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DICHOTOMOUS SEARCH BASED ALGORITHM FOR TRACKING GLOBAL PEAK IN PARTIAL SHADED PHOTOVOLTAIC ARRAY

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Key words: Photovoltaic array, Partial shading, Maximum power point tracking (MPPT), Dichotomous search.

Partial shaded conditions introduce multiple peaks in the voltage-power characteristics of photovoltaic (PV) array. Conventional tracking algorithms cannot differentiate between local and global peaks and results in lower harvest efficiency. This inadequacy has led to the development of global tracking algorithms. This paper proposes a new dichotomous search based global peak power tracking (GMPPT) algorithm that can track the maximum power under all irradiation conditions. The algorithm is a two-stage algorithm where the first stage narrows down the search range to the vicinity of the global peak while the second stage locates the global maximum by dichotomous search algorithm. The reliability of the algorithm is tested for various shading patterns. The simulated and experimental results show that the algorithm tracks the global peak reliably under both uniform and non-uniform irradiation conditions.

1. INTRODUCTION

Power generation by solar PV modules is much more attractive than other renewable sources due to abundant availability and favorable government policies. Photovoltaic cells convert solar energy into electrical energy. The electrical characteristics of a PV cell are non-linear, and the voltage-power curve exhibits a single peak called maximum or peak power [1]. The low conversion efficiency of the PV cells makes it mandatory to operate the PV cell at the optimal point. However, the maximum power point of a PV cell is not constant but depends on various environmental factors including temperature and irradiation [2]. This necessitates the need of a tracking algorithm that can track the optimal power point under all irradiation conditions. Many such tracking algorithms are reported in literature with varied complexity, speed and accuracy [3–8]. Though these algorithms track effectively under non-shaded or uniformly shaded conditions, they fail under partially shaded conditions as they are trapped in the first peak they detect.

Shading is unavoidable especially in building integrated urban installations due to space limitations. Though the panels are installed in shade free areas, the panels or part of them are shaded by the dirt, bird litters, nearby structures, passing clouds etc. Generally, PV panels are connected in series and/or parallel according to the voltage and current specifications to form an array. When a panel is shaded, it receives less irradiation and hence generates lesser photocurrent than the non-shaded panels [2]. When the shaded panel is a part of a series connected string, it imposes current limitation.

Bypass diodes are provided to overrule the limitation as they provide an alternate path for current when activated. However, these bypass diodes introduce multiple steps in the voltage-current characteristics and multiple peaks in the voltage-power characteristics. The maximum power tracking is difficult under these circumstances, as the conventional algorithms oscillate around the first peak they detect. This results in reduced power generation and under utilization of PV source. The conventional algorithms are modified to sweep the entire voltage range and track the maximum peak. Many such algorithms reported in literature have two or three stages, where, the initial stage narrow down the search interval and the later stage track the exact location [9]. Many algorithms have been proposed and compared; however, it is difficult to adjudge the best.

This paper proposes a two-stage algorithm where the first stage shrinks the search interval closer to the global peak and the second stage locates it in less iteration. The first stage makes use of the critical inference deduced from the detailed shading analysis reported in literature to search for the peaks at significant locations and the second stage is based on the dichotomous search method.

2. SYSTEM DESCRIPTION

The maximum power can be extracted from the PV source if the source impedance is matched with that of the load impedance. The source impedance (PV) however varies with irradiation and temperature. To match the impedances, the maximum power point tracker includes a dc-dc converter placed between the source and the load controlled by tracking algorithm. The converter is a boost converter operating in continuous conduction mode. The schematic diagram of the system is presented in Fig. 1.

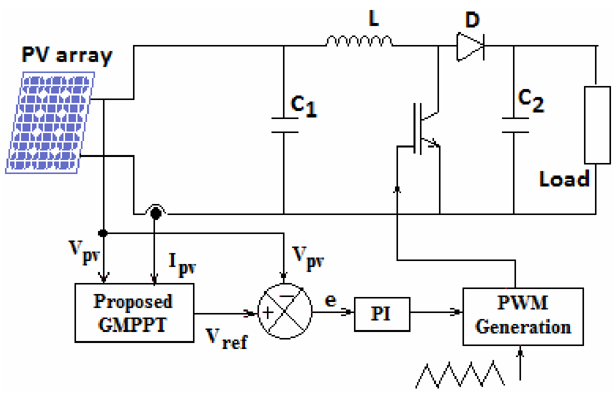

Fig. 1 – Schematic diagram of PV system with proposed GMPPT.

