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Preliminary communication

# POWER OPTIMIZATION IN PARTIALLY SHADED PHOTOVOLTAIC SYSTEMS

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**Abstract:** The Power-Voltage characteristic of a photovoltaic (PV) array exhibits non-linear behaviour when exposed to uniform solar irradiance. Maximum Power Point (MPP) tracking is challenging due to the varying climatic conditions in a solar PV system. Moreover, the tracking algorithm becomes more complicated due to the presence of multiple peaks in the power voltage characteristics under the condition of partial shading. This research is devoted to the Stochastic Beam Search (SBS) based algorithm and Stochastic Hill Climbing (SHC) for a maximum power point tracking (MPPT) at a partial shading condition in the PV system. To give a partial shading effect over the entire array of a PV system, a mast is placed in front of the modules. The modules in the array are connected in such a way that one does not need to rewire the electrical connection during the rearrangement of modules. It is validated that the power generation performance of an array under a moving shading condition is increased. Furthermore, it is observed that the SHC method outperforms the SBS method in the MMP tracking.

**Keywords:** partial shading; photovoltaic; MPPT; stochastic beam search; variable neighbourhood search

## 1 Introduction

Among the available alternative energies, photovoltaic (PV) is one of the most promising energy sources. The PV power generation has attracted attention in recent years due to a decrease in the prices of PV panels. Moreover, developments in smart grids provide opportunities for load control and dispatch of storage units that make the solar PV more valuable to the grid operation. According to the statistics, during the past decades, the world PV industry has grown on average for 30% annually [1]. The commercial PV modules' conversion efficiency is still rather low. Besides that, the P/V characteristics are non-linear and highly weather dependent [2, 3].

A PV array is the power generating unit, consisting of any number of PV panels. When a PV array is exposed to uniform solar irradiance, the array Power/Voltage (P/V) and Current/Voltage (I/V) characteristic presents non-linear behaviour. The optimal operating voltage point of the PV array is called the Maximum Power Point (MPP). MPP is defined as the point at which the PV array supplies maximum power at this particular voltage. The Maximum Power Point Tracking (MPPT) system's aim is to improve and optimise the use of the photovoltaic systems and to maximize the array efficiency in order to guarantee maximum power production.

When the PV array is subjected to the uniformly solar irradiance, it is simple and usual to determine the MPP. Due to some environmental effects, for example, a rapidly varying irradiance or changing weather condition such as clouds etc., shading occurs on the PV panels and the optimal voltage point might vary. When one or more of the PV modules in the array receives a lesser amount of solar irradiance, the PV array experiences a partially shaded condition (PSC). If PSC occurs, the generating current of the entire PV array being limited due to the shaded module and the P/V curve become characterised by multiple peaks and analysis becomes more complicated. Therefore, the conventional MPPT algorithms fail to identify the Global Maximum Power Points (GMPP) among the local point, which leads to a reduction in the overall efficiency of the PV system, distinguishing the absolute MPP and local MPP [4, 5].

A bypass diode is connected parallel to each of the PV modules to permit the excessive current from the un-shaded module to flow through.

In literature, various computational algorithm-based MPPT methods, such as the neural network [6], fuzzy control [7], Differential Evolution (DE) [8, 9], neural network-based modified Incremental Conductance (IC) algorithm and Particle Swarm Optimization (PSO) [10] etc., can be found. For tracking the global MPP, all these methods have shown to have a good performance. However, each has its own limitations. For example, most of them require experienced skills in setting the parameters used for the MPPT algorithm. For some algorithms, the processing time is long. Furthermore, most of them take a relatively long time to reach the global MPP. Some other methods such as the interconnection method [11], voltage compensation method [12] and multilevel dc-link inverter [13], etc. have also been proposed to solve the partial shading problem. Unfortunately, either their tracking speed is slow or their control process is complex. The stochastic search theory-based algorithms are generally used for the computation of MPPs. In the stochastic search, the theory uses the iterative process to control the operating voltage of the PV array according to the update scheme of the individual algorithm.

In this paper, a PV system is constructed that consist of a microcontroller, a buck DC/DC converter and a serial connected four panel PV array. The microcontroller collects the current and voltage data from the PV system. For the PV system operating under the PSCs, Stochastic Beam Search (SBS) and Stochastic Hill Climbing (SHC), algorithms are applied for the maximum power point tracking. The advantage of these methods is that they have a simple control structure. Moreover, under different shading patterns, they have the ability to quickly track the global

MPP. Moreover, there is no need to use expensive irradiance sensors.

## 2 MAXIMUM POWER POINT TRACKING

The solar cell equivalent circuit can be modeled as in Fig. 1. The representation of the solar cell as in Fig. 1 is generally known as a one-diode model.

