A Fast GMPPT Algorithm For PV Array Under Non-uniform Shading Conditions

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***Abstract*—The major challenge in operating the PV arrays with maximum efficiency is non-uniform irradiation over it. These conditions lead to multiple peaks in the P-V curve. This paper proposes a new global maximum power point tracking (GMPPT) algorithm which tracks the global peak irrespective of shading conditions. It takes voltage as a reference and starts tracking for the global peak. It first finds the minimum voltage below which absence of the global peak is ensured. Then the local peaks present in the P-V curve are estimated by calculating the knee points. The algorithm uses a maximum power triangle concept and a skipping scheme to speedup the tracking process. The region where the global peak is present is estimated and P&O is used to track the exact global peak. The proposed algorithm is simulated in MATLAB Simulink and results are verified experimentally. Delta SM100AR75 PV simulator is used as a PV source connected to a boost converter. TMS320F28335 digital signal processor is used to implement the proposed algorithm. The results show that using the proposed algorithm tracking time is low.**

***Index Terms*—DC-DC converter, Global maximum power point tracking (GMPPT), Partial shading conditions (PSC), Solar energy conversion system, Solar power generation**

I. Introduction

The emerging demand for electrical energy and the more concern about environmental issues encouraged the use of non-conventional energy sources for electrical power generation. One of the most abundantly available non conventional energy source is solar energy. With the use of PV panels electrical energy can be easily generated. PV panels are free from pollution and have a long life. The major drawback is its nonlinear characteristics and the high initial cost. The nonlinear characteristic of PV array gives only one maximum power point. The characteristics further depend on solar irradiation and temperature. Irrespective of the atmospheric conditions it is required to operate at the maximum power point to increase the efficiency and minimize the generation cost. The PV arrays are operated with a dc-dc converter. By varying the duty cycle of these converters maximum power is extracted. Several tracking techniques are proposed. Popular tracking techniques [1] are perturbation and observation (P&O) technique, incremental conductance technique, short-circuit current (SCC) technique, and open-circuit voltage (OCV) technique. Various methods are proposed to ease the implementation and to improve the performance.

The above-mentioned tracking techniques are effective under uniform shading conditions, where the P-V curve consists of only one maximum power point. But under partial shading conditions, the entire PV array doesn't receive the same insolation, the characteristics become more complex with multiple peaks [2]. The above mentioned MPPT techniques assume that there is only one peak and traps at the local peak resulting in under utilization of PV array. To overcome this problem several MPPT algorithms are proposed in the literature to track the global maximum power point. MPPT methods can be categorised into distributed [3]- [4], reconfiguration [5] and centralized MPPT [6]–[8]. In distributed MPPT (DMPPT), each module of the PV array is connected to an individual power converter. These converters extract maximum power from the respective modules thus maximum power is extracted from PV arrays under partial shading conditions. The requirement of power converters to each module, sensors and controllers increases the overall installation cost. Therefore, DMPPT is used in low power PV systems. In reconfiguration MPPT, PV arrays are configured in such a way to extract maximum power. Centralized MPPTs (CMPPT) consist of a single power converter connected to PV arrays. Thus, the initial installation cost is low.The global maximum power point is reached by using a special algorithm without changing any hardware.

In [6], a GMPPT algorithm is proposed, in which the local peaks are assumed to be present at integer multiples of $0.8 * V_{oc}$. At these points P&O is applied to reach the exact local peak. The global peak is obtained by comparing these local peaks. This algorithm is simple but it scans the entire P-V curve which leads to higher tracking time. To minimize the tracking time maximum power triangle (MPT) concept and skipping mechanism are used in [9]- [10].

A new GMPPT algorithm is proposed in this paper, which improves the tracking performance. This algorithm uses the MPT concept and voltage skipping mechanism along with local peak estimation to improve the tracking speed. The change in the current near knee point region of the I-V curve is used to adjudge the presence of a local peak. These local peak powers are compared to find the global peak region. P&O is applied in these region to reach the exact global peak.

