplying it to the load. This concept depends on the fact of maximum power transfer theorem i.e. when $Z_o=Z_L$, load will get a maximum power ($P_{max}$). DC-DC converter which is a power interface/power conditioning device between solar module and load fulfils aimed to transmitting superlative power from photovoltaic array to output side. They are used in applications where there is a requirement of average load voltage whose value may ismore than or less than the source voltage.[12] Duty cycle (D) is an important parameter which can be changed to vary the input impedance and matched it with load impedance. This matching is done at the peak point called MPP. Numerous techniques/algorithms are adopted to change the duty ratio. Hence the MPPT device will be connected to power conditioner block, where converter block duty ratio will get changes depending on MPPT output.

![Fig. 10 Power conditioning block with MPPT](image)

Various types are classified for the converter according to their design specifications, position of components, switching devices output and input voltage relationship and values of voltage, current and power generated by each, DC-DC converters are having following 3 basic types.[12]

1) Step down/Buck converter
2) Step up/Boost converter
3) Combination step up and step down/Buck-boost
4) SEPIC (inverted buck boost)
5) Cuk converter

DC-DC converters are used a switch mode controller for changing input DC value of the voltage, which is not regulated, into output DC voltage which will be in a controlled from. This will be achieved using pulse width modulation technique and the switches used are generally BJT, power BJT, MOSFET, or IGBT. Along with the semiconductor switching devices, L-C filter is used converter circuit for the filtering purpose. Each power converter has some advantages and disadvantages which depends on the application used at load side.[10] All the above said converters show the different regions of operation of the MPP and load line which varies with duty cycle (D).

1) Buck converter-load side voltage always less as compared to source side voltage and load current greater as compared to source current.
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Fig. 11 Step down Converter

The conversion ratio for buck converter is

\[ \frac{V_o}{V_{in}} = \frac{I_{in}/I_{o}}{D} = \frac{D}{1 \cdot D} \quad \text{(1)} \]

From eq. 1 \( V_{in} = \frac{V_o}{D} \) and \( I_{in} = I_{o} \cdot D \) \( \text{(2)} \)

\( R_{in} \) – input resistance of converter can be calculated

\[ R_{in} = V_{in}/I_{in} = \frac{V_o}{I_{o}} \cdot D = \frac{V_o}{I_{o}} \cdot D^2 = R_0/D^2 \quad \text{(3)} \]

Where \( R_o \) is load resistance. Duty cycle \( D \) changes from zero to \( \infty \) (i.e. 0 to 1). Therefore \( R_{in} \) will changes from \( \infty \) to \( R_o \) according to the change in duty cycle from 0 to 1. If \( R_{MPP} \) will not come within range of values permitted for \( R_{in} \) then MPP catching is not possible, it is only possible for \( R_{in} \leq R_{MPP} \). Range of \( R_{in} \) values are shown in a figure.

Fig. 12 Operating region for \( R_{in} \) for step down converter and MPP tracking zone

Working: According to the circuit of buck converter, when the \( s/w \) is closed, there is a current which takes its path via \( s \), \( L \), load. Hence the input voltage \( V_s \) is totally applied to load. But if the switch is in off state, stored energy in an inductor will generate the current and voltage. Due to this stored energy, inductor current flows through the load which is discontinuous in nature. And the voltage coming across the load side is less than the input voltage \( V_s \) hence in step down converter load side gain in terms of voltage will be always smaller as compared to source potential. Also, it requires bigger costlier capacitor for refining out the disconnected source current from photovoltaic array. For this reason, buck converter is not much used in MPPT algorithms as a power interface for solar system.

2) Boost converter – load potential will be always larger as compared to source potential. Load current will be less as compared to source current.

Fig. 13 Step up Converter

The conversion ratio for boost converter is

\[ \frac{V_o}{V_{in}} = \frac{I_{in}/I_{o}}{1-\frac{V_o}{I_{o}}} = 1 \frac{1}{1 - D} \quad \text{(1)} \]

From eq. 1 \( V_{in} = V_o \cdot (1 - D) \) and \( I_{in} = I_{o}/(1 - D) \) \( \text{(2)} \)

\( R_{in} \) – input resistance of converter can be calculated

\[ R_{in} = \frac{V_{in}}{I_{in}} = V_o \cdot (1 - D)/(1 - D) = R_0(1 - D^2) \quad \text{(3)} \]

The MPP tracking system changes \( R_{in} \) and tries to achieve \( R_{in,R_{MPP}} \). But this is impossible if the value of \( R_{MPP} \) not coming under the range allowed for \( R_{in} \) therefore achieving is bit difficult MPP \( iR_{L} < R_{MPP} \), and the catching of MPP is only possible for \( R_{in} \leq R_{MPP} \).

