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A GMPPT Algorithm for PV Systems Using Current Reference and P-I Curve Under Partial Shading Conditions

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***Abstract*—Photo-voltaic (PV) system has non-linear relation between its output power and operating voltage.It is desired to extract maximum power from the PV system i.e. by operating at maximum power point all the time. Under partial shading conditions, the conventional maximum power point tracking algorithms can't detect the global peak. A most efficient global maximum power point tracking (GMPPT) technique with less tracking time is required when the change in shading is more rapid. In this paper, a novel GMPPT algorithm is proposed which tracks the global peak using P-I curve, PV curve and I-V curve of the PV system taking current as reference. As the PV current varies with irradiation, the tracking time for the proposed algorithm is low under shading conditions. The tracking time is minimized by calculating I_{min} and V_{min}. The knee point regions are estimated by detecting the change in voltage at every iteration. Each knee point region will have one peak point. The regions where global peak does not exist is discarded by adopting a novel current skipping technique. These techniques reduces the tracking time. MATLAB Simulink is used to evaluate the performance of the proposed algorithm for different shading patterns and the results shows that tracking time is less.**

***Index Terms*—DC-DC converters, Global maximum power point tracking (GMPPT), Partial shading conditions, Photovoltaic systems**

I. Introduction

THE generation of electrical energy using PV systems mainly depends on the solar irradiation and temperature. Irradiation level on the PV panels decreases due to the shadows of nearby objects causing partial shading. Shading on a single cell causes a reduction in the total power from the entire string. Partial shading causes effects like cracks, reduction in efficiency and life of PV modules. The PV system exhibits complex characteristics under partial shading with multiple peaks in P-I curve and P-V curve. The conventional MPPT techniques [1] like Fractional Short Circuit current (FSCC), Fractional Open Circuit Current (FOCC), Perturbation and Observation (P&O), Incremental Conductance (I&C) methods are effective under uniform shading conditions but under partial shading conditions, they cannot reach the global peak and may settle at local peaks. When operating at local peak the efficiency of system is reduced. Authors have proposed some GMPPT techniques that are categorized into 3 types. In distributed MPPT (DMPPT) technique [2], each module will have a separate power converter that extracts maximum power from the respective module. The tracking algorithm is simple but this method uses many sensors, power converters which increases the overall installation cost. In Reconfiguration MPPT (RMPPT) technique [3] the configuration of the PV system is changed such that maximum power is extracted during partial shading conditions. This technique takes more time to select the best configuration and the tracking algorithm is more complex. The physical connections for these techniques are more and hence installation cost is also high. In centralized MPPT (CMPPT) techniques [4], maximum power is extracted without using any physical arrangements. One large power converter is connected to the entire PV system. Installation cost is low as it uses a single power converter and few sensors. A complex algorithm is used to track the global peak.

These CMPPT techniques can be easily implemented and have less tracking time. The $0.8 * V_{oc}$ model [5] is one among the popular GMPPT algorithms. The algorithm works on the assumption that local peak exists at every integral multiples of $0.8 * V_{oc}$. At these points the local peaks are tracked by using P&O method. All the powers at local peaks are compared to determine the global peak. When the shading is more complex this technique may not be effective and may trap at the local peak. Another method proposed in [6], is to find the local peaks using the I-V curve. The I-V curve and P-V curve are divided into number of regions same as number of peaks. Each region will have a knee point where local peak exists. The tracking time of this method is more as it reaches to exact peak every time during complex shading conditions. Authors have proposed techniques like the maximum power triangle concept [7], skipping mechanism [8] [9] to improve the tracking speed.

A new GMPPT algorithm is proposed in this paper taking PV current as a reference and operates at maximum power point. The main advantage of using the P-I curve is that current is proportional to irradiation and hence tracking time is less during shading. This algorithm sets the current and voltage

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limits such that the global peak lies within the limits. This reduces the tracking time. The upper current limit varies with the irradiation and hence it is not fixed. But the upper limit is taken as the short circuit current of the PV module under standard test conditions. A novel skipping technique is also proposed to skip the region where no peak exists.