II. Modeling of PV system

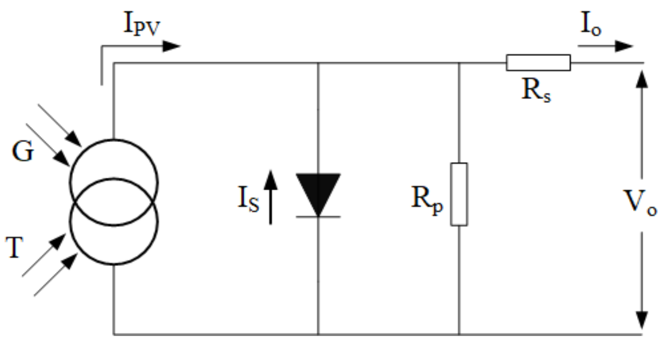

Fig. 1. Modeling of a PV cell

A PV cell can be modelled as shown in Fig. 1 [11]-[12]. PV model consists of diode, a series resistance and a parallel resistance. The output current of a PV cell is given by eq((1)).The PV current is dependent on irradiation (2) and temperature (3).

$$I_o = I_{pv} - I_s \left[exp\left(\frac{q(V_o + R_s I_o)}{NKT} \right) - 1 \right] - \frac{V_o + I_o R_s}{R_p} \quad (1)$$

where I_o id the output current of PV cell, V_o is the output voltage of PV cell, I_{pv} is the PV current, R_s is the series resistance, R_p is the parallel resistance of the PV cell, A is the ideality factor of the diode.N is a number of modules in series, k is Boltzmann constant and q is the charge of the electron.

$$I_{pv} = I_{pvn} * \frac{G}{G_n} \quad (2)$$

where I_{pv} is PV current at irradiation G, I_{pvn} is PV current at nominal irradiation G_n

$$I_{pvt2} = I_{pvt1}(1 + K_o(T_2 - T_1)) \quad (3)$$

where I_{pvt1} is the PV current at temperature T_1 and I_{pvt2} is the PV current at temperature T_2.

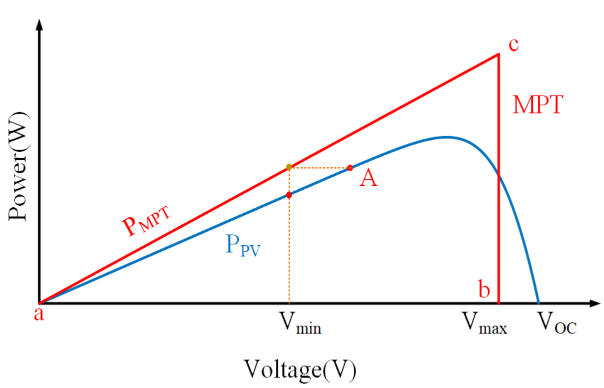

Fig. 2. Illustration of Maximum power triangle concept

III. Proposed Algorithm

A. Maximum power triangle (MPT) Concept

The MPT concept is used to minimize the search region at the starting of the algorithm by calculating V_{min} (4). This ensures that the region to the left of V_{min} will not contain any global peak. The maximum voltage point of the triangle is determined by studying various shading patterns, which concludes that the global peak will not be present beyond $0.9{*}V_{oc}$, where V_{oc} is the PV array open-circuit voltage under uniform full irradiation. So, the extreme limit of maximum power triangle is determined at point b as shown in Fig. 2 i.e. V_{max} = $0.9 * V_{oc}$. Also, the current at the global peak I_{gmpp} under shading conditions never exceeds the maximum current at standard test conditions I_{mpstc} ($I_{gmpp} < I_{mpstc}$). Based on the above information maximum power triangle with vertices a,b,c is formed which determines that the global peak will lie inside this triangle. V_{min} is calculated as

$$V_{min} = \frac{P_{gmpp}}{I_{mpstc}} \quad (4)$$

B. Selection of step-size (V_{gstep})

A V_{gstep} is determined as the step voltage change in the P-V curve which is used to track GMPP at every iteration. It is important to choose the right V_{gstep} as it is immediately related to the tracking speed and its efficiency. The value should be less than the minimum voltage difference between the two peaks. This ensures that no peak is missed. V_{gstep} is chosen such that estimated local peaks would lie near to the actual local peaks. This will increase the skipping region after the estimation of local peaks.

C. Skipping mechanism

This mechanism is used to shrink the search region in the P-V curve for tracking GMPP. It increases the tracking speed without any additional circuits and sensors.

