JPE 19-6-22

https://doi.org/10.6113/JPE.2019.19.6.1566
ISSN(Print): 1598-2092 / ISSN(Online): 2093-4718

Adaptive Partial Shading Determinant Algorithm for Solar Array Systems

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Abstract

Maximum power point tracking (MPPT) under the partial shading condition is a challenging research topic for photovoltaic systems. Shaded photo-voltaic module result in complex peak patterns on the power versus voltage curve which can misguide classical MPPT algorithms. Thus, various kinds of global MPPT algorithms have been studied. These have typically consisted of partial shading detection, global peak search and MPPT. The conventional partial shading detection algorithm aims to detect all of the occurrences of partial shading. This results in excessive execution of global peak searches and discontinuous operation of the MPPT. This in turn, reduces the achievable power for the PV module. Based on a theoretical investigation of power verse voltage curve patterns under various partial shading conditions, it is realized that not all the occurrences of partial shadings require a global peak search. Thus, an intelligent partial shading detection algorithm that provides exact identification of global peak search necessity is essential for the efficient utilization of solar energy resources. This paper presents a new partial shading determinant algorithm utilizing adaptive threshold levels. Conventional methods tend to be too sensitive to sharp shading patterns but insensitive to smooth patterns. However, the proposed algorithm always shows superb performance, regardless of the partial shading patterns.

Key words: Global maximum power point, Maximum power point tracking, Partial shading condition, Photovoltaic system

I. INTRODUCTION

Photovoltaic (PV) generation is going to continue gaining importance due to its free energy with zero environmental pollution. In order to maximize the efficiency of PV array utilization, maximum power point tracking (MPPT) algorithms are used. They help locate the operating point on the power peak in the characteristic curve. However, in real environments, insolation shadows on PV arrays are unavoidable, and the partial shading of PV arrays can lead to considerable energy loss in a PV system [1]. This occurs because multiple local peaks can occur on the P-V curve (power vs. voltage curve), and the obtainable output power cannot be maximized without relocating the operating point. In this case, the global MPPT algorithm is required to select the highest peak among various local peaks, and give the new operating point to the MPPT algorithm.

Manuscript received Jul. 28, 2019; accepted Aug. 20, 2019
Recommended for publication by Associate Editor Kyo-Beum Lee.
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Global MPPT consists of partial shading detection (PSD), global peak search (GPS), and an MPPT algorithm as shown in Fig. 1. While a great deal of research has been focused on GPS and MPPT algorithms, only a few studies have been conducted on PSD algorithms [2]-[9]. In [2], an accurate GPS algorithm was proposed by determining the real time V_{OC} using two operating points. However, an inefficient dP/P criterion is used as the PSD. A suboptimal operating point condition mitigating technique was proposed in [3]. ΔP along with a timer interrupt is used for the PSD criteria. However, it takes as much as 4s for the GPS. A power-increment based GMPPT algorithm was proposed in [4]. A critical power threshold was defined and compared with ΔP to detect the partial shading condition. An interesting idea that can successfully identify the global shading condition and skip the GPS was proposed in [5]. In a change of the global shading condition, ΔV is very small. Thus the PSD criterion is upgraded as $\Delta P/(\Delta V \cdot P)$. A PV array configuration-independent GMPP was introduced in [6]. In this scheme, only a timer interrupt was used to trigger the GPS. An artificial neural network (ANN)-based GMPP algorithm was proposed in [7]. This algorithm uses two kind of systems: with and without an irradiation sensor. In both cases, while the

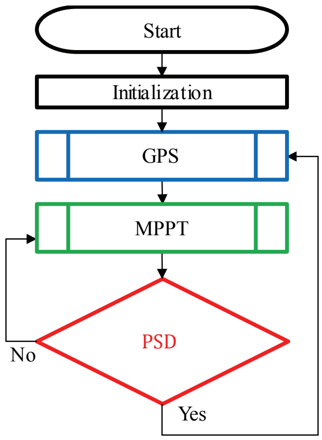


Fig. 1. Simple flow chat of a GMPPT.

experiment results are similar, the ΔP criterion is used for the PSD. The authors of [8] used a voltage comparison technique for the PSD. They assumed that MPP occurs in the vicinity of $0.8V_{OC}$, and the summation of the local V_{mpp} and $0.8V_{OC}$ is used as a PSD criterion. The authors of [9] used a similar strategy with an irradiation sensor for the GPS. However, the PSD is implemented by a timer and a voltage comparison.

However, all of the above conventional PSD methods aim to detect every partial shading occurrence or periodic GPS. This sometimes leads to a reduction in system efficiency, since detections that are too frequent wastes time on a sequence of GPSs that consumes a few seconds per routing and generates a considerable ripple in the PV string current. This in turn, hinders the optimal operation of the PV system. Therefore, it is clear that PSD algorithms play a crucial role and determine the performance of the global MPPT. This is due to the fact that it takes time for the GPS to re-establish the search region for the MPPT in the case of partial shading, whose occurrence should be determined by the PSD algorithm.