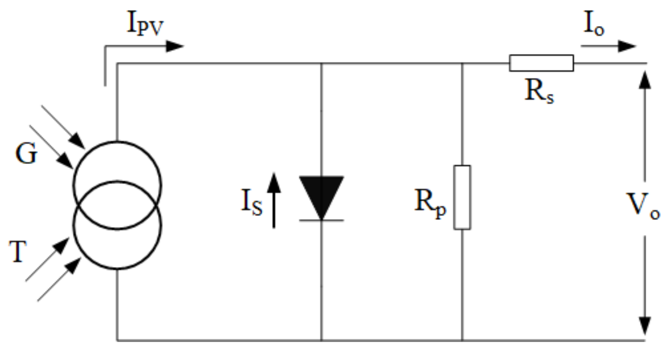

Fig. 1. Modeling of a PV cell

II. Modeling of PV system

A PV cell can be modelled as shown in Fig. 1. PV model consists of diode, a series resistance and a parallel resistance. The output current of a PV cell is given by (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 is 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.

III. Proposed GMPPT algorithm using P-I curve

A. Importance of P-I curve

In the proposed GMPPT algorithm, the global maximum is tracked using the P-I curve. The main advantage of using the P-I curve instead of using the P-V curve is that the search region varies with irradiation. The P-I curve of a PV module for different irradiation levels is shown in Fig. 2. Under full irradiation, the range of current is 0 to 3.74A. As the irradiation level decreases the range of current also decreases With 0.2 irradiation the current range decreases to 0.7A. Therefore current is taken as the reference to track the global peak which reduces the tracking time.

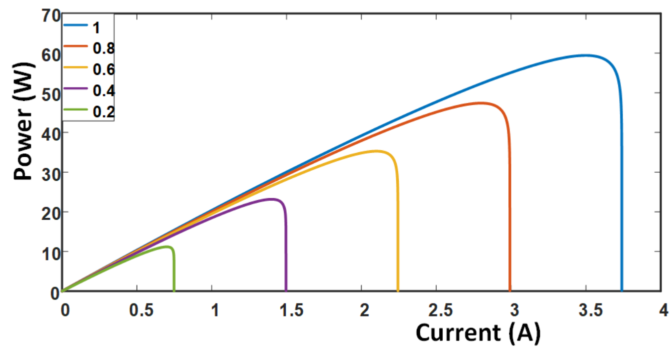

Fig. 2. P-I curves under various irradiation

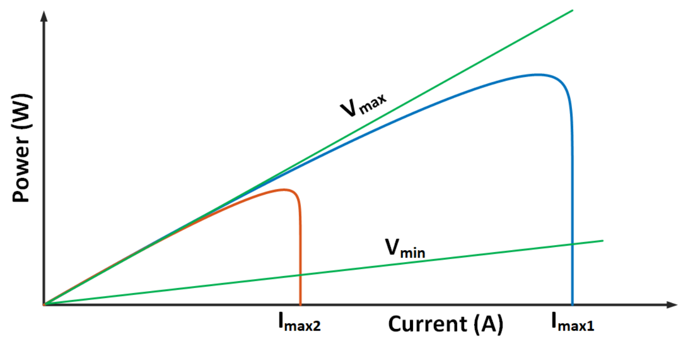

Fig. 3. Importance of V_{min}

B. Importance of V_{min} and I_{min}

I_{min} is defined as the minimum PV current below which global peak does not exist. Calculating I_{min} discards lower current values where no global peak exists, thus reducing the search region. I_{min} is calculated using maximum power triangle concept. I_{max} is defined as the maximum current from the PV array i.e, short circuit current under standard test conditions. Short circuit current is dependent on the irradiation level. Hence the maximum limit in P-I curve cannot be fixed. Under shading conditions, the algorithm continuous to check for GMPP even after the maximum current is reached. To overcome this problem V_{min} is used to stop the algorithm once it reaches the maximum current. V_{min} is calculated as given by (4). In Fig. 3 when the operating point crosses V_{min} the algorithm stops and operates at I_{gmpp}. In this way V_{min} is used to reduce the tracking time under shading conditions.