The array voltage and current are sensed and the proposed two stage GMPPT algorithm generates the reference voltage while the PI controller controls the array voltage by altering the duty cycle of the pulses given to the switch. The system parameters including the specifications of the PV source are given in Table 1.

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Table 1

Specifications of converter and the PV array.

Converter Specifications	
Parameters	Specification
L	2.8 mH
C_1	29 μF
C_2	2500 μF
Switching frequency	10 kHz
Switch	IGBT

PV panel Specifications		
Electrical parameters	PV panel	PV Array (6×1)
Open circuit Voltage V_{oc}	21.24 V	127.4
Short circuit Current I_{sc}	2.55 A	2.55 A
Maximum Power P_{max}	37.08 W	222.48 W
Voltage at maximum power V_{mp}	16.55 V	99.3 V
Current maximum power I_{mp}	2.245 A	2.245 A

A 6×1 PV array is considered in this work where all the panels are connected in series. Each of the PV panel has 36 series connected poly crystalline PV cells provided with single bypass diode. The electrical characteristics of the panel are simulated by developing the mathematical model.

2.1. PV MODEL

Mathematical model that mimics the PV panel is developed in Matlab based on the standard single diode model [1]. The developed model and the simulated results are validated with experimental data at different irradiation levels. The simulated electrical characteristics presented in Fig. 2 shows that the short circuit current and the maximum power falls with irradiation. However, the variation in maximum power point voltage with irradiation is relatively less. The characteristic curves exhibit unique peak under homogeneous irradiation conditions while multiple steps and peaks under partial shaded conditions. The number of peaks depends on various factors and hence, prior knowledge on the effects of partial shading is required to develop suitable tracking algorithm to track the global peak.

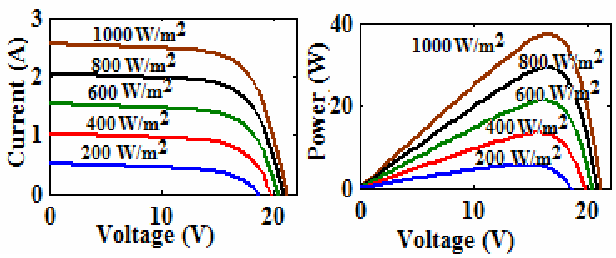

Fig. 2 – Characteristics of PV panel at various irradiation levels.

A generalized program is written in MatLab to simulate the characteristics of PV array under partially shading conditions as experimental analysis is difficult due to the continuously varying atmospheric conditions. It is inferred that the number of peaks and the location of global peak are dependent on the array size, shade intensity and pattern, number and configuration of bypass diode and the interconnection scheme. Besides, the peaks occur at almost multiples of k×$V_{oc\text{-}module}$ where k ranges between 0.7 and 0.85. A two-stage algorithm is proposed in this work to track the global peak under partial shaded conditions.

3. **THE PROPOSED GMPPT ALGORITHM**

The proposed algorithm is a two-stage algorithm. In the first stage of the algorithm, the region of global MPP is identified and in the second stage the actual MPP is located accurately [9]. The algorithm initially sweeps the entire voltage range to identify the region of global peak. To speed up the process, only significant points are searched for peaks.

The maximum number of peaks that can occur in a m×n array that is connected in series-parallel configuration ('m' panels in series string and 'n' strings in parallel) is 'm'. It is assumed that one bypass diode is provided per panel. The voltage range to be swept by the first stage of the algorithm extends from 0 to mV_{oc_module}.

The peaks are likely to occur at multiples of kV_{oc_module} (kV_{oc_module}, 2 kV_{oc_module}, 3 kV_{oc_module}, ..., m kV_{oc_module}). The range of 'k' usually lies between 0.7 – 0.85 depending on the environmental conditions. In this work, the value of k is considered to be 0.8 and hence the first stage searches the search interval of the 6×1 PV array at 0.8 V_{oc_module}, 1.6 kV_{oc_module}, 2.4 V_{oc_module}, 3.2 V_{oc_module}, 4 V_{oc_module} and 4.8 V_{oc_module}.

