Comparative Study Of Maximum Power Point Tracking Algorithms Under Partial Shading Conditions

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Abstract: *In this study, an experimental study was carried out to compare the tracking performance of the maximum power point tracking algorithms under partial shading conditions. These algorithms are Stochastics Beam Search, Simulated Annealing, Fractional Open Circuit Voltage and Stochastics Hill Climbing. The test setup consisted of 4 series connected solar panels, Buck type DC/DC converter, microcontroller and PC. Current/Voltage (I/V) characteristic of the PV system was collected under different shading scenarios and these data were used to compare the success of the algorithms in the MATLAB environment. The comparison results show that the Stochastics Beam Search algorithm finds the highest power point in all shading conditions with high speed and accurcy.*

Keywords: *Solar Energy, Partial Shading, MPPT.*

1. Introduction

Nowadays, fossil fuels meet most of energy needs in transportation and electricity generation. The largest use of fossil energy is for electricity and heat production, both globally and in the EU. Fossil fuels including coal, oil and fossil gas supplied approximately 82% of global primary energy in 2011 [1]. Consumption of fossil fuels can lead to serious environmental issues such as global warming and air pollution. These effects of the fossil fuels are increasing the interest in renewable energy sources. Solar power systems generate electricity with no pollution, no fuel costs, and no risks of fuel price spikes [2]. In Turkey, solar energy has an important place among other renewable energy sources with the radiant potential [3].

Photovoltaic (PV) systems can convert 15-25% of the solar energy to electrical energy [4]. Therefore, PV systems require Maximum Power Point Tracking (MPPT) systems. MPPTs are electronic systems that operates the PV systems to produce all the power they are capable of in different atmospheric conditions [5]. From an electronics engineering point of view, MPPTs are electronic loads which are forcing the PV systems to operate at maximum available power.

Over the past decades, various MPPT methods have been developed. These methods differ in many aspects such as sensor type and count, complexity, cost, effectiveness, convergence speed and hardware needed for implementation, among others. A review of 40 different MPPT algorithms can be found in [6].

Among these techniques Hill Climbing (HC), Perturb and Observe (P&O), Fractional Open Circuit Voltage (FOCV) and Incremental Conductivity (InCond) are common. Advantages of these techniques are easy implementation and low cost. Therefore, their performance under the partial shading conditions is not acceptable.

In this paper, a detailed examination was made on the experimental data to investigate the success of the various search algorithms for MPPT problem. In this work, Stochastics Beam Search (SBS) , Simulated Annealing (SA), Fractional Open Circuit Voltage (FOCV), and Stochastic Hill Climbing (SHC) algorithms have been compared.

The application of the local MPPT algorithm that is proposed in [7] proposes an improvement on conventional P&O algorithm to eliminate ripple problem.The experimental setup of this work includes a 10W PV panel, a boost DC/DC converter, a microcontroller board and battery [7]. The P&O algorithm has the disadvantage of choosing the first maxima as the Maximum Power Point (MPP). The InCond based MPPT method with PID controlled DC/DC converter is applied in [8]. The application of evoluationary algorithms that are proposed in [9] used for PID controller in PV systems. Under partial shading conditions, both [7-9] fail to guarantee successful tracking of the Global MPP (GMPP).

This study consists of 5 chapters. Detailed information about the designed MPPT equipment is given in the section 2. Partial shading is examined in section 3. The MPPT algorithms in the literature are briefly discussed, and SBS, SA, FOCV and HC algorithms are examined in Section 4. The results of the study are presented in section 5.

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1.1. PV cell model

PV is the direct conversion of solar energy into electricity. PV panels consist of PV cells which are produced with semiconductor technology. The electrical model of the PV cell is given in in Fig.1. This model consisting of a current source in parallel with a diode and two resistors [10].