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

C. Concept of Maximum Power Triangle (MPT)

I_{min} and V_{min} are calculated by the maximum power triangle (MPT) concept proposed in [7]. This triangle is drawn

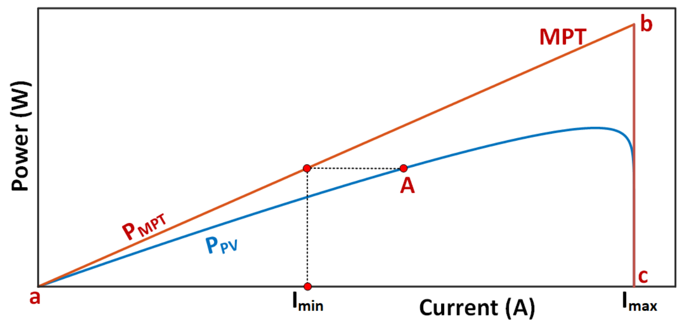

Fig. 4. Maximum power point concept in P-I curve

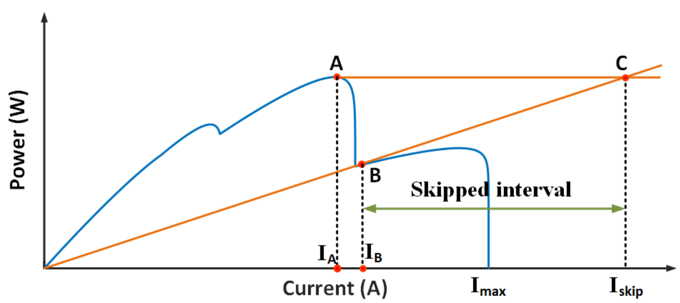

Fig. 5. Current skipping scheme

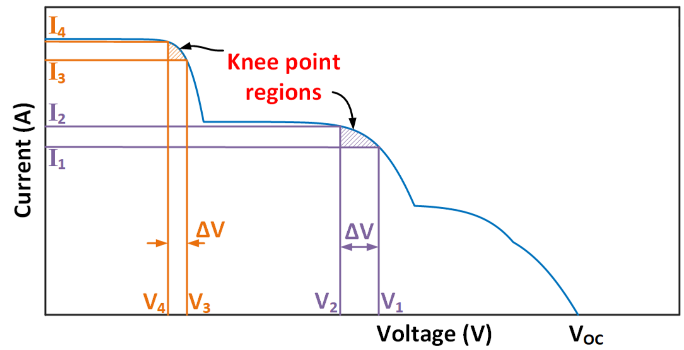

Fig. 6. Knee point calculation

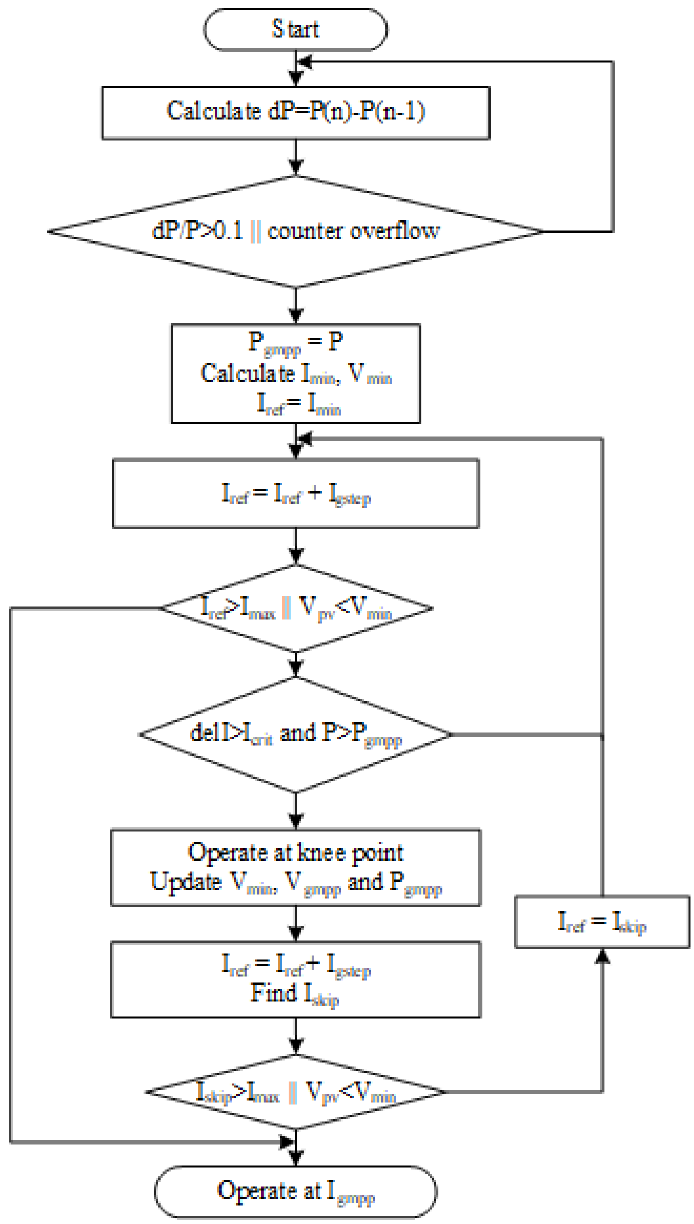

Fig. 7. Flowchart for the proposed algorithm

over the P-I curve as shown in the Fig. 4 which ensures that the entire P-I curve lies inside the maximum power triangle (MPT). The maximum current from the PV module is the short circuit current (I_{sc}) at standard test conditions. Hence the maximum point is chosen at point c. the slope of the triangle is decided by the maximum voltage across the PV array i.e, open circuit voltage V_{oc} at standard test conditions. Based on V_{oc} and I_{sc} point b is determined. Thus maximum power triangle MPT is constructed with vertices a, b, c.

$$I_{min} = \frac{P_{gmpp}}{V_{oc}} \tag{5}$$

To illustrate, consider a point A as shown in Fig. 4. The line ab is known as the power line with slope V_{oc}. The point A is projected to the power line and the current at which point A intersects power line is considered as I_{min}. It is observed that by calculating I_{min} the algorithm does not start at zero but it starts at I_{min} reducing the search area. It is guaranteed that the power value in the region [0,I_{min}] is lower than PA.