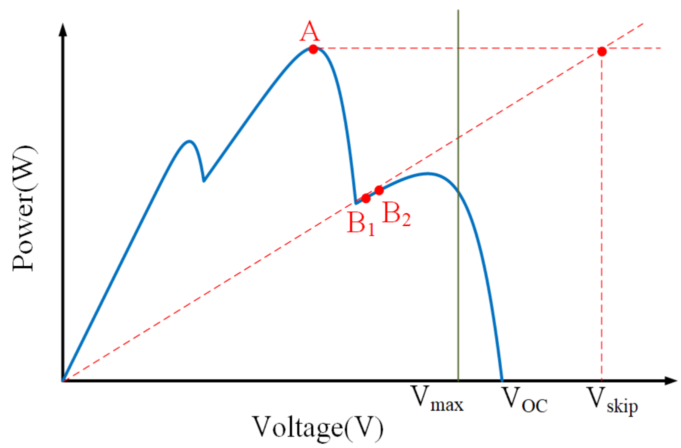

Fig. 3. Explanation of skipping mechanism using P-V curve.

To understand the operating principle of this scheme, consider a P-V curve with 3 different peaks as shown in Fig.

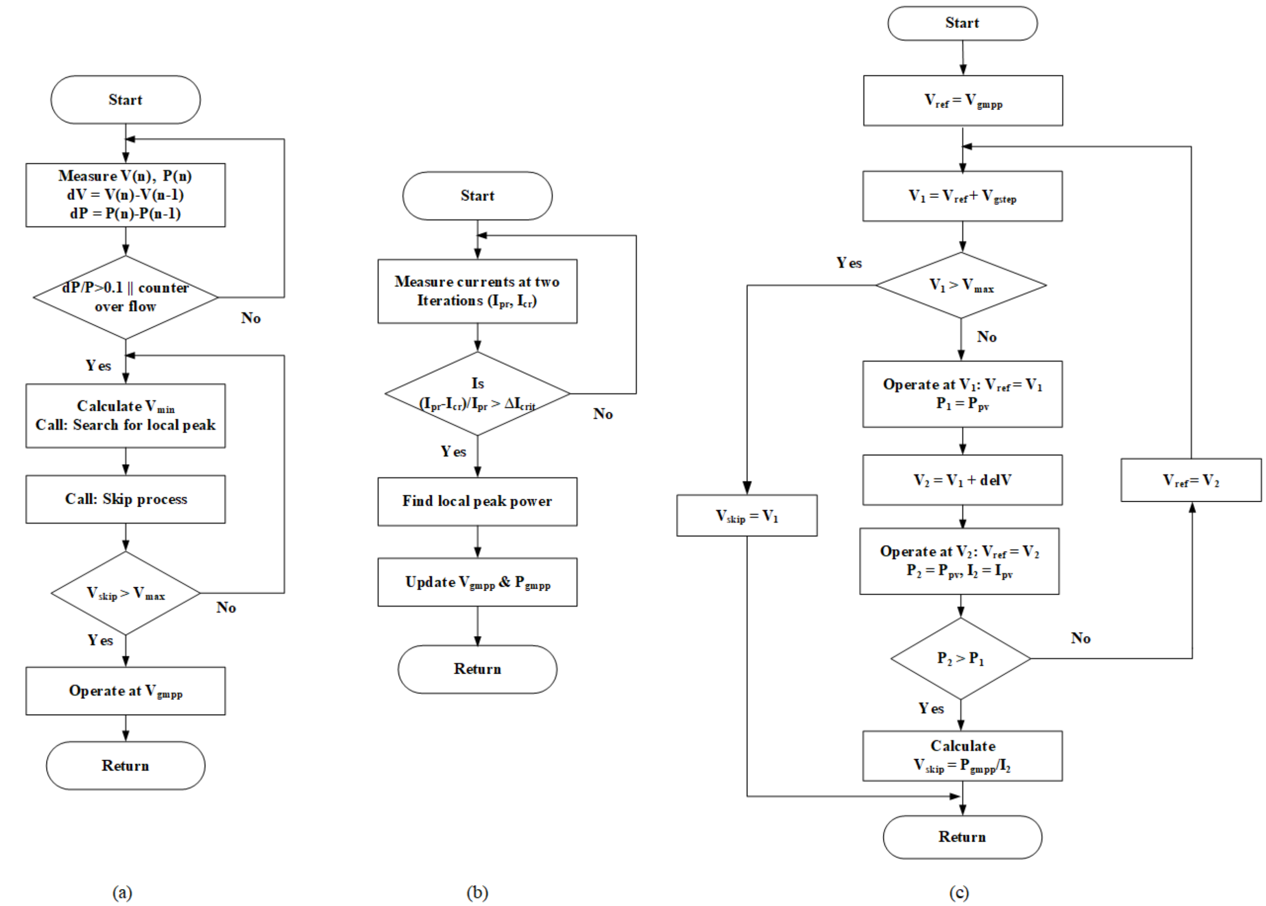

Fig. 4. Flowchart for the proposed algorithm, (a) GMPP algorithm (b) Estimating local peaks, (c) Skipping process

3. The algorithm reaches to point A which is one among the 3 local peaks in the P-V curve with voltage(V_A), current(I_A), Power(P_A). Now the operation is perturbed forward with a large change in the voltage (V_{gstep}). After large perturbation, a small forward perturbation is applied. The slope $\frac{dP}{dV}$ is observed at that point. The two test points are V_{B1} and V_{B2}.

The powers at these two points are measured, i.e., P_{B1}, P_{B2}. If $P_{B2} > P_{B1}$, the $\frac{dP}{dV}$ is positive which indicates that some portion of the P-V curve can be skipped as the point B is located in the next region. Now V_{skip} is calculated using (5). The voltage region in the interval V_{B2} and V_{skip} can be skipped as the power in between these points is less than the previous recorded P_{gmpp}. If $P_{B2} < P_{B1}$, the $\frac{dP}{dV}$ is negative and the iterations are repeated until $\frac{dP}{dV}$ becomes positive. If the skip voltage is more than V_{max} which means GMPP is tracked and it operates at respective GMPP. Otherwise, the algorithm goes to the next process until the operating point reaches V_{max}.

$$V_{skip} = \frac{P_A}{I_{B1}} \tag{5}$$

D. Searching for local peaks

In the proposed algorithm the local peaks are determined from the I-V curve. The P-V curve consists of multiple peaks due to partial shading. I-V curve can be divided into same number of sections as number of peaks. Each section consists of a local peak between constant current region and a constant voltage region. These peaks are determined by varying the voltage in steps and observing the current change. Whenever the operating point shifts from the constant current region to the constant voltage region, there will be a change in the current