Initially, the reference voltage $V_{ref\ 1}$ is set as 0.8V_{oc_module}. The corresponding power (P_1) is estimated by multiplying the observed voltage and current. Now the voltage perturbation is applied, and the new reference voltage is set as $V_{ref2} = V_{ref\ 1} + (0.8\ V_{oc\_module})$. If the power measured at this new reference P_2 is greater than P_1, then $P_{max} = P_2$, $V_{ref\_max} = V_{ref2}$ else $P_{max} = P_1$ and $V_{ref\_max} = V_{ref1}$. The perturbation is continued in the same direction until V_{ref} reaches 4.8 V_{oc_module}. Thus, at end of first stage, with 'm' voltage perturbations, the location of global peak is narrowed down to V_{ref_max}.

The second stage is initiated by expanding the search interval around the reference voltage (V_{ref_max}) obtained from the first stage as the value of k is an approximate value that depends on environmental conditions. Further, the interval fixed for the second stage will have a unique peak and dichotomous search (DS) algorithm is used to track the GP. The search interval for the second stage is fixed as (V_{ref_max} – 20 % of V_{oc_module}) and (V_{ref_max} + 20 % of V_{oc_module}). DS algorithm divides and eliminates regions within this interval to locate the exact location of the GP.

3.1 THE DS ALGORITHM

The DS algorithm locates the maximum or peak of a unimodal function (function with single peak) in the given interval (a, b) by repeated division and elimination. The midpoint 'c' (c = (a+b)/2) of the interval is computed and two search points x_1 = (c-ε) and x_2 = (c+ε) are inserted on either side of the midpoint. Value of ε is chosen to be a very small value. This results in two sections (a, x_1) and (x_2, b) as shown in Fig. 3.

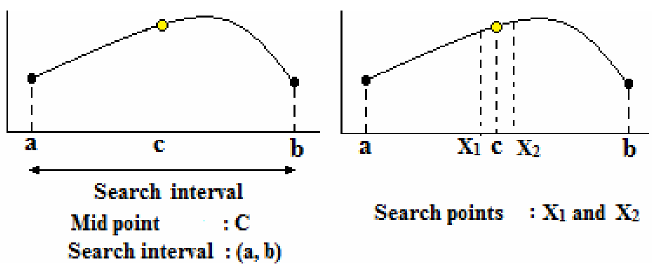

Fig. 3 – Searching by DS algorithm.

One of the sections is eliminated at the end of the iteration and the search continues with the remaining one. To eliminate the section, the function is evaluated at the two search points x_1 and x_2. If $f(x_2) > f(x_1)$, the section (a, x_1) can be eliminated as maximum lies in section (x_1, b).