D. Selection of I_{gstep}

I_{gstep} is defined as the step change in current reference at every iteration. It is selected such that the algorithm should not miss any peaks in the P-I curve and tracking time should be less. The minimum change in current with change in irradiation is considered as $0.1 * I_{sc}$. Therefore I_{gstep} should not be more than $0.1 * I_{sc}$. In the proposed algorithm, I_{sc} is considered as 3.74 A and 3 strings are connected in parallel.

So I_{gstep} should not be more than $3*0.1*I_{sc}$. In the proposed algorithm I_{gstep} is taken as 1 A.

E. Current Skipping Scheme

A skipping scheme proposed in [8] which skips the region where no global peak exists. This scheme is modified in the proposed algorithm to be use in the P-I curve. To understand the current skipping scheme, consider a P-I curve as shown in Fig. 4 with three peaks. It is observed that in the P-I curve, after every peak there is a sudden fall in the curve. Using this sudden change in power, I_{skip} is calculated at the immediate next iteration in the P-I curve. Consider that the operating point is at one of the peak points A with current I_A and power P_A. In the next iteration, at point B the PV voltage is measured as V_B. A straight line is drawn passing through the point B with slope V_B and point A is projected onto this line, meets at point C. I_{skip} is calculated using (6). Therefore the region between I_B and I_{skip} is discarded.