$$\frac{I_{pr} - I_{cr}}{I_{pr}} > \Delta I_{crit} \tag{6}$$

where I_{pr} and I_{cr} are currents at two consecutive iterations and

$$\Delta I_{crit} = \frac{I_{sc} - I_{mpp}}{I_{sc}} \tag{7}$$

where I_{sc} is short circuit current and I_{mpp} is current at maximum power point under uniform shading conditions. Whenever eq(6) is satisfied, the algorithm operates at a point in between two iterations and compares the power with previous peak power and updates P_{gmpp} and V_{gmpp}.

Fig. 4 shows the flowchart for the proposed algorithm. When the shading has occurred there will be sudden change in power. The algorithm detects this change and starts to track the global peak. First, it eliminates some region on the left side of the curve by calculating V_{min} using the maximum power triangle (MPT) concept(4). Then the operating point starts at V_{min} and moves towards the right in steps and checks for the local peaks using the I-V curve. When one of the peaks is reached, the algorithm tries to skip some region using a skipping mechanism. Skip voltage V_{skip} is calculated using(5). If the skip voltage is more than V_{max}, the algorithm stops searching for peaks and applies P&O at V_{gmpp} to track the exact global peak. If the skip voltage is less than V_{max} the algorithm again starts checking for local peaks. this process is continued until V_{max} is reached.

IV. Simulation Results

The proposed algorithm is simulated with various partial shading conditions using MATLAB Simulink. A boost converter connects the PV array and resistive load as shown in Fig. 5. The converter duty cycle is varied to obtain the maximum power point of PV array. The simulation paramaters of the PV system and boost converter are shown in Table I and Table II. The proposed algorithm is verified with the different shading patterns, the P-V and I-V curves for respective shading patterns are shown in Fig 6.