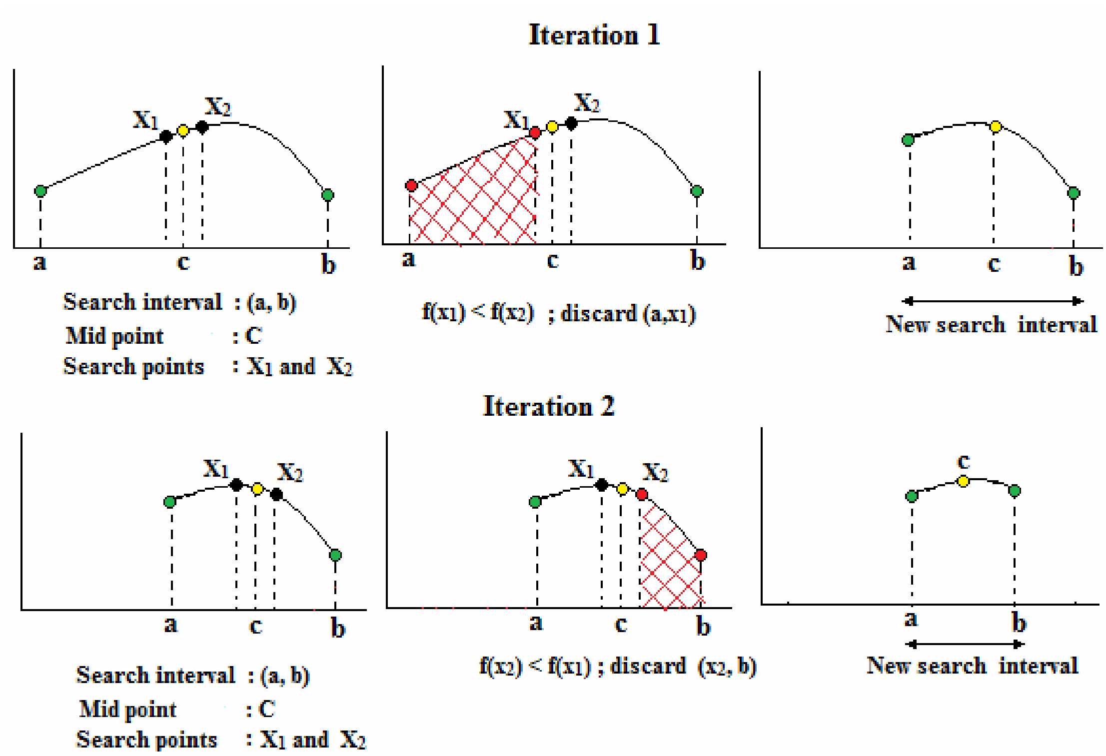

Fig. 4 – Reduction of search interval by DS algorithm.

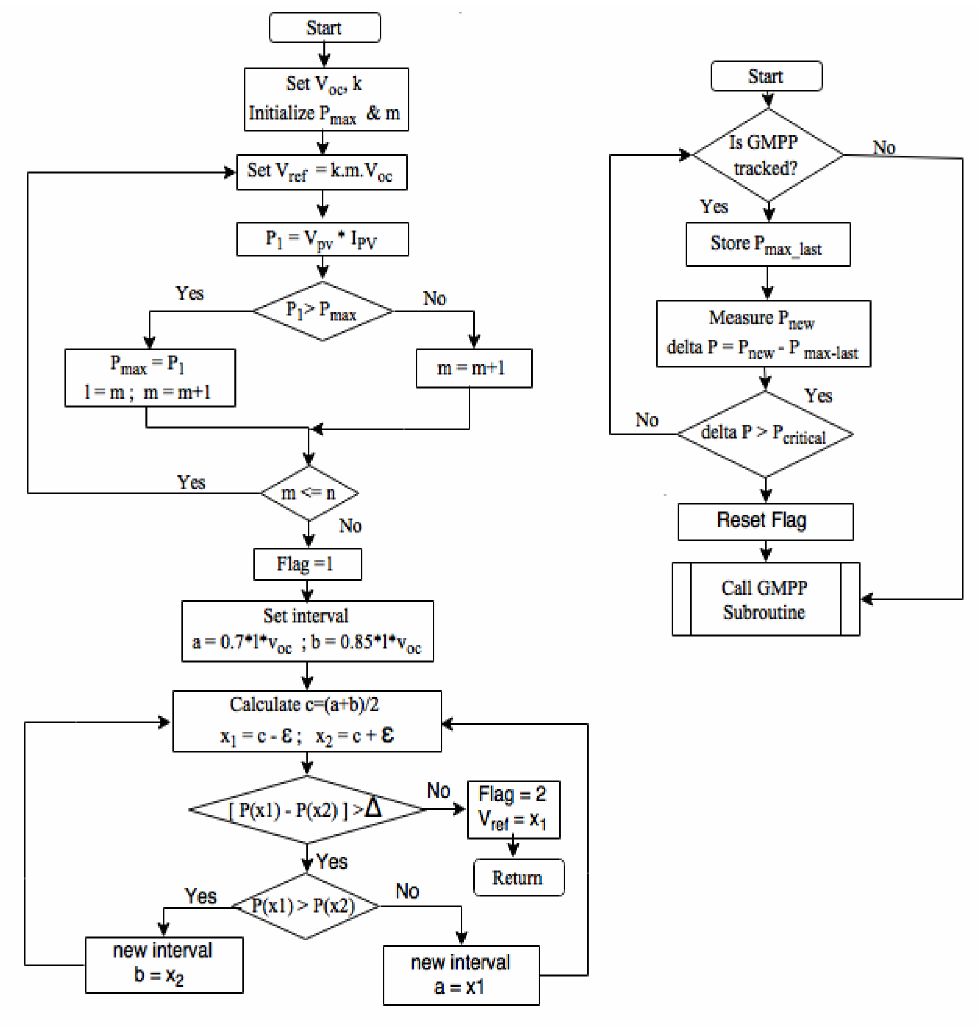

Fig. 5 – Flow chart of DS algorithm based GMPPT

If $f(x_1) > f(x_2)$, section (x_2, b) is eliminated and the maximum lies in the section (a,x_2). Thus, a section is eliminated at the end of each iteration and new search points are introduced in the narrowed interval for further iterations.