In this paper, by analyzing P-V curves under partial shading, it is recognized that a specific region in the P-V curve does not require GPS to achieve the global maximum power point (GMPP). Hence, this study aims to investigate an effective PSD to avoid unnecessary GPSs and to further improve the system performance. The basic idea of the proposed algorithm is briefly introduced in [10], and the complete algorithm with experimental results are further articulated in this paper.

II. Principle of Operation

A. Operating Region Characteristic of a Photovoltaic Module under Partial Shading

PV arrays are engaged with different kinds of shadings, as shown in Fig. 2. The global shading in Fig. 2(a) can occur due to changes in mist, cloudiness or daylight. If a part of a PV array is covered by different shadow levels, it is called partial shading, which is shown in Fig. 2(b). In real environments, a PSD algorithm should be able to distinguish between the two

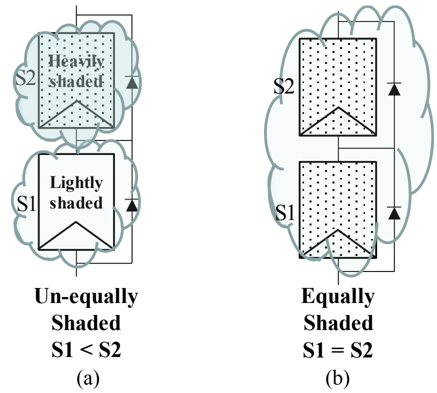


Fig. 2. Definition of shading. (a) Global shading condition. (b) Partial shading condition.

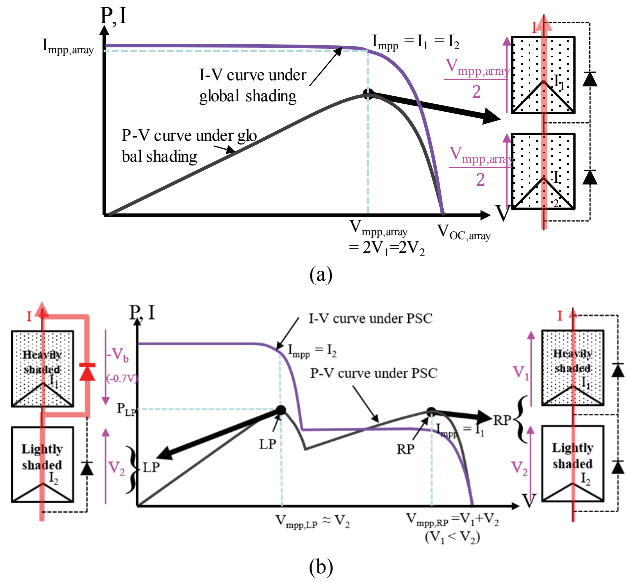


Fig. 3. P-V and I-V curves in two identical panels (NS = 2) under different shadings. (a) Global shading condition. (b) Partial shading condition.

different shading conditions.

Fig. 3 shows the P-V and I-V curves of a PV array with two identical modules connected in series. When global shading occurs, the array output is reduced without activating the bypass diodes, as shown in Fig. 3(a), and the operating point is successfully determined by MPPT. However, in partial shading, the behaviors of the characteristic curves change differently, as shown in Fig. 3(b), where two peaks appear on the P-V curve: a left-side peak (LP) and a right-side peak (RP). The MPPT may not identify the other peak on the P-V curve and may continuously stick to the current peak. Thus, a PSD algorithm is used to trigger the GPS algorithm.

The current flowing through the PV module is determined by the selection of an operating peak. When the RP is selected by the GPS, both modules contribute to the array power delivery. Although the array current is small and limited by the heavily shaded module, the array voltage is determined by the sum of the two PV module voltages. On the other hand, if the

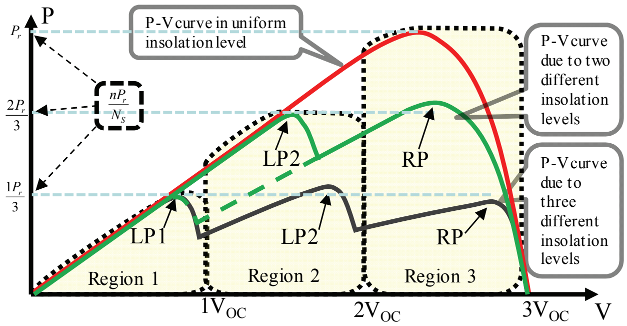


Fig. 4. Three identical PV modules under different shading conditions.