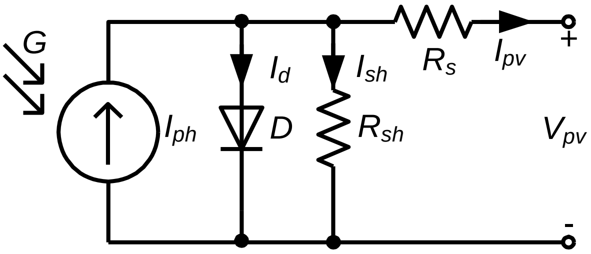


Figure 1. PV solar cell model

The output current (I_{pv}) of the PV cell model can be defined as in equation (1).

$$I_{pv} = I_{ph} - I_s\left(e^{\frac{q(V_{pv}-R_sI_{pv})}{NKT}} - 1\right) - \frac{(V_{pv}-R_sI_{pv})}{R_{sh}} \qquad (1)$$

In Eq.1, I_{ph} represents the illumination dependent current source, I_s diode reverse saturation current, q electron charge, V_{pv} terminal voltage, K Boltzmann constant, T cell temperature in Kelvin, N ideality factor, R_{sh} parallel resistance and R_s series resistance. Simulation results for different radiation values using Eq.1 are given in Fig.2. As seen on Fig.2, the PV cell has a nonlinear characteristic.

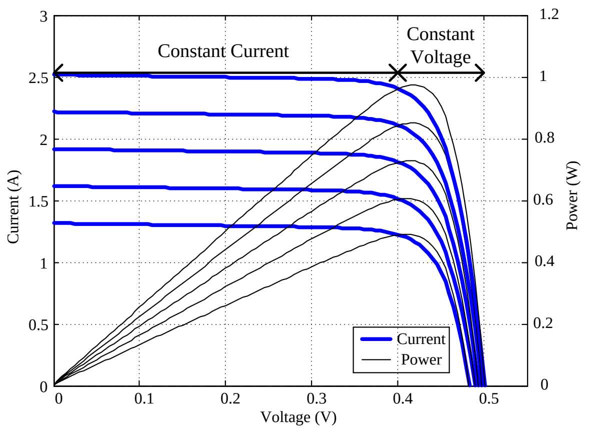


Figure 2. I/V and P/V curves for differential radiation values

In Fig.2, the output current of the cell can be considered constant as long as the output voltage is below a certain voltage. When this voltage is exceeded, the body diode starts conduction and the I_p current tends to flow through this diode. Thus, the FV cell starts to operate in the constant voltage region. Power/Voltage (P/V) characteristics for the different radiation values also given in Fig.2, it is seen that each curve has one unique peak value called Maximum Power Point (MPP).

A PV arrays contains more than one solar panel. These PV panels can be shaded by clouds, trees, dust or buildings. This results a non-uniform illumination on the PV array. The P/V curve of PV array under non-uniform light is also nonlinear but also contains multiple MPPs. This phenomenon is known as partial shading effect which is discussed in detail in chapter 3.

The aim of a MPPT system is to obtain the maximum available power from PV array. In this work, a low cost MPPT system is developed. This system consisting of Buck type DC/DC converter and an 8bit micro controller. Detailed description of the designed system is given following section.

2. MPPT Hardware Design

The block diagram of the MPPT system used in this study is given in Fig.3. MPPT equipment consists of a microcontroller, Buck type DC/DC converter and 4 PV panels.

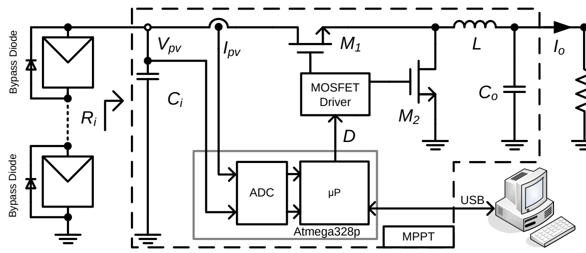


Figure 3. Block diagram of the MPPT equipment

2.1. Microcontroller

In this study, Arduino Uno R3 was used as a microcontroller card (considering the ease of use and availability). This card has an 8bit ATMEGA328p microcontroller running on 16MHz frequency which is designed by Atmel. This controller also has a 10bit presition ADC, 8 and 10-bit presition Pulse Width Modulation (PWM) hardware. In this work, PWM hardware used in 8bit mode.

2.2. DC/DC Converter

The buck type DC/DC converter consists of 2 N-channel MOSFET (IRF540), 100µH toroidal coil and half bridge MOSFET driver (IR2104). ATMEGA328p performs the tasks of sampling the Current-Voltage (I/V) values, generating PWM signals and communicating with the PC. The ACS712 current sensor with a measurement range of ± 5A was used to measure the output current (I_{pv}) of the PV array. A resistance based voltage divider circuit was used to scale down the FV array voltage (V_{pv}) to the ADC measurement range.