In the example presented in Fig. 4, the initial interval is (a, b) and the midpoint is c. The function is evaluated at the two search points and as $f(x_2) > f(x_1)$, the section (a,x_1) is discarded. Then new interval is (x_1,b) and $a = x_1$. The new midpoint c is computed, and the function is evaluated at the two new search points. The iteration is continued until $f(x_1) - f(x_2) < \Delta$, where, Δ is a very small value. The flow chart of the proposed two stage MPPT algorithm is presented in Fig. 5. Flags indicate the completion of the stages. The algorithm searches for the global peak and after locating, it terminates the search by setting the flag to 2. The reference voltage remains unaltered until the irradiation or shading conditions change. The algorithm senses changes of this sort by calculating the deviation in peak power (ΔP) periodically. If there is a change in the environmental conditions or the shade pattern, the deviation will be large. Smaller deviation can however be neglected. If $\Delta P > P_{critical}$, new search is initiated, and the main program calls the GMPP subroutine to rescanning the entire range and track the new peak.

4. RESULTS AND DISCUSSIONS

The tracking capability of the proposed two-stage GMPPT algorithm is tested under full irradiation as well as partially shaded conditions. Under non-shaded case the V-P curve exhibits single peak with the maximum power of 223.6 W occurring at 99.5 V. The proposed algorithm has tracked the peak effectively. The change in reference voltage as the algorithm tracks and the controlled PV array voltage are shown in Fig. 6.

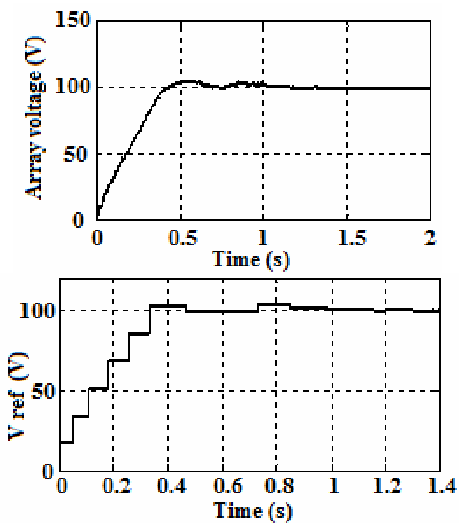

Fig. 6 – Change in reference voltage and array voltage.

The proposed GMPPT algorithm is tested with the first shading pattern as given in Fig. 7 where panels are subjected to 4 different irradiation levels. Three panels are not shaded and receive irradiation $G_1 = 1000$ W/m^2 while the shaded panels receive $G_2 = 800$W/m^2, $G_3 = 600$W/m^2 and $G_4 = 400$ W/m^2 respectively. The panel currents are hence different and I_1 $(I_1 = I_2 = I_3) > I_4 > I_5 > I_6$. Consequently, the V-P curve exhibits four different peaks with the global peak of 131.2 W occurring at the voltage 69.1 V as shown in Fig. 7.

The first stage of the proposed algorithm has identified the region of global peak within 6 iterations at t = 0.485s and the second stage is triggered. At t = 0.7s, the global peak is tracked, and the array voltage settles at 68.5 V. The tracked maximum power is 130.5 W. The change in the reference voltage, array voltage and power as the tracking progresses are shown in Fig. 8.