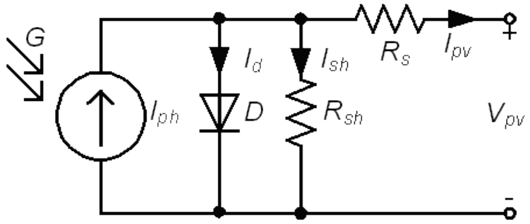


**Figure 1** Single diode model of a solar cell

The equivalent PV cell model is composed of a diode and photo current source, series ($R_s$) and parallel resistors ($R_p$). The p-n junction leakage current in the solar cell is mainly modeled as a parallel resistor, $R_p$. The $R_s$ is used to symbolize the metal base contact resistance within the semiconductor layer [14]. The diode $D$ has I/V characteristic which is described by the Shockley diode equation as shown in eq. (1).

$$I_d = I_s \left( e^{\frac{q\left(V_{pv}+R_s I_{pv}\right)}{aKT}} - 1 \right) \tag{1}$$

where the current flowing through the diode $D$ is defined as $I_d$ , the diode reverse bias saturation current is defined as $I_s$, the ideality factor of the diode D is defined as $a$, $K$ is the Boltzmann constant (1,3806503 × $10^{-23}$ J/K), cell's operating temperature in the degree Kelvin is defined as $T$ and $q$ is the electron charge (1,60217646 × $10^{-19}$ C).

By using the general model of the solar cell, the derivation of the I/V characteristic of the solar cell is done as in Eq. (2).

$$I_{pv} = I_{ph} - I_s \left[ e^{\frac{q(V_{pv}+I_{pv}R_s)}{aKT}} - 1 \right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \tag{2}$$

where $I_{pv}$ is the solar cell terminal current, $I_{ph}$ is the the solar cell light dependend current, $V_{pv}$ is the terminal voltage of the solar cell, $R_{sh}$ is the equivalent parallel resistance and $R_s$ is the equivalent series resistance. The resistances $R_s$ and $R_{sh}$ in Eq. (2) can be obtained iteratively by making the maximum power calculated from the model to coincide with the peak power from the datasheet at MPP [15].

A PV panel under a constant uniform irradiance has an I/V characteristic like the one shown in Fig. 2.

As seen in Fig. 2, the I/V cure has a unique Maximum Power Point (MPP) which the array operates with maximum efficiency and produces maximum output power. A MPPT system is a device employing a controller to achieve both the function of the MPP output and tracking by sampling the power output of the array with the highest possible speed.

In this work, a system designed for the MPPT algorithm comparison is described. This system is comprised of a PV array, a microcontroller, and a buck type DC/DC converter. Arduino Uno R3 is used as microcontroller which collects the current and voltage data from the PV prototype. The buck type DC/DC converter consist of a 2 N-channel MOSFET (IRF540), a 100 μH toroid coil and half-bridge MOSFET driver (IR2104).

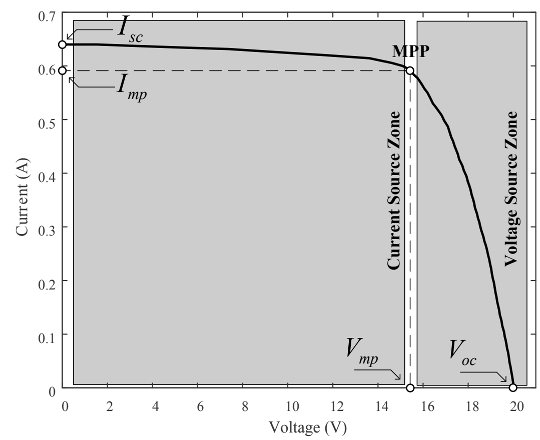


**Figure 2** I_V characteristics of a PV cell under no shading

Here, the PV voltage and current are sampled and converted by a built-in analog to a digital converter (ADC). The output current ($I_{pv}$) is measured by the ACS712 current sensor which has a measuring capacity of ±2.5 A. The microcontroller generates a duty ratio $D$ and the DC/DC converter is activated. In the experimental setup, the load resistance is chosen as $R_o$ = 0.5 Ω and $P_L$ = 30 W. The value of load resistance is capable of absorbing the power generated by a PV module.