The output voltage of the Buck converter can be controlled by the duty cycle (D) of the PWM signal and can be controlled from 0 to the input voltage. The relation between the input voltage (V_{in}) and the output voltage (V_o) is given in Eq. (2-3).

$$V_o = DV_{in} \quad (2)$$

$$\frac{V_o}{V_{in}} = D \quad (3)$$

The relation between the input current (I_{in}) and the output current (I_o) in a Buck type DC/DC converter is given in Eq. (4).

$$\frac{I_o}{I_{in}} = \frac{1}{D} \quad (4)$$

The resistance seen by PV array (R_{in}) and load resistance (R_o) are given Eq.(5-6).

$$R_o = \frac{V_o}{I_o} \quad (5)$$

$$R_{in} = \frac{V_{in}}{I_{in}} \quad (6)$$

Combining Eq (2-6) give that R_{in} can be controlled by D as given in Eq. (7). This feature makes possible to control R_{in} by using D value.

$$R_{in} = \frac{R_o}{D^2} \quad (7)$$

In this study, a 0.5Ω, 30W R_o resistor is chosen. The load resistor is large enough to dissipate all the power that the PV array can generate. Field applications may use batteries or DC/AC inverters instead of load resistor. The microcontroller is programmed to produce PWM at a 62 kHz frequency in 8bit presition. In this work, the value of D varies in steps of $\frac{1}{255}$ and can be selected in the range of $\frac{1}{255} \leq D \leq 1$. If this D value is applied to Eq. (7), the range of the R_{in} will be $0.5\Omega \leq R_{in} \leq 32.5k\Omega$. The experimental results show that this range of R_{in} can scan the I/V curve of the PV array between V_{oc} and I_{sc} values. Also, Eq. 8 and 9 can be used to determine the limit values of the D value of the PWM.

$$D_{max} = \sqrt{\frac{R_o}{R_{in_{min}}}} \quad (8)$$

$$D_{min} = \sqrt{\frac{R_o}{R_{in_{max}}}} \quad (9)$$

2.3. PV Array

PV array consists of a series connected 4 PV panels The characteristics of these panels are presented in Table 1. The total power of the array is 26W. As previously stated, aim of this work is examining the success of the various MPPT algorithms under partial shading conditions. Therefore, it is not necessary to construct a high power array. The designed system is capable of operating on a high power system with minor modifications.

Table 1. Panel specifications

Electrical characteristics	STC conditions
Short circuit current I_{SC}	5.0 [A]
Open circuit voltage V_{OC}	2.2 [V]
Temperature coefficient of I_{SC}	0.065 [%/◦C]
Temperature coefficient of V_{OC}	−80 [mV/◦C]

2.4. Partial Shading

PV panels can be connected in series and parallel to obtain desired power values. Some panels can be exposed to less light than others with an environmental factor such as dust, clouds or building shade. These shaded panels generate less current than full radiation panels. In PV panels, since all PV cells are connected in series, the same amount of current have to flow through every PV cell. Unshaded cells behave as a load and produces heat. As a result, the shaded PV cells will dissipate power. This is called as hot spot effect. One way to prevent the hot spot effect is to use bypass diodes. Bypass diodes are connected in reverse bias between PV panel terminals and has no effect on its output in normal operation. Besides, bypass diodes cause the power output to have multiple power peaks which increases the complexity in MPPT. The partial shading phenomenon has been given in Fig. 4-5.

In Figure 4, an FV array without by-pass diodes is modelled under partial shading. As can be seen, the fully shaded panel will not have the ability to generate current. In this case, the main branch current passes through the R_s and R_{sh} resistors of the shaded panel, some of the power is dissipated on these resistors. In addition, the voltage drop across these resistors will reduce the terminal voltage of the array.

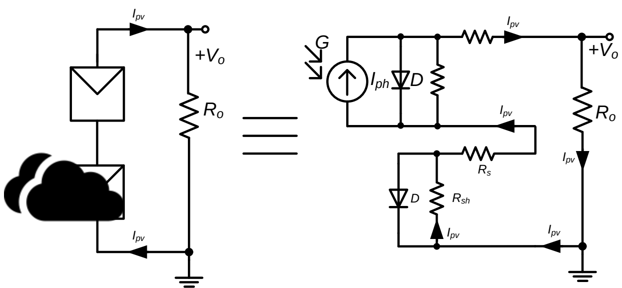


Figure 4. PV array under partial shading (without bypass diode)

If bypass diodes are not used in the partial shading condition, the terminal voltage of the PV array will drop. Also, the internal resistances (R_s-R_{sh}) will be dissipate power and generate heat (hot spot effect).