$$I_{skip} = \frac{P_A}{V_B} \tag{6}$$

F. Knee point calculation

It is required to identify the regions in the curves where peaks exists. These regions are called knee point regions. To determine the knee point regions consider a PV system with complex partial shading which has multiple peaks. I-V curve can be divided into regions based on the current magnitudes and number of regions are same as number of peaks. Each region consists of a constant current region and a constant voltage region between which knee point region exists. The power in the knee point region is approximated as the peak power. The comparison of powers in these regions gives the region in which global peak exists. Knee point region is estimated by changing the current reference and observing the voltage at two iterations. These regions are determined by using (7).

$$\frac{V_{pr} - V_{cr}}{V_{pr}} > \Delta V_{crit} \tag{7}$$

where V_{pr} and V_{cr} are PV voltages at two consecutive iterations and

$$\Delta V_{crit} = \frac{V_{oc} - V_{mpp}}{V_{oc}} \tag{8}$$

Consider a I-V curve as shown in Fig. 6. In the iteration from I_1 to I_2 (7) is satisfied and the knee point region is detected. Power at this point is compared with P_{gmpp} and Peak current I_{gmpp} and peak power P_{gmpp} are updated. Similarly one more knee point region is detected at the iteration from I_3 to I_4 as shown in Fig 6.

Fig. 7 shows the flowchart for the proposed algorithm. When shading has occurred it detects the change in power and starts tracking the global peak. It first calculates I_{min} and V_{min} using MPT concept in P-I curve and P-V curve and then starts checking for the knee point regions towards right side of the P-I curve by increasing the current reference in steps of I_{gstep}. Once knee point region is detected V_{min}, peak current (I_{gmpp}) and peak power (P_{gmpp}) are updated. In the next iteration skipping mechanism is initiated and I_{skip} is calculated using (6). If I_{skip} is less than I_{max}, algorithm again starts tracking for knee points. This tracking process is continuous until I_{max} or V_{min} is reached. Once I_{max} or V_{min} is reached the algorithm operates at I_{gmpp} and Perturb and Observe method is called in the global peak region to track the exact global point.

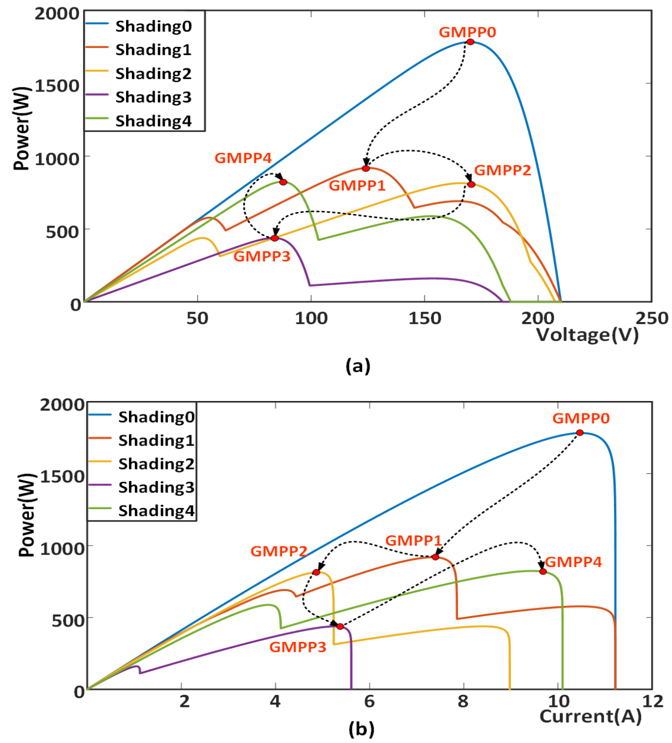

Fig. 8. (a) P-V curves and (b) P-I curves of different shading patterns for simulation analysis

IV. Performance Evaluation and Discussion

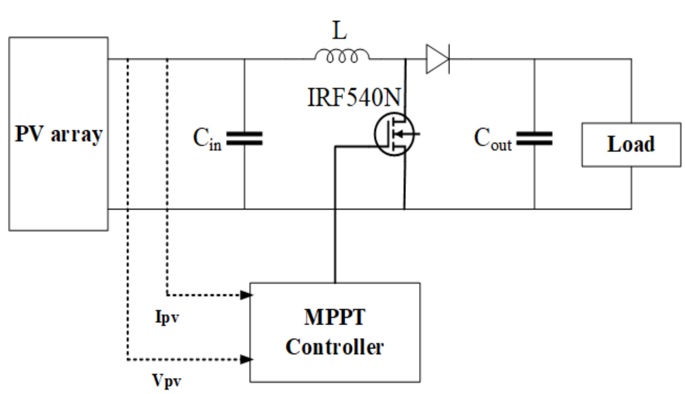

Fig. 9. PV array connected to boost converter.