LP is selected, the heavily-shaded module is bypassed through the diode, and the array current and voltage are determined solely by the lightly-shaded module. Hence, the power is delivered solely by the lightly-shaded module. Therefore, the higher peak among those two peaks should be selected by the GPS. According to the above-described behavior of the characteristic curve, it is clear that the height of the RP (power of the RP) is mainly affected by the most heavily-shaded module [2]. Meanwhile, the height of the LP (power of the LP) is always determined by the most lightly-shaded module. Note that the temperature effect due to changes in shading is assumed to be negligible.

This concept can be extended to series connected arrays with different numbers of modules. For example, the three-module array (N_S=3) is explained in Fig. 4. When the module behavior in the global shading condition shows a single peak, there can be two or three peaks in partial shading, where the possible number of peaks is determined by the number of modules (bypass diodes) in the series connected PV array [11]. In order to classify the origins of the peaks, it is useful to divide the operating voltage region into NS parts, where the region "n" ($1 \le n \le N_S$) denotes the voltage band from $(n\text{-}1)V_{oc}$ to nV_{oc}. The "n" in this case is clearly defined in section 2.3. When the array is covered by two different insolation levels, two scenarios can be identified. One scenario contains two peaks: LP2 and RP, where LP2 is caused by two lightly-shaded modules and RP is caused by one heavily shaded module. In the next scenario, two peaks appear on LP1 and RP, where LP1 is caused by one lightly shaded module and RP is caused by two heavily shaded modules. If three insolation levels cover the array, three peaks appear: LP1, LP2 and RP. LP1 and LP2 appear due to the most lightly shaded module and the next-most lightly shaded module, respectively. Meanwhile, LPn reflects the left peak located in the nth region. The RP always occurs when the array current is dominated by the heavily shaded module.

According to above observations, the maximum power at LPn is closely related to the global shading level, as presented in (1).

$$P_{LPn} = \frac{nP_r}{N_S} \tag{1}$$

where N_S is the number of series-connected PV modules. In addition, P_r is the output power of the array if all of the modules are globally-shaded with the most lightly-shaded level. This is called the reference power in this paper. P_r is the key piece of information in the proposed algorithm, and it can be calculated using the maximum output power from the present solar insolation.

B. Conventional PSD Method

The conventional PSD detection algorithm, as shown in Fig. 5(a), monitors the rate of change in the receiving power between two consecutive power or voltage measurements [2]-[9]. Therefore, in a sudden change of insolation, dP/P can become considerably higher, and if it becomes greater than a certain threshold, which was 0.1 in the literature, the algorithm triggers a GPS. This method can fail to call a GPS in a smooth shading pattern, especially with a low insolation level. In addition, it can unnecessarily activate a GPS in a high insolation level. Due to the absolute test condition in |dP/P|, a GPS is called either in a power increment or a power decrement. However, there are three drawbacks in the conventional algorithm. First, when the system operates on the most left peak, the operating point is stuck there and it is not easy to return it back to another operating point, because the information about the power on the RP is no longer available. Second, in the case of a power increment on some other operating point (other than the most left peak), GPS calling is not necessary. However, it tries to trigger a GPS. Third, it is tested only by a sharp insolation changing patterns. However, real shading patterns are sometimes too smooth to be detected by the dP/P criterion. Thus, it is also necessary to consider smooth patterns.

C. Proposed Method

According to the above observations, since triggering a GPS should be determined by both the power level change and the operating region characteristic, it is possible to optimize the GPS execution. Fig. 5(b) shows an algorithm flow chart of the proposed method. For initialization, the GPS subroutine is called, and number of local peaks is identified. Accordingly, a region number (n) is issued for each peak by comparing the voltages between the open circuit voltages V_{oc}, and the measured operating voltages of the PV module, $V_{received}$ as in (2).

$$(n-1)V_{OC} < V_{received} < nV_{OC} \tag{2}$$

If the maximum peak is on LP, it is necessary to regularly check the other peaks, and periodic calling of a GPS is implemented with a timer T_{count}, with a set time, T_{set}. If the operating point is on the RP, there are two possible scenarios. If the number of peaks is more than one, P_r needs to be updated by the left-most peak level. Thus, P_r is re-calculated with the left-most P_{LPn} by (3).