Figure 5 illustrates a PV array equipped with bypass diodes under partial shading condition. By using bypass diodes current can flow through these diodes and hot spot effect can be prevented. However, this causes more than one maximum power point in the P/V curve of the FV array. The Global Max Power Point (GMPP) is the largest one of these power points and the other power points are called as Local

Maximum Power Points (LMPP). The position of the GMPP on the curve varies according to the state of shading.

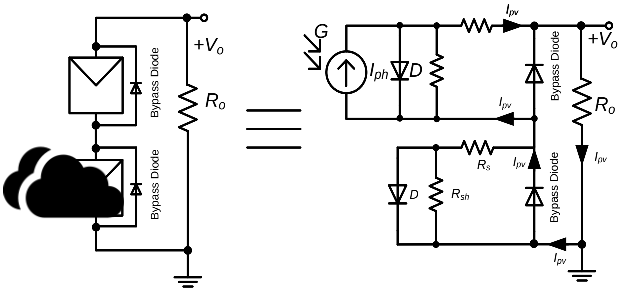
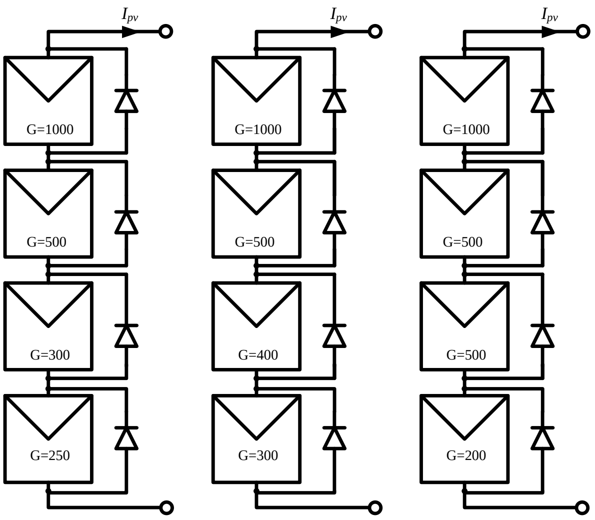


Figure 5. PV array under partial shading (with bypass diode)

In this study, 4 panels are connected in series and a set of experiments were made for partial shaded conditions. Fig. 6 illustrates the panel configuration and illumination levels for 3 different partial shading conditions. In the figure *G* values represent the radiation values in W/m^2 on the PV panels.



a)SC1 b)SC2 c)SC3

Figure 6. PV array configuration under shading

Experimental I/V and P/V curves are given in Fig.7-8, respectively. Figures 7 and 8 contain three different shading conditions (SC1-SC3). These curves have multiple MPPs. Values and palaces for each MPP are given in the curves. As seen on Fig. 8, P/V curve for each Shading Condition (SC) contains multiple MPP values and one of them is GMPP. Aim of the MPPT equipment is selecting the largest power point under different radiation conditions.