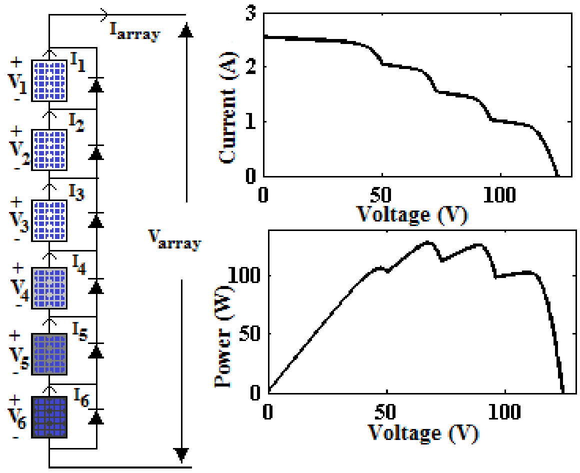

Fig. 7 – Shaded array and its characteristics (pattern 1).

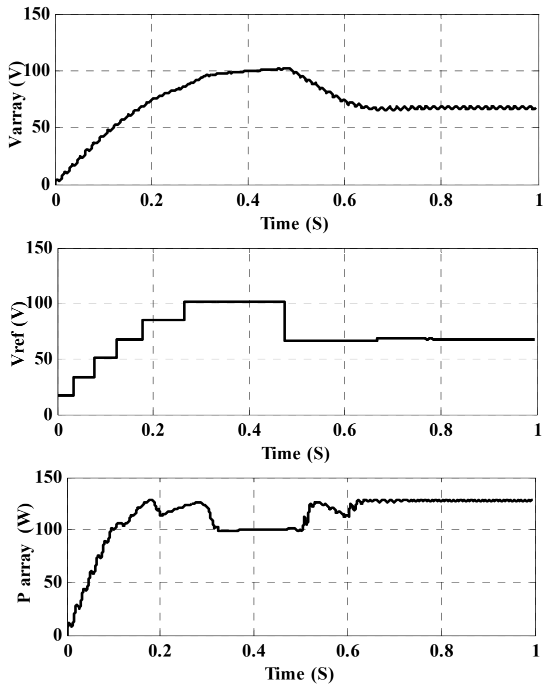

Fig. 8 – Change in array voltage, reference voltage and array power.

The second shade pattern had six different shade intensities. All the panels are shaded at different intensities form 400 W/m^2 to 1000 W/m^2. As the panel currents are different, the V-P curve exhibits six peaks. The shade pattern along with the V-P curve is shown in in Fig. 9.

The global peak in this case lies on the left side and the power difference between the global peak (102.8 W) at 87.5 V and one of the local peaks (99.3 W) at 106.4 V is relatively small (3.5 W). The algorithm differentiated the peaks and tracked the global peak effectively. The algorithm has shrunk the interval at t = 0.3 s and the second stage located the global peak after 10 iterations at t = 0.8 s. The change in reference voltage and the array voltage are presented in Fig. 10.

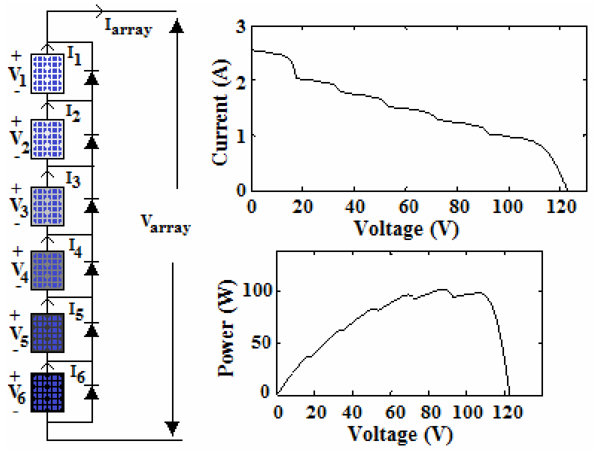

Fig. 9 – Shaded array and its characteristics (pattern 2).