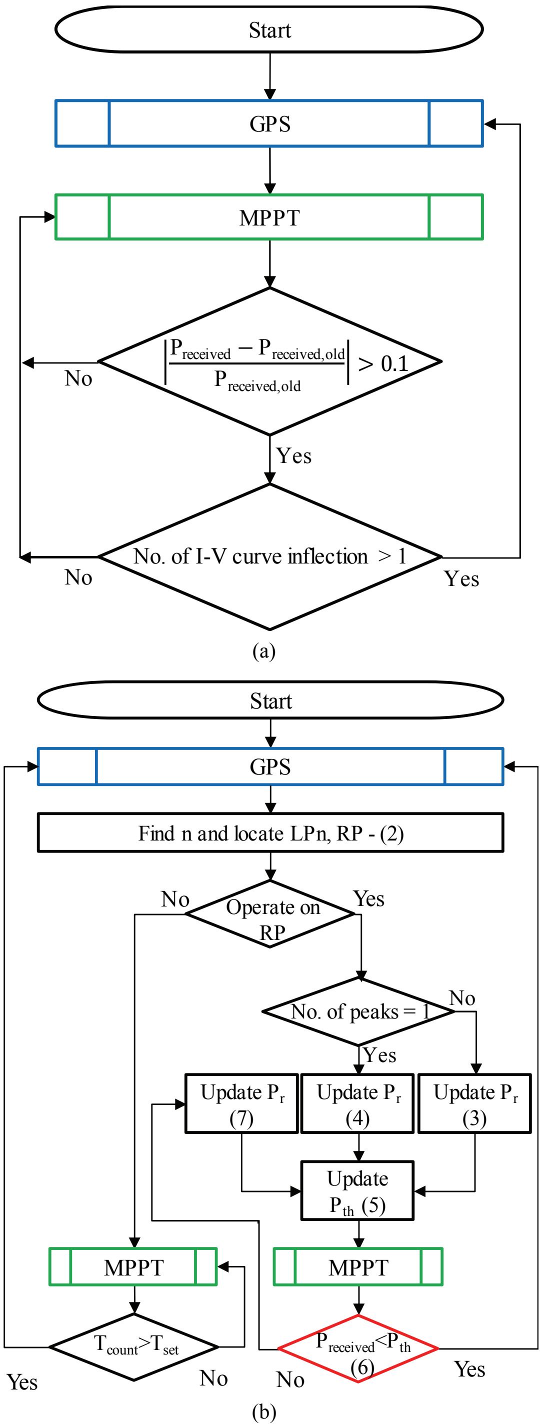


Fig. 5. Flowcharts of PSD algorithms. (a) Conventional dP/P-based algorithm in [2]. (b) Proposed region-based algorithm.

$$P_r \leftarrow \frac{N_S}{n} P_{LPn} \quad (3)$$

If the PV curve has a single peak, the reflects that the system is in global shading and the measured power can be regarded as the global power level. Thus, P_r is updated using (4).

$$P_r \leftarrow P_{received} \quad (4)$$

In the next step, the threshold power level (P_{th}) is calculated in order to monitor the left-most peak according to the power level using (5). Note that $P_{LP(Ns)} = P_r$.

$$\begin{cases} P_{th} \leftarrow P_{LP(N_S-m)}, if \_ P_{LP(N_S-m)} < P_{received} \le P_{LP(N_S-m+1)} \\ P_{th} \leftarrow P_{LP1}, if \_ 0 < P_{received} \le P_{LP1} \end{cases} \quad (5)$$

where m = 1, 2,…, (N_S-1). After the local MPPT is run, the GPS triggering criterion determines the activation of the GPS routine. If $P_{received}$ is larger than P_{th}, GPS calling is unnecessary, since the powers of the other peaks are always lower than $P_{received}$. Thus, GPS triggering criterion is given by (6).

$$P_{received} < P_{th} \quad (6)$$

If this condition is met, a GPS is called. Otherwise, P_r is updated to catch up with the increment in P_r by (7). In addition, P_{th} is updated again by (5).

$$P_r \leftarrow max\left(P_r, P_{received}\right) \quad (7)$$

Subsequently, a local MPPT is repeated and the GPS criterion is tested again.

III. Algorithm Implementation

The conventional dP/P algorithm in [2] and the proposed algorithm are comparatively implemented as partial shading determinant methods in PSIM software, as shown in Fig. 6. A perturb and observation (P&O) algorithm with a duty variation of ΔD=0.007 is used as a master local MPPT algorithm and programmed into the DLL block. The GPS algorithm in [12] is adopted to complete the GMPPT algorithm in the simulation. In the schematic of Fig. 6, two SCM 60 modules are serially connected as an array, and a boost converter is used for the MPPT. The voltage probes, P1 and P2, monitor the maximum obtainable power from each module, and the output power is calculated by the product of the PV array voltage and the current. Then it is assigned to $P_{received}$.

In order to test the GMPPT response to partial shading patterns, P1 is supplied by time-varying shading patterns and P2 is kept to a constant insolation pattern of 1000W/m^2. Sawtooth and sinusoidal patterns are used to simulate varying insolation. The insolation is varied smoothly between 1000W/m^2 and 200 W/m^2 in Test 1, as shown in Fig. 7(a), while it is varied sharply from 1000W/m^2 to 500 W/m^2 in Test 2, as shown in Fig. 8(a).