The microcontroller is programmed to generate a signal in a pulse width modulation (PWM) with a 62 kHz frequency and 8 bit resolution. The value of the PWM signal is denoted as $D$ and the value of $D$ is between 1/255 and 1. The relationship between the input voltage and output voltage; the input current and output current for the buck type DC/DC converter can be modeled as

$$I_o = DV_{in}, \quad I_{in} = DI_o \tag{3}$$

Moreover, the relationship between the input and output resistances can be found by using the Eq. (3) as

$$R_{in} = \frac{R_o}{D^2} \tag{4}$$

If the range of $D$ is used in Eq. (4), one can get the input resistance $R_{in}$ range as 0,5Ω ≤ $R_{in}$ ≤ 32,5 kΩ. The experimental results indicate that the $R_{in}$ range can span a whole space of $V_{oc}$ and $I_{sc}$. The occupied/unoccupied ratio of the signal $D$ in the pulse width modulation can be found as

$$\sqrt{\frac{R_o}{R_{in_{\max}}}} < D < \sqrt{\frac{R_o}{R_{in_{\min}}}} \tag{5}$$

The PV array characteristic is modeled by a superposition of each of the individual PV module characteristics. When the panels are operated under the same condition, both will have the same amount of current. However, if somehow a PSC occurs, the current generated by the shaded module will be lesser. Since modules are connected in series, this will cause a drop in the generated current and the entire PV array current will be limited. With a bypass diode, the excess current by the unshaded PV module is permitted to flow through the external diode so that limitation imposed by a shaded module can be prevented. Moreover, the formation of hot spots in the PV array can be prevented by a bypass diode. Generally, hot spots are formed due to the PSC when the solar cells become reverse biased. At the same time, the PV module gets hotter, dissipating power in the form of heat. It is undesirable for the hot spots to exceed the sustainable power limit of the PV cells. If the hot spots' heat exceeds the sustainable power limit of the PV cells, it will cause permanent damage to the PV module and the array will be open circuited [16].

### 2.1 Stochastic Beam Search Algorithm

The local beam search algorithms may suffer from getting concentrated on a small region of the whole search space. To overcome this problem, a variant of the local search, Stochastic Beam Search algorithm, is developed. It is similar to the stochastic hill climbing method. The stochastic beam search selects $\beta$ successors at random, instead of choosing the best $\beta$ from the pool of candidate successors. The probability of choosing a given successor is an increasing function of its value. Lowerre (1976) first used this search technique in the artificial intelligence area to solve the speech recognition problem. Later, Sabuncuoğlu and Karabük (1998), Ow and Morton (1988) and Sabuncuoğlu and Bayiz (2000) applied it to job shop scheduling problems [17].

**Table 1** Pseudo code for the **SBS Algorithm**

```
Inputs: P/V data, iteration_count, starting_points
Output: Power
for i = 1 to starting_points
|       Power_initial(i) ← Random(P)
end
Power = max(Power_initial)
for i = 1 to iteration_count
|       Power_new ← Neighbor(Power)
|       if Power_new ≥ Power then
|       |       Power ← Power_new
|       end
end
return Power
```

While using the beam search algorithm, one must take into account two important issues: (1) how the search tree representation is done and (2) how the search methodology is applied. In our study, theoretically, we have 255 different node values. However, using so many node values requires more memory and more work force. Moreover, it does not assure more benefit. Therefore, by trial and error, six node points are found as optimum. The pseudo code for the SBS algorithm is given in Tab. 1.

### 2.2 Stochastic Hill Climbing Algorithm

The Stochastic Hill Climbing (SHC) algorithm is an improved version of the hill climbing algorithm. The strategy of the Stochastic Hill Climbing algorithm is randomly selecting a neighbor for a candidate solution and only accepting it if it results in an improvement. The greater of the neighbor power value is selected as the active power and is compared to the next randomly assigned power value [18]. A pseudo code for the stochastic climbing algorithm is given in Tab. 2.

**Table 2** Pseudo code for the SHC Algorithm

```
Inputs: P/V data, iteration_count
Output: Power
Power ← Random(P)
for i = 1 to iteration_count
|       Power_new ← Random(P)
|       if Power_new ≥ Power then
|       |       Power ← Power_new
|       end
end
return Power
```

## 3 RESULTS AND DISCUSSION

Three different conditions are analyzed for different shading patterns or conditions (SC). These are SC1 when the array is operated under the same conditions without shading, wherein SC2 and SC3 are at different shading conditions. In SC2, the characteristic is obtained by shading one by one out of the four PV panels at midday, while in SC3 it is obtained with the same condition but after midday. SC1 has one peak value, while others have multiple peaks. The solar irradiance values for each shading conditions are given in Tab. 3.