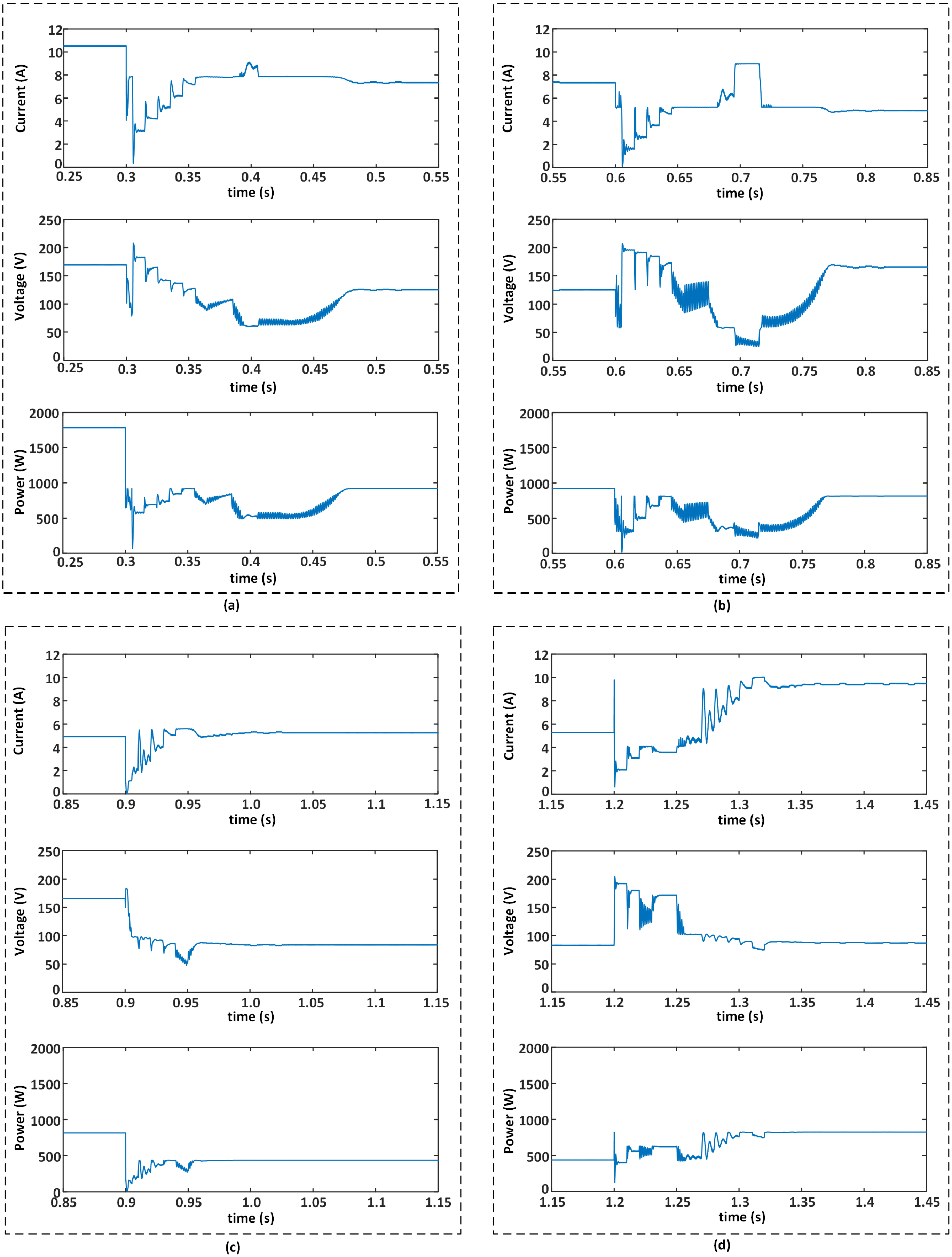

Fig. 10. Simulated waveforms of Current, Voltage and Power for different shading patterns in Fig 8 (a) First transition from shading-0 to shading-1 (b) Second transition from shading-1 to shading-2 (c) third transition from shading-2 to shading-3 (d) Fourth transition from shading-3 to shading-4

TABLE I
PV MODULE PARAMETERS

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

TABLE II
BOOST CONVERTER PARAMETERS

Parameter	L	C_{in}	C_{out}	R	Switching frequency (F_s)
Value	1 mH	$2000\mu F$	$2000\mu F$	200Ω	$50kHz$

The performance of the proposed algorithm is evaluated using a boost converter circuit in MATLAB Simulink as shown in Fig. 9. The parameters of the PV module and boost converter are given in Table I and Table II. Initially all the panels are having uniform irradiation which is taken as reference. Four different shadings (Fig. 8) are applied at all the possible changes in GMPP at an interval of 0.3 sec.

Initially, the PV system is under uniform shading condition. At t = 0.3 sec shading-0 has occurred. First, it calculates V_{min} and I_{min} using MPT concept. I_{min} eliminates some region of the P-I curve. Then, the operating point moves towards right side of the curve and starts checking for the knee point regions. A knee point region is detected around I_{pv} = 7 A. At this knee point I_{min}, I_{gmpp} and P_{gmpp} are updated. Then current skipping mechanism starts in the next iteration and I_{skip} is calculated using (6). As I_{skip} is more than I_{max}, the algorithm stops checking for knee points and sets the reference to I_{gmpp}. The tracking time for the first transition is observed as 0.11 sec. Once the knee point region is detected exact global peak is tracked using P&O method.

At t = 0.6 sec, second transition occurred, i.e, from shading-1 to shading-2. The algorithm first calculates V_{min} and I_{min} using MPT concept. I_{min} eliminates some region of the P-I curve. Then the operating point moves towards right and starts checking for the knee point regions. Once a knee point is reached