The patterns of a local MPPT are shown in Fig. 7(b) and Fig. 8(b), where this behavior is generated by the local MPPT algorithm without a GMPPT function. Now, GMPPT is enabled with the conventional PSD algorithm under smooth and sharp insolation changes, and the results are shown in Fig. 7(c) and Fig. 8(c), respectively. The behaviors of the proposed PSC detection algorithms are shown in Fig. 7(d)

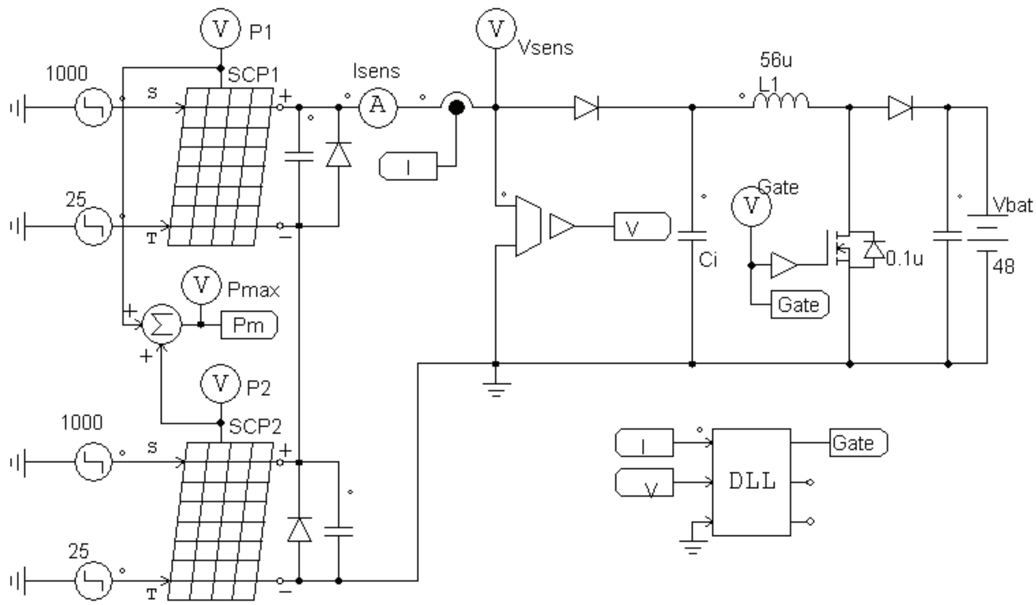


Fig. 6. PSIM simulation schematic.