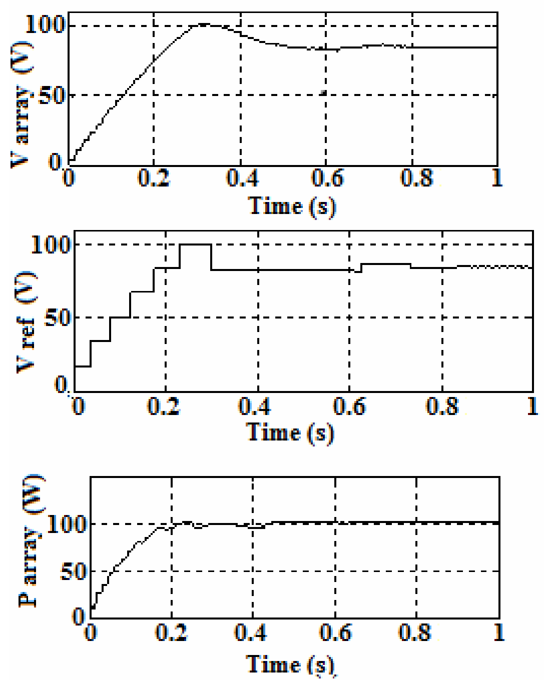

Fig. 10 – Change in array voltage and reference voltage.

Finally, the efficacy of the proposed algorithm is tested for varying environmental conditions as presented in Fig. 11. The array is subjected to the first shade pattern for 1.5 s and the shade pattern is changed to the second at t =1.5 s and then to the third at t = 3 s. The change in the shade patterns and the V-P characteristics of these three conditions are presented in Fig. 11 with the peak powers marked red.

The first peak (123.6 W) occurs at 101.2 V, the second peak (159.3 W) at 84.34 V and the third peak (198.7 W) at 103.7 V.

The algorithm starts scanning the initial search interval at t = 0 s from the left side. The region of global peak is detected after the seventh iteration and the second stage continues the search with dichotomous algorithm and generates the reference voltage as 101.2 V. The maximum power point is tracked at t = 1.0 s. The algorithm periodically checks for the change in peak power. It senses the deviation at t = 1.5 s as there is a larger deviation in power (ΔP > P critical). The algorithm calls the GMPP subroutine to rescan the voltage range for new peak.

The new peak occurs at 84.34 V which is on the left side of the previous peak. This new peak is tracked at t = 2.5 s. The next disturbance is made at t = 3s with the third shade pattern. The algorithm recognizes the change in irradiation received by checking ΔP. In this case, the peak lies to the right of the previous one and is tracked at t = 4 s. The variation in the reference voltage generated by the proposed algorithm and the corresponding change in the array voltage are presented in Fig. 12.

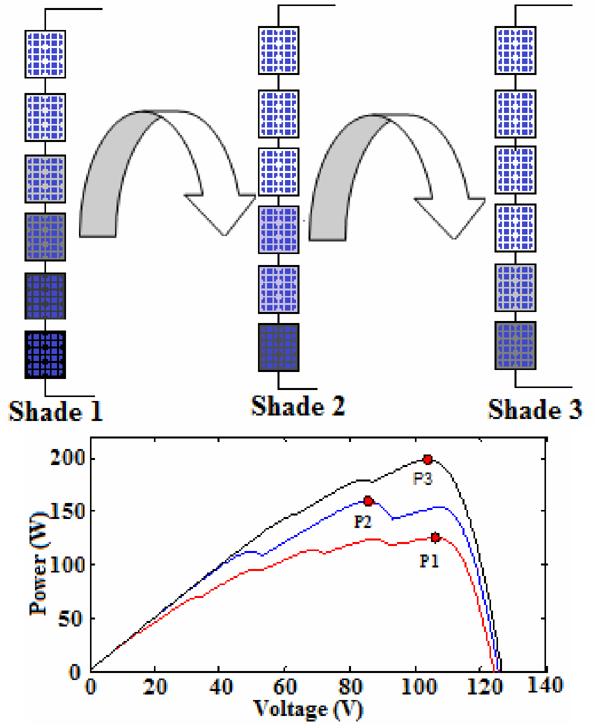

Fig. 11 – Dynamic shading and its characteristics.