the current skipping mechanism is initiated and I_{skip} is calculated using (6). As I_{skip} is less than I_{max} and the process has to repeat until I_{ref} reaches I_{max}. But, the PV voltage is less than V_{min} at this point. Hence, the algorithm stops and sets the reference to I_{gmpp}. In this way V_{min} helps to stop the algorithm before reaching I_{max}. The tracking time for second transition is observed as 0.12 sec. Once the knee point region is detected the exact global peak is tracked using P&O method.

At t = 0.9 sec third transition occurred i.e. from shading 2 to shading 3. The algorithm starts and at t = 0.95 sec PV voltage become less than V_{min}. Here it is clearly observed that the algorithm did not check the entire P-I curve but global peak is detected in less time. The tracking time for third transition is observed as 0.5 sec. At t = 1.2 sec, fourth transition occurred i.e, from shading-3 to shading-4. The tracking time for fourth transition is observed as 0.12 sec. Once the knee point region is detected exact global peak is tracked using P&O method.

V. CONCLUSION

A novel GMPPT algorithm is proposed in this paper to track global peak under non uniform irradiation. The proposed algorithm tracks the global peak of a PV system under partial shading conditions. It takes PV current as a reference and tracks the global peak using I-V curve and P-I curve. The search region in the P-I curve is reduced during the shading and hence the operating time is less. MPT concept is used to find I_{min} and V_{min} which discards the region in the P-I curve that does not contain a global peak. Knee point regions are estimated by detecting the change in voltage in the I-V curve. The global peak will lie in one of these regions. This method uses the novel current skipping scheme to skip the region in the P-I curve. Use of MPT concept and the novel current skipping scheme reduces the tracking time. The proposed algorithm tracks the global peak in less time and it is validated through simulation results.

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