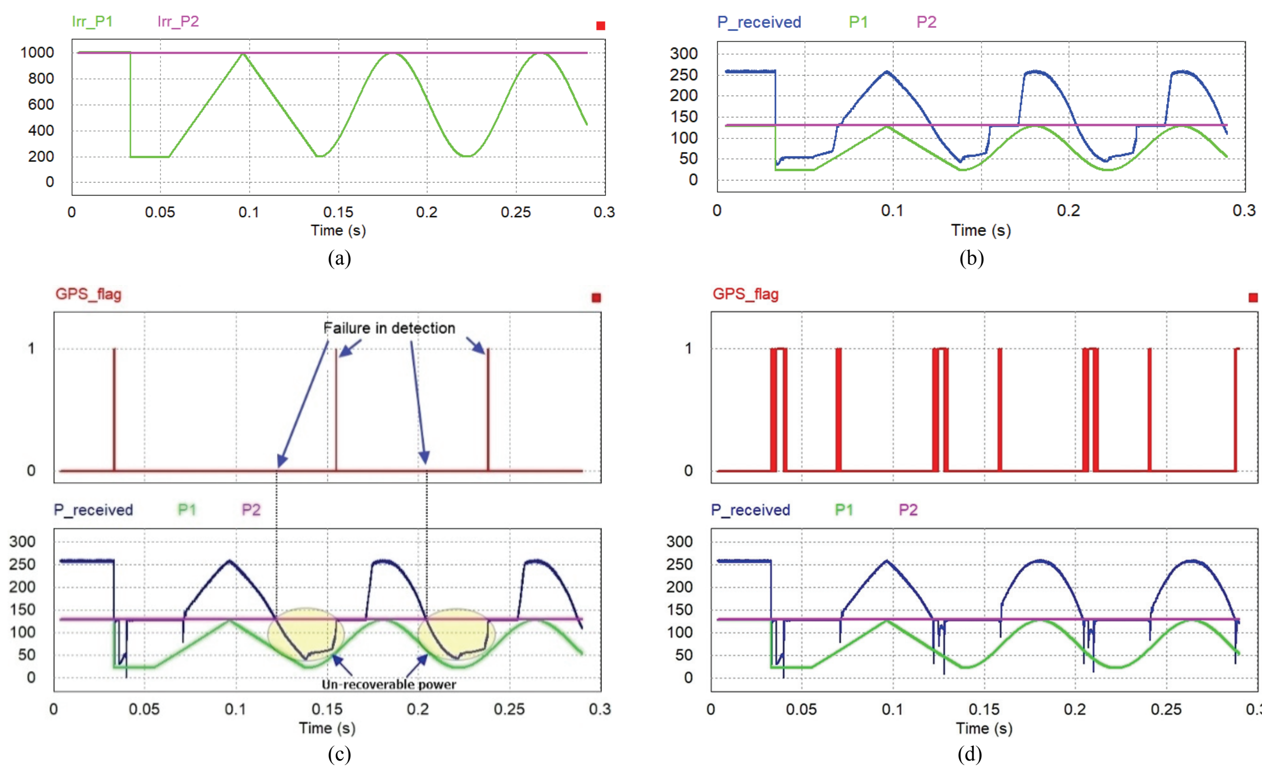


Fig. 7. Test 1 (smooth insolation change). (a) Insolation patterns. (b) MPPT without PSD. (c) GMPPT with a conventional PSD. (d) GMPPT with the proposed algorithm.

and Fig. 8(d). Here, the logical high level, namely "1", indicates an event of GPS calling. The highlighted area shows the solar power wasted by inadequate GPS triggering, which clarifies that the dP/P-based algorithm makes a mistake in smooth or sharp patterns. Meanwhile, the proposed method can make a correct decision in both cases. The key observations of the simulation are summarized in Table I.

IV. Experiment Results

An experimental setup consisting of a PV simulator, a boost converter and an electric load is shown in Fig. 9. The TerraSAS PV simulator is configured for two identical monocrystalline Solar Center SCM60 modules, and the solar module specifications and the boost converter circuit

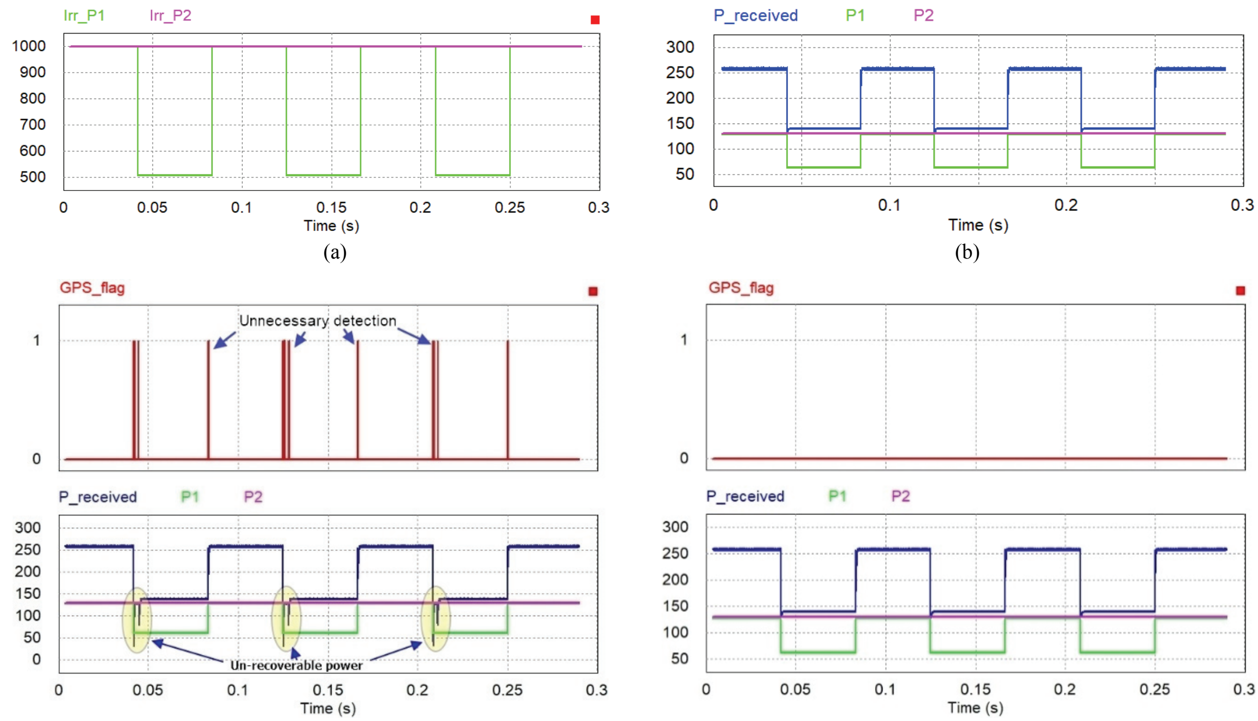


Fig. 8. Test 2 (sharp insolation change). (a) Insolation patterns. (b) MPPT without PSD. (c) GMPPT with a conventional PSD. (d) GMPPT with the proposed algorithm.