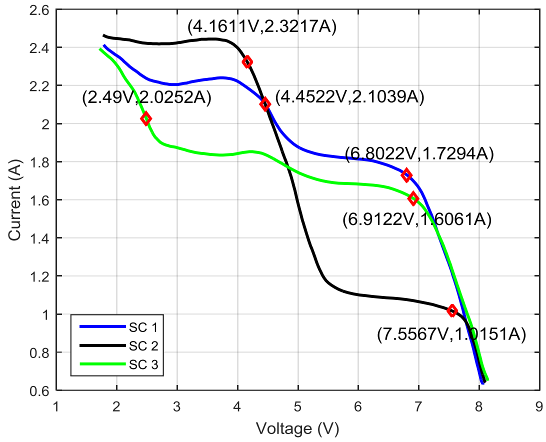


Figure 7. I/V curves under partial shading condition

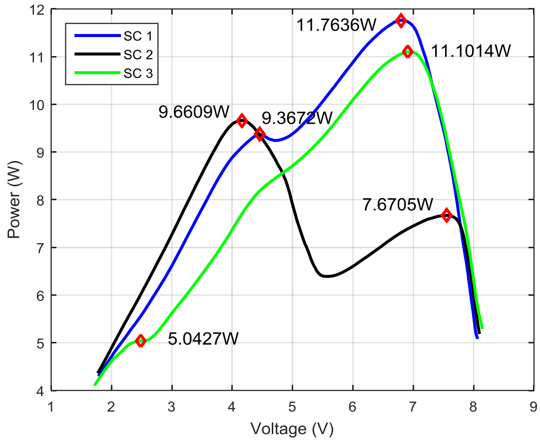


Figure 8. P/V curves under partial shading condition

3.MPPT algorithms

In literature various methods have been suggested to solve MPP problem. These methods can be classified as sensor type-count, complexity, cost, effectiveness, convergence speed and hardware necessity. The MPPT market has been seen as an opportunity by integrated circuit manufacturers and various products have been marketed for solar power systems. Unfortunately, these products do not offer a solution to partial shading. For example, the LT3652, LTC4121 and ADP5090 use the fractional open circuit voltage method [11, 12, 13].

In the literature there are easy to implement algorithms but these are not capable of finding MPP under partial shading. They can be listed as follows: Hill Climbing (HC), Perturb and Observe (P&O), Fractional Open Circuit Voltage (FOCV) and Incremental Conductivity (InCond) [6]. Nowadays, there is a tendency to use the nature-inspired search algorithms for the MPPT in partial shading conditions. Some of these algorithms can be listed as follows: firefly algorithm [14], Simulated Annealing (SA) algorithm [15], ant and bee colony algorithms.

In this paper, a study was conducted according to efficiency of SBS, SA, FOCV, SHC algorithms to MPP in partial shading conditions. These results are given in chapter 5.

4.1. Stochastic Beam Search Algorithm

The Stochastic Beam Search (SBS) algorithm first entered the literature as local beam search [16]. This algorithm can be defined as an improved version of the hill climbing algorithm. The local beam search algorithm is an algorithm that tries to pick a random starting point in search space and tries to go in that direction if one of its neighbors has a value increment. The SBS algorithm begins with multiple randomly selected starting points for the search. From these random starting points, the one with the greatest value is taken as the starting point and the others are ignored. This process is called pruning. After the pruning process, the hill climbing algorithm is executed from the highest valued starting point and the search is continued. Increasing the number of starting points increases the probability of finding a global maximum, as well as increasing the memory requirement. It also prolongs the searching time relatively. The search space in this study consists of 255 points. It has been observed that the number of starting points in the work done above the 6 starting points does not cause a serious increase in success. For this reason, the number of starting points is limited to 6.

4.2. Simulated Annealing Algorithm

The objective of the SA Algorithm is to achieve global optimization for any problem. The algorithm is similar to iron annealing, which is a hot metal forming process. In this process, the metal is heated and slowly cooled in a controlled manner. By heating the metal and cooling it under control, the dimensions of the metal crystals are increased so that the strength of the metal is increased. Heat energy allows the atoms to increase their energy and move freely. When the energy is low, the movement is reduced. In this study, the starting temperature was chosen to be 100 °C. This temperature value is reduced by the alpha parameter and the cooling process is imitated.

4.3 Stochastic Hill Climbing Algorithm

The Stochastic Hill Climbing (SHC) algorithm can be explained as searching for the highest peak in the foggy weather. For this task, steps are taken from the starting point in random directions to find upward slope. The SHC algorithm is often preferred because its simplicity and does not require any PV panel parameters. However, the success under partial shadows is quite low.

4.4 Fractional Open Circuit Voltage Method

The FOCV method assumes that maximum power can be found on the ratio of the open circuit voltage. The expression that summarizes this approach is given in Eq. (10). The k value is a constant between 0.78 and 0.92.

$$V_{MPPT} = k.V_{oc} \tag{10}$$

The open-circuit voltage method is not a solution to partial shading conditions, but also requires a periodic isolation of the DC/DC converter from PV panel to find the V_{oc} value, which means that the output power is cut off for a period of time. This means energy loss in this time duration.