If variation of \( R_{in} \) is from \( R_o \) to zero according to the variation in \( D \) from zero to 1 correspondingly

Fig. 14 Operating region of \( R_{in} \) for step up converters and MPP tracking zone

Working: After closing \( s/w \) pn junction diode attains reverse biased mode of operation due to which there is a linear increment in current which will start flowing through \( L \) and \( s/w \). After opening the \( s/w \) pn junction diode attains a forward biased mode and \( L \) releases stored energy and afterword current starts flowing via \( L \) and \( C \). In this way process gets repeated which results in stepping up of the voltage transferred to load.

3) Step up and step-down converter – this converter shows the combine effect of step down and step up converter in its operation. Load voltage can be raised or lowered by keeping the reference source voltage, making change in duty ratio.

Fig. 15 Buck-Boost converter

Conversion proportion for step-up step-down converter, \( V_0/V_{in} = I_{in}/I_{o} = D/(1 - D) \) \( \text{(1)} \)

From eq. 1 \( V_{in} = V_o/(1 - D)/D \) and \( I_{in} = I_{o} \cdot (D/(1 - D)) \) \( \text{(2)} \)

\( R_{in} \) – source resistance is evaluated

\[ R_{in} = \frac{V_{in}}{I_{in}} = R_0(1 - D^2/D) \quad \text{(3)} \]

Variation of \( R_{in} \) from \( \infty \) to zero accordingly \( D \) changes from zero to 1

Fig. 16 Range of \( R_{in} \) for step up-step-down converter and MPP tracking zone
It permits MPP cover up in both ways. Rin will be of any value using this type of converter. Due to which the PV system can catch MPP irrespective of present radiation alignment with $R_L$; this helps in achieving good MPP-capturing efficiency. MPP will be achieved for variety of $R_L$ value, irrespective of the relationship between $R_L$ and $R_{\text{MPP}}$.

**Working:** operation of step-up step-down converter mainly depends on the opposition from $L$ due to abrupt changes in source current. In closed position of s/w $S_1$, L accumulates energy from source side in the form of magnetic energy and releases it when switch is opened. Considering the capacitor for load side to be sufficiently large for getting RC time constant high. This ensures with the comparison with switching period that in steady state a constant load voltage $V_{L}(t) = V_{s}\text{(constant)}$ prevail at load terminals.

4) SEPIC converter-

**Fig. 17 Single ended Primary Inductor Converter**

This converter allows the voltage at its load side sometimes larger than, smaller than, or same to equal to the input voltage. Control transistor regulates the load voltage using its duty cycle. It is nothing but a step-up converter followed by a step-up step-down converter. Its output possesses same voltage polarity as input while its output is not inverted. The coupling capacitor connected in the circuit works as a confinement for load and source side. MPP catching in this type is easier and simpler due to the lesser source ripple current.

**Fig. 18 Operating Area of SEPIC Converter**

With simplicity because of low input ripple current. This type is most decisive as compared to step-up step-down converter.

**Working:** in the stable mode, average potential at $C_1\text{ i.e. } V_{c1}$ will be same as input voltage $V_{in}$. As capacitance $C_1$ blocks direct current, average current of it will be $I_{c1}\text{zero}$. This makes only $L_2$ the source of DC load current. Hence current via $L_2 \text{ i.e. } I_{c2}$ will be equal to load current. Voltage equation is given by,

$$V_{in}=V_{c1}+V_{11}+V_{12}$$

As average voltage $V_{c1}= V_{in}, V_{11}=V_{12}$. The ripple currents of 2 inductors are equal in magnitude due to similarity of 2 voltages in their magnitudes. Hence average currents are added together as

$$I_{D1}+I_{c2}=I_{L2}$$

After closing s/w $S_1$ $I_{D1}$ raises and $I_{c2}$ becomes negative. Energy required to raise $I_{D1}$ is the energy from source voltage. In a closed condition of s/w s1 instantaneous voltage $V_{L1}$ will be approximately $V_{in}$ and $V_{L2}$ is approximately -$V_{c1}$. Hence to increase the value of $I_{L1}, D1$ is opened so that capacitor $C1$ can give energy and store it in $L2$. $I_{c1}$ is supplied by $C2$. Hence a bias voltage in a circuit will be considered in dc state, and then closing the s/w $S1$. After opening s/w $S1$ current $I_{c1}$ will become equal to current $I_{c1}$. As per the characteristics of inductor to not allow the instantaneous current change, $I_{c2}$ starts flowing in negative direction and it never reverses its direction. This negative $I_{c2}$ will add to the $I_{c1}$ so that there is increment in current given to the load. According to KCL, $I_{c1}=I_{c2}=I_{c1}-I_{c2}$. Conclusion is if $S1$ is off, power is supplied to the load from both $L2$ and $L1$. $C1$ is charged by $L1$ during this off cycle (as $C2$ by $L1$ and $L2$), and recharge $L2$ during the following on cycle.