TABLE I
KEY SIMULATION OBSERVATIONS

Sensed power (W)		Detection criterion		PSD flag		Comments	
$P_{received,old}$	$P_{received}$	dp/p	P_{th}	Conventional	Proposed	Conventional	Proposed
255	225	0.12	127.5	1	0	Un-necessary detection	Appropriate detection
130	120	0.08	127.5	0	1	Failure in detection	Appropriate detection

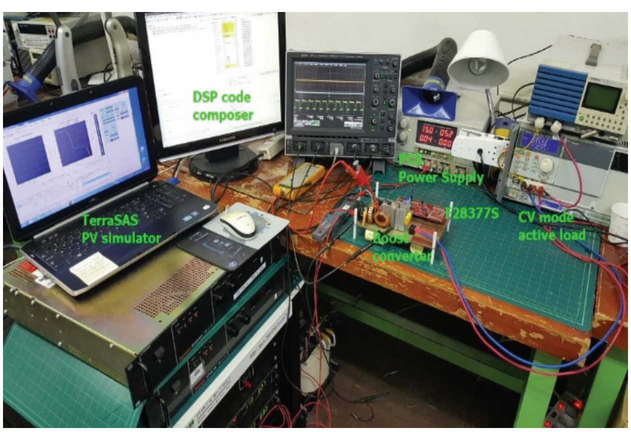


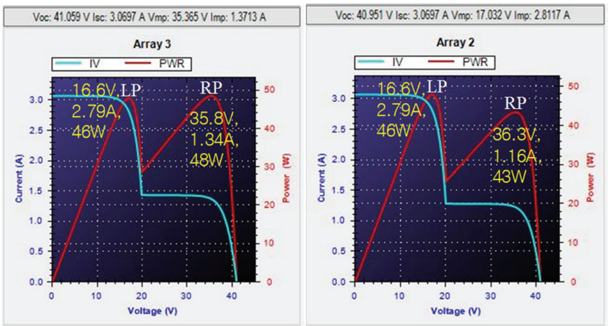
Fig. 9. Experimental setup.

TABLE II
CIRCUIT PARAMETERS

Category	Parameter	Value	Item	Value
PV panel SCM 60	P_{max}	60W	DSP	TMS320 F28377S
	V_{mpp}	19.0V		
	I_{mpp}	3.16A	Electric load	Prodigit 3314F
	V_{oc}	23.0V		
	I_{sc}	3.30A		
Power circuit	C_i	22uF	C_o	22uF
	L	56uH	V,I sensing	LT1366
	V_o	48V	Diode	FYPF2010DN
	f_{sw}	100kHz	MOSFET	11NM60

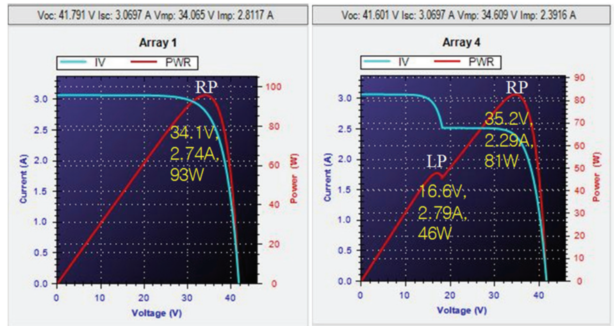
parameters are listed in Table II. Due to the performance limitations of the solar array simulator, below a slew rate of less than $100Wm^{-2}\cdot s^{-1}$ is considered to be a smooth change of insolation patterns.

The proposed algorithm is operated under smooth partial shading patterns, as shown in Fig. 10. At first, the two insolation levels are kept at $800W/m^2$ and $360W/m^2$ as shown in Fig. 10(a). In addition, the GMPP is located on RP (35.8V, 1.34A). When the insolation level, S2, is dropped to $320W/m^2$, as shown in Fig. 10(b), the GMPP is changed into



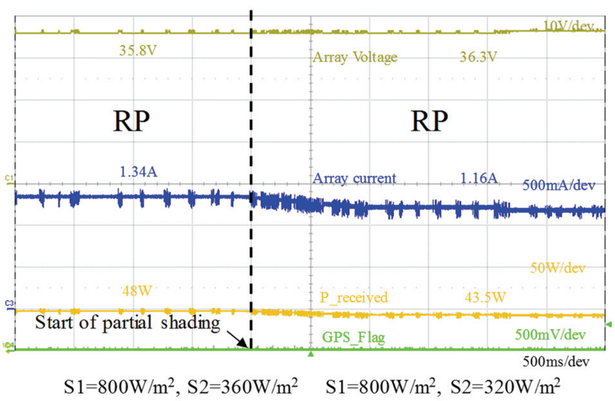
(a) (b)

Fig. 10. P-V and I-V curves. (a) S1=800W/m². S2=360W/m². (b) S1=800W/m², S2=320W/m².