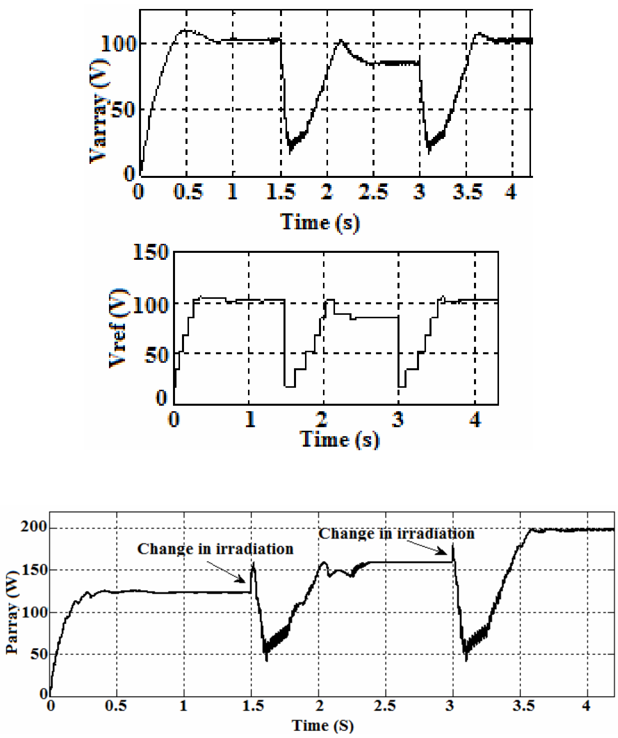

Fig. 12 – Change in array voltage and reference voltage.

The proposed algorithm is verified by comparing the peaks obtained from the V-P curves with the actual peaks tracked by the algorithm in Table 2.

Table 2

Validation of the proposed GMPPT results.

Shade Pattern	V_{mp} (V)		P_{mp} (W)	
	V-P curve	DS GMPPT	V-P curve	DS GMPPT
1	102	101.2	124.6	124.2
2	84.34	84.3	159.3	159.3
3	103	102.4	198.7	198

The results presented in Table 2 shows that the proposed DS GMPPT algorithm is effective in tracing the global peak under non-homogeneous irradiation conditions.

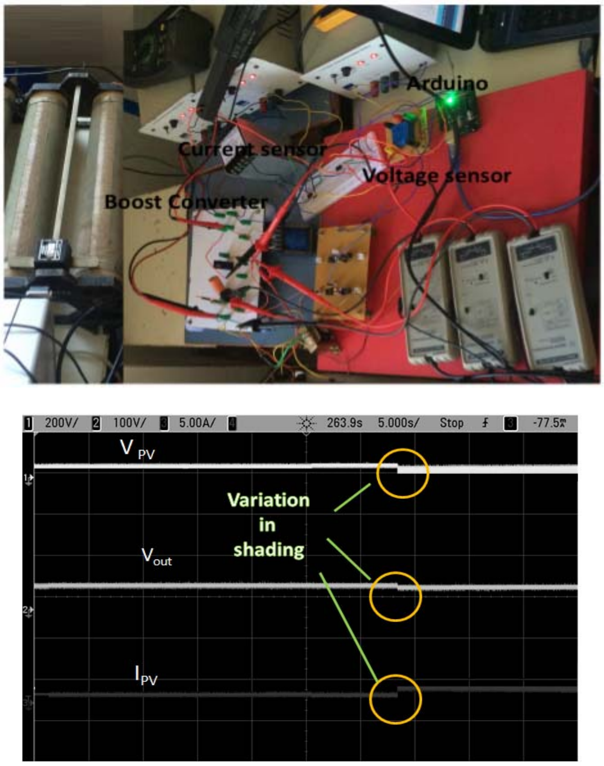

Fig. 13 – Experimental setup and the results for the shade pattern 2 of Table 2.

The experimental setup is presented in Fig. 13. The array current is sensed by the sensor LA 55P and the voltage is sensed by the voltage sensor LV 20 P. The developed DS based two stage MPPT algorithm is embedded in Arduino. The control algorithm generates the reference signal and the duty cycle of the gating pulse to the boost converter is adjusted according to the error signal (V_{ref} – V_{act}). The variation in the array voltage, current and the output voltage are captured by the Agilent oscilloscope and are presented in Fig. 13 (shade pattern 2). The algorithm tracked the maximum power point successfully according to the changes in irradiation as highlighted in the Fig. 13.

5. CONCLUSIONS

The paper has proposed a two-stage tracking algorithm to track the maximum power from PV source under varying irradiation conditions. The initial stage of the algorithm shrinks the search interval to the vicinity of the global peak and the dichotomous search based second stage locates the exact peak. The two-stage algorithm is explained in detail and the working of the proposed algorithm is tested under standard and shaded conditions for a 6×1 PV array. The simulated and the experimental results are presented to show the ability of the algorithm to track the global peak under rapidly changing irradiation conditions.

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