5) Cuk converter

**Fig. 19 Cuk Converter**

In this type load voltage can be more or less than the source voltage, with load voltage having reverse polarity of the input voltage. $L$ on the source side works as a filter to prevent high harmonic current. Amount of energy transmitted to $L$ by this converter is related with the capacitor $C$.

Optimization algorithms are used to control the position of MPP in a solar system. These algorithms help in fixing location of MPP always in such way that, system will operate at its optimum level and will give optimum efficiency. Output of mppt block is given to converter block to change the duty cycle. Following are some of the computational control algorithms for the solar system (conventional and advanced)

A) Conventional methods- these are also called as real time algorithm as these methods uses actual data in a system like voltage, current, and power for the working. The following MPPT algorithms can be applied on PV based system. They have advantages like less oscillation, faster response, simplicity in operational so tracking of MPP by them for fast changing atmospheric conditions in real-time is good ([17])

1) Perturb & observe (P and O)  
Adaptive P&O  
Variable step size P&O  
Multivariable P&O  
Variable perturbation size adaptive P&O  
PSO based P&O

2) INC  
Modified Incremental Conductance  
Variable step size Incremental Conductance  
Improved variable step size INC  
Power incremental based INC  
Modified adopted INC

B) Soft computing / advanced/intelligent methods-these methods are useful in to tracking...
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the MPP along with rapid response & lesser fluctuations.\(^{[17]}\)

1. FLC based MPPT
2. NN
3. Particle swarm optimization
4. Grey wolf algorithm
5. Ant colony
6. Bat algorithm
7. Artificial bee colony
8. Sudoku puzzle-based algorithm
9. Microprocessor based algorithm

Comparative analysis of various converters and performance parameters are given in the below mentioned tables.

Table I. step-up, step-down, step-up step-down comparison

<table>
<thead>
<tr>
<th>Component</th>
<th>step-up</th>
<th>step-down</th>
<th>step-up step-down</th>
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<tbody>
<tr>
<td>Power Factor correction is high</td>
<td>V&lt;sub&gt;n&lt;/sub&gt;V&lt;sub&gt;n&lt;/sub&gt;</td>
<td>V&lt;sub&gt;free&lt;/sub&gt;</td>
<td>V&lt;sub&gt;n&lt;/sub&gt;V&lt;sub&gt;n&lt;/sub&gt;</td>
</tr>
<tr>
<td>Size is needed</td>
<td>V&lt;sub&gt;n&lt;/sub&gt;V&lt;sub&gt;n&lt;/sub&gt;</td>
<td>V&lt;sub&gt;n&lt;/sub&gt;V&lt;sub&gt;n&lt;/sub&gt;</td>
<td>V&lt;sub&gt;n&lt;/sub&gt;V&lt;sub&gt;n&lt;/sub&gt;</td>
</tr>
<tr>
<td>Switching voltage is V&lt;sub&gt;n&lt;/sub&gt;</td>
<td>Switching voltage rating is V&lt;sub&gt;n&lt;/sub&gt;V&lt;sub&gt;n&lt;/sub&gt;</td>
<td>Switching voltage rating is V&lt;sub&gt;n&lt;/sub&gt;V&lt;sub&gt;n&lt;/sub&gt;</td>
<td></td>
</tr>
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Table II. Comparison between step-up step-down, sepic and cuk converters

<table>
<thead>
<tr>
<th>Specification</th>
<th>step-up step-down</th>
<th>Sepic</th>
<th>Cuk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance of MPPT</td>
<td>ideal</td>
<td>ideal</td>
<td>ideal</td>
</tr>
<tr>
<td>Components used</td>
<td>Less</td>
<td>more</td>
<td>more</td>
</tr>
<tr>
<td>Facility of Control</td>
<td>Confined</td>
<td>Non confined</td>
<td></td>
</tr>
<tr>
<td>array current</td>
<td>Disconnecte d</td>
<td>regular</td>
<td></td>
</tr>
<tr>
<td>Method of Current scaling</td>
<td>difficult</td>
<td>smooth</td>
<td>smooth</td>
</tr>
<tr>
<td>System transients</td>
<td>more</td>
<td>Moderat e</td>
<td>Less</td>
</tr>
<tr>
<td>Efficiency of tracking</td>
<td>Poor</td>
<td>Moderat e</td>
<td>More</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

Proper converter selection is a crucial point, to enhance working of photovoltaic system. Hence the comparison between different converter topologies is discussed in the paper. The paper focuses on different conventional and advanced methods of MPPT algorithms used for getting optimum power point as per the performance of the solar system and also studied correct power interface circuit for the application. It has been found that a step-up step-down converter is a best suitable power interface for this and soft computing methods gives better MPP results traditional techniques.

REFERENCES


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