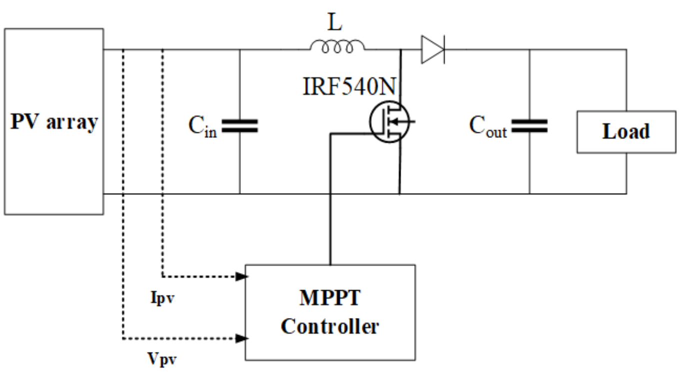

Fig. 5. PV array connected to boost converter.

TABLE I
PV MODULE PARAMETERS

Parameter	I_{SC}	V_{OC}	P_{mpp}	I_{mpp}	V_{mpp}
Value	3.74A	21V	59.9W	3.5A	17.1V

TABLE II
BOOST CONVERTER PARAMETERS

Parameter	L	C_{in}	C_{out}	R	Switching frequency(F_s)
Value	5mH	$10\mu F$	$2000\mu F$	65Ω	$50kHz$

A. First transition from pattern 1 to pattern 2

The Fig. 7 shows the simulation results for the first transition. Initially, at uniform irradiation, the operating point