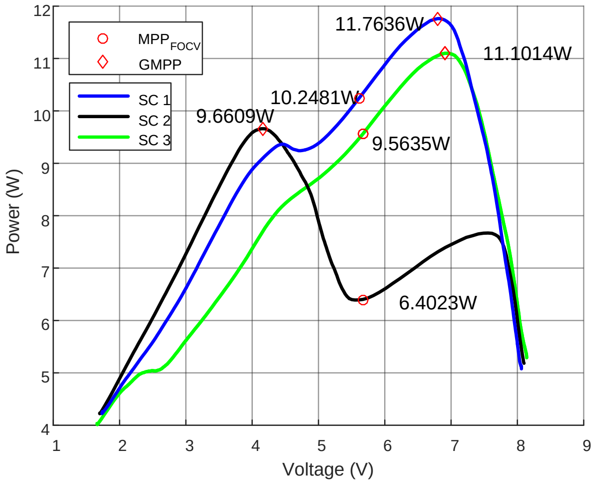


Figure 9. MPP and GMPP values for FOCV method

In Fig. 9, GMPP points V_{MPPT} values for FOCV are illustrated with red diamonds and red circles respectively. For each curve, V_{oc} *value* is approximately 8.1V. By using Eq.10, V_{MPPT} values can be found as 5.6V for each curve. FOCV method assumes these voltage points as GMPP. As seen on figure these values are far form the MPPT.

5. Conclusions

In this study, SBS, FOCV, SHC, SA search algorithms are utilized and compared under partial shading conditions. Most of the MPPT techniques fail to guarantee successful tracking of the GMPP. This results in significant reduction of the generated power. There are also various comparison criteria for MPPT techniques. Some of the key criteria in choosing an algorithm can be listed as follows:

- •Ability to run on a microcontroller, DSP or analog hardware in the field application,
- •Ability to find GMPP with high speed and lowest iteration count in partial shading conditions.

According to the results of this study, the SBS algorithm is suitable to work on the microcontroller and success of the algorithm is high in partial shading conditions. Detailed comparison for both, SBS, SA, FOCV, SHC algorithms are given below. In this study, experiments were performed for different Shading Conditions (SC). During the partial shading experiments, different conditions were created on the PV panels using optic filters with different permeability. Obtained data were used for success tests for SBS, SA, FOCV, SHC algorithms in MATLAB environment. These algorithms repeated 100 times for the specified shading conditions (SC1-3) and the average of the results is obtained. Averaged power values are presented in Table 2. From table it is seen that the SBS, SA and SHC algorithms follows the GMPP value with great success. In the table Lowest extracted power value is the reported for the FOCV.

Table 2. Comparison of the power obtained

	Average Power Values (W)				
	GMPP	SBS	SA	FOCV	SHC
SC1	11.763	11.234	11.425	10.248	11.125
SC2	9.660	9.440	9.592	6.402	9.115
SC3	11.101	10.736	10.699	9.563	10.748

Efficiency, average iterations and average tracking time of the algorithms are presented in Table 3. The MPPT efficiency is calculated as follows:

$$\eta_{MPPT} = \frac{GMPP}{P_{MPPT}} \times 100 \quad (11)$$

Table 3. Algorithm success comparison

	Algorithm	Efficiency η_{MPPT} (%)	Average Iteration	Average Time
SC1	SBS	95.503	13	81.7µs
	SA	97.129	24	3.130ms
	FOCV	87.116	1	123µs
	SHC	94.571	24	217µs
SC2	SBS	97.715	15	98µs
	SA	99.294	24	2.492ms
	FOCV	66.270	1	128µs
	SHC	94.353	24	228µs
SC3	SBS	96.708	16	105µs
	SA	96.376	24	2.796ms
	FOCV	86.146	1	166µs
	SHC	96.816	24	352µs

Table 3 indicate that, the MPPT efficiencies of the SBS, SA, SHC MPPT algorithms are essentially the same. Also, FOCV had a significantly lower efficiency than others under partial shading conditions. Lower efficiency can be understood by Fig. 9. FOCV method assumes the GMPP point as a portion of V_{oc} but that approximation would never be satisfied for partial shading conditions.

Both SBS, SA and SHC techniques are iterative approaches that search the MPP of the PV power curve for maximizing the output power. The average iteration count values are given in Table 3. Iteration count value does not give distinctive information due to complexity differencies among the algorithms. SA and SHC algorithms achieve 24 iteration but average time for algorithms are 2.8ms and 265µs respectively.

Tracking speed values for all algorithms are presented in Table 3 as average time. The SA is a complex algorithm and its tracking speed is slower but more accurate than that of other presented methods. The FOCV technique is simple and fast method but it is not a accurate method. SBS algorithm is the fastest method among the presented methods.

This article provides a classification of available MPPT techniques based on the efficiency, iteration time and count. Result of this classification shows that SBS is the fast and efficient algorithms among other presented algorithms.

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