**Table 3** Solar Irradiance Values for different shading conditions

| Solar Irradiance Values (W/m$^2$) | | | | |
|---|---|---|---|---|
| | Panel1 | Panel2 | Panel3 | Panel4 |
| SC1 | 1000 | 1000 | 1000 | 1000 |
| SC2 | 1000 | 1000 | 1000 | 160 |
| SC3 | 1000 | 1000 | 400 | 160 |

The obtained I/V and P/V curves for each shading conditions (SC1-3) are given in Figs. 3 and 4, respectively.

In the shadowing experiments, the shadow of a pillar the height of 1.5 m above the panels is over-shaded naturally by the movement of the Sun in the four hour time period when the data were collected. The collected data is processed in MATLAB by the Stochastic Beam Search (SBS) and the Stochastic Hill Climbing (SHC) algorithms. The process is repeated 100 times for every condition and the results are averaged.

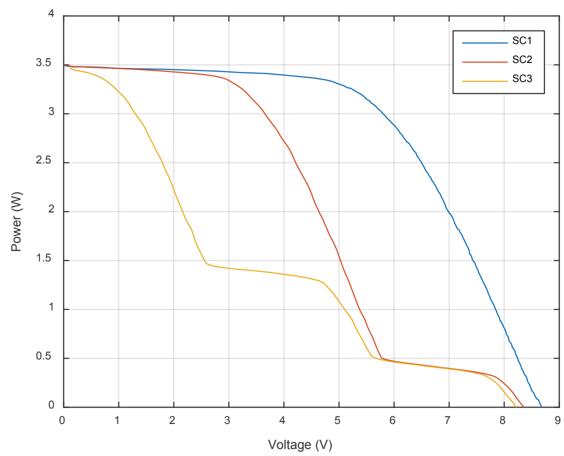


**Figure 3** The I/V characteristic curve of the Photovoltaic Array

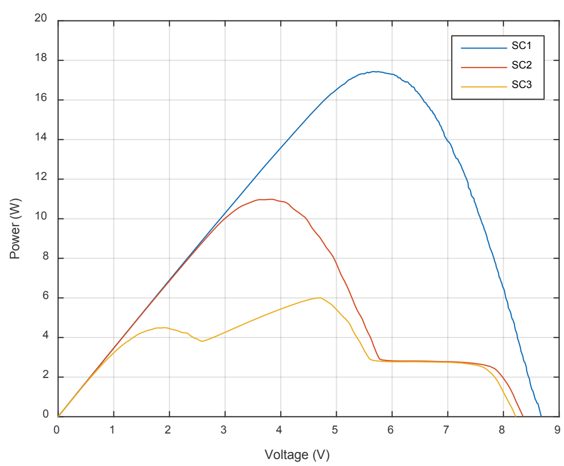


**Figure 4** The P-V characteristic curve of the Photovoltaic Array

The obtained power comparison is given in table 4. As it can be seen from Tab. 4, the maximum power point found by the Stochastic Hill Climbing algorithm is higher than the Stochastic Beam Search algorithm.

**Table 4** Ideal and calculated power values

| Obtained Power Values (W) | | | |
|---|---|---|---|
| | Ideal value | Stochastic Beam Search | Stochastic Hill Climbing |
| SC1 | 17,44 | 17,02 | 16,07 |
| SC2 | 10,98 | 10,22 | 10,38 |
| SC3 | 6 | 5,02 | 5,16 |

The convergence rate and average calculation time values are given in Tab. 5. The convergence rate represents how many times the algorithms can capture real values. The success rate of SHC is generally better than the SBS algorithm. The average step size is for how many points the algorithm checks to get the best of all, that is, the number of iterations. It can be seen from table 3 that the algorithms check nearly the same amount of data points for SC1. However, for SC2 and SC3, SHC visits more data points. Thus it requires more time.

**Table 5** Success rates of algorithms

| | Algorithm | Convergence Rate (%) | Average Time |
|---|---|---|---|
| SC1 | SBS | 97,61 | 48 µs |
| | SHC | 92,18 | 47 µs |
| SC2 | SBS | 93,03 | 49 µs |
| | SHC | 94,53 | 45 µs |
| SC3 | SBS | 83,69 | 48 µs |
| | SHC | 86,03 | 44 µs |

## 4 CONCLUSIONS

In this paper, the Stochastic Beam Search and Stochastic Hill Climbing algorithms are compared for three PSCs. The SBS algorithm only showed a good convergence rate for the SC1 condition. By using the same conditions, the results prove the advantage of the SHC algorithm to ensure the rapidity and stability of the output PV power for the partial shaded conditions. The SHC algorithm has the following advantages: accurate MPP tracking performance, the capability of dealing with both the PSC and uniform insolation conditions. The experimental results on an 18 W prototype PV system showed that the SHC algorithm can be used for partial shading conditions.

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