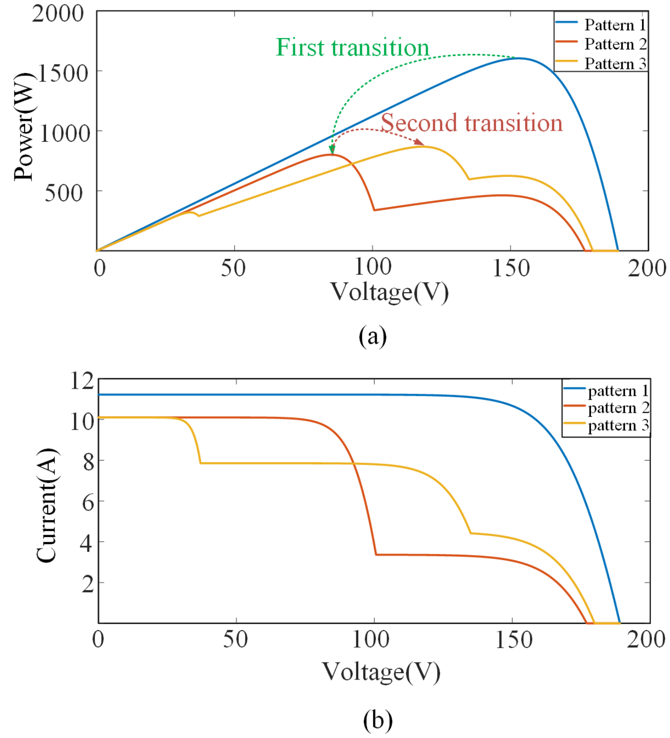

Fig. 6. Partial shading patterns used in simulation. (a) P-V curve (b) I-V curve

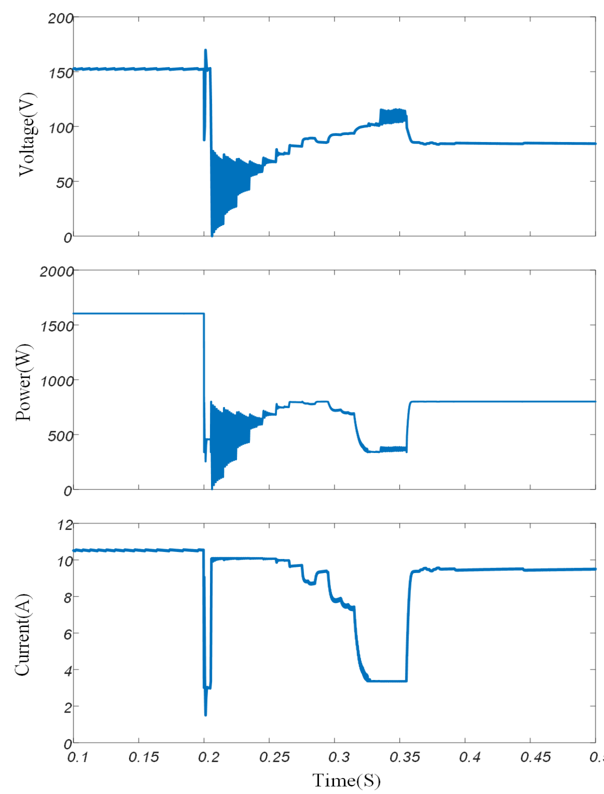

Fig. 7. Simulation results for the first transition, V_{PV}, P_{PV}, I_{PV}

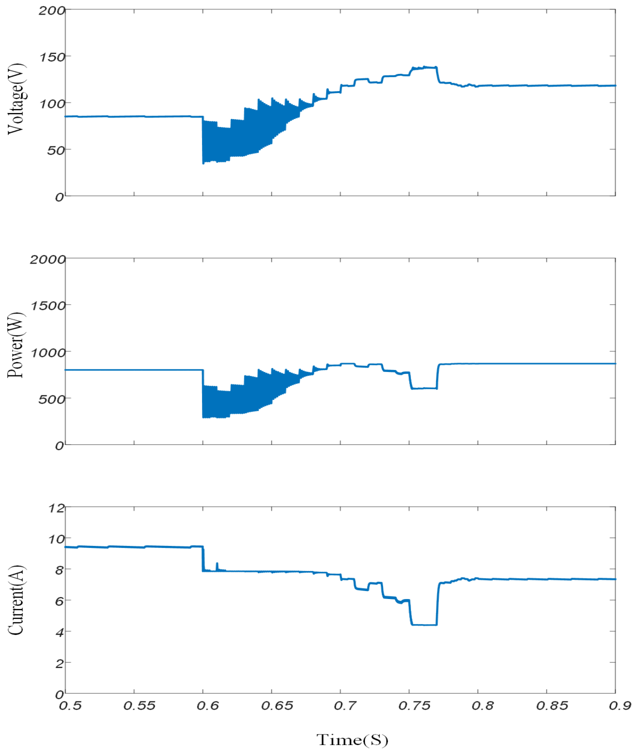

Fig. 8. Simulation results for the second transition,V_{PV}, P_{PV}, I_{PV}

is at 153 volts. At t=0.2sec shading has occurred, it is detected by the change in power, and the algorithm starts tracking the global peak. First, it calculates V_{min} to fasten the search process. The algorithm starts at V_{min} and checks for the peaks by increasing the V_{min} in steps of V_{gstep}. A local peak is detected around 80 volts. This peak power and respective voltage are stored in P_{gmpp} and V_{gmpp}. Then skipping mechanism is initiated to further minimize the search region. At a voltage of around 110V, V_{skip} is calculated. The skip voltage is more than V_{max} and hence the algorithm stops tracking and operates at V_{gmpp} which is around 80V and then calls P&O to track the exact global peak i.e, at V=85V.

B. Second transition from pattern 2 to pattern 3

The Fig. 8 shows the simulation results for the second transition. Initially, the operating point is at 85 volts which is the global peak for pattern 2. At $t = 0.6sec$ shading has changed from pattern 2 to pattern 3. It is detected by a change in power, hence the algorithm starts tracking the global peak for pattern 3. First, the algorithm calculates V_{min} to minimize the search region. Here in this pattern one of the peaks falls outside the search region by calculating V_{min}. The algorithm starts at V_{min} and checks for the peaks by increasing the V_{min} in steps of V_{gstep}. A local peak is detected around 120 volts. This peak power and respective voltage are stored in P_{gmpp} and V_{gmpp}. Then skipping mechanism is initiated to further minimize the search region. At a voltage of around 140V, V_{skip} is calculated. The skip voltage is more than V_{max} and hence the algorithm stops tracking and operates at V_{gmpp} which is around 120V and call P&O to track the exact global peak i.e, at $V = 118V$.