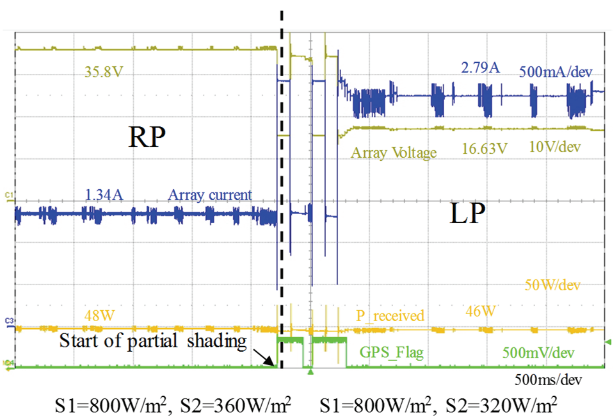


(a) (b)

Fig. 12. P-V and I-V curves. (a) S1=800W/m², S2=800W/m². (b) S1=800W/m², S2=650W/m².

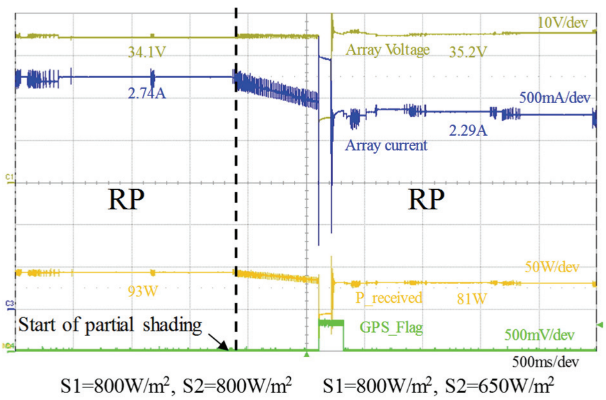


(a)

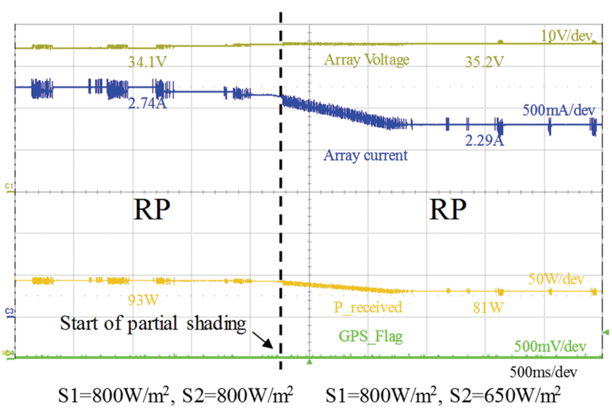


(b)

Fig. 11. Voltage and current waveforms of a PV array under a smooth insolation change. (a) Conventional method. (b) Proposed method.



(a)



(b)

Fig. 13. Voltage and current waveforms of a PV array under a sharp insolation change. (a) Conventional method. (b) Proposed method.

the LP (16.6V, 2.79A). Due to a small power change ($dP/P < 0.1$), the conventional method fails to detect the partial shading as shown in Fig. 11(a). On the other hand, a GPS is triggered in the proposed method and the operating point on the GMPP is relocated to the LP, which shows the new maximum power, as shown in Fig. 11(b).

In the case of a sharp insolation change, the two insolation levels are kept equal at 800W/m² as shown in Fig. 12(a). Then the insolation level, S2, is dropped to 650W/m² as shown in Fig. 12 (b). Because, P_{LP} is lower than P_{RP}, the conventional PSD criterion detects this power difference ($dP/P > 0.1$) and triggers a GPS. However, it returns back to the current peak (RP) as shown in Fig. 13(a). On the other hand, the proposed method is intelligent enough to not trigger a GPS and continue operating on the RP as shown in Fig. 13(b). All of the experimental results are summarized in Table III. By eliminating unnecessary GPS callings, the proposed method eliminates glitches in the voltage and current waveforms, which increases the amount of obtainable power from solar panels.

TABLE III
SUMMARY OF THE TESTS

Test	Insolation change on S2	Method	Measurement	Before transition	After transition	Detection criterion (dP/P or P_{th})	PSD flag	Comments
Smooth insolation change	360W/m^2 → 320W/m^2	Conventional	P	48W	43.5W	dP/P = 0.08	0	Failure in detection
			V	35.8V	36.3V			
			I	1.34A	1.16A			
		Proposed	P	48W	46W	P_{th} = 47W	1	Successful detection
			V	35.8V	16.6V			
			I	1.34A	2.79A			
Sharp insolation change	800W/m^2 → 650W/m^2	Conventional	P	93W	81W	dP/P = 0.13	1	Un-necessary detection
			V	34.1V	35.3V			
			I	2.74A	2.29A			
		Proposed	P	93W	81W	P_{th} = 47W	0	Successful decision
			V	34.1V	35.2V			
			I	2.74A	2.29A			

V. CONCLUSIONS

In