V. Experimental Results

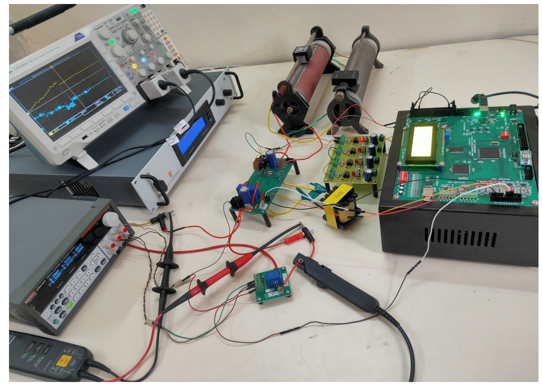

Fig. 9. experimental setup for hardware implementation

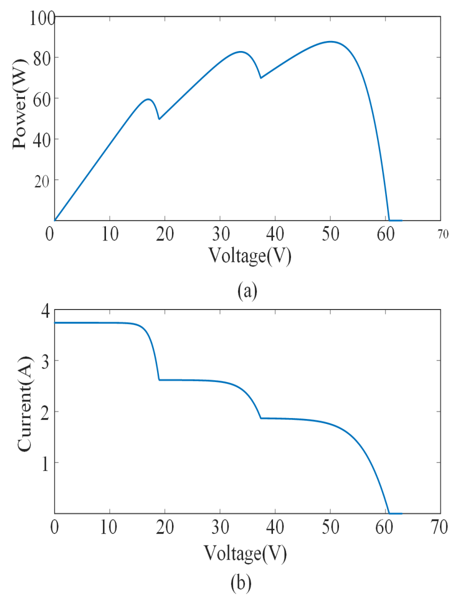

Fig. 10. Partial shading pattern for experimental verification, (a) P-V curve, (b) I-V curve

The proposed GMPPT algorithm is validated using an experimental setup shown in Fig. 9. The PV simulator is used to emulate the behavior of the PV array. The PV array consists of 3 PV modules each of 60 watts, connected in series. Boost converter is designed to extract maximum power from the PV source. It is designed using an inductor (L) of 5mH and an input capacitor(C_{in}) of 1000μF. The load with a typical value of 65Ω is used as a load to the boost converter. The switching frequency of converter (f_s) is set to 50kHz. The proposed algorithm is implemented using the TMS320F28335 digital signal processor (DSP). The sampling period is set to 100ms. A voltage divider circuit is used to sense the input and output voltages. A LEM-25NP current sensor is used to sense

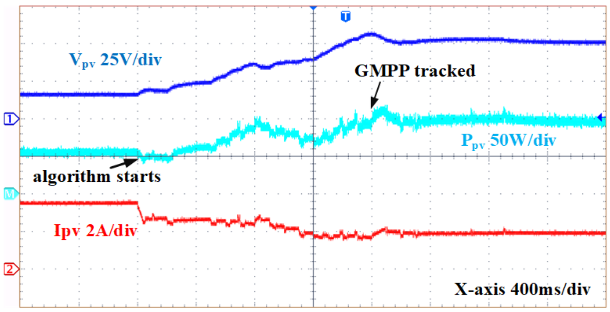

Fig. 11. Experimental waveforms, PV voltage(V_{pv},25V/div), PV power(P_{pv},50W/div), PV current(I_{pv},2A/div)

the input current. The shading pattern in Fig. 10. is emulated using the PV simulator delta SM100AR75. Initially, the PV modules are under uniform irradiation, when partial shading occur the algorithm detects the change in power and starts tracking for global peak. The tracking performance of the newly proposed algorithm is shown in Fig. 11. The tracking time is observed as 1.6sec.

VI. Conclusion

A new GMPPT algorithm is proposed to track the global maximum point for PV systems under partial shading conditions. During partial shading conditions, P-V curves will exhibit multiple peaks and I-V curve will be having same number of sections. Local peaks in the P-V curve will be nearer to the respective knee points in the I-V curve. The algorithm estimates the local peaks by observing the change in current in the I-V curve. Estimating local peaks from the I-V curve will improve the tracking performance as P&O is implemented only once to track the exact global peak. Estimated local peaks will also help in reducing the search region. An MPT concept and a skipping mechanism are used to further improve the tracking performance. The proposed algorithm is simple and faster. The proposed algorithm is demonstrated with simulation and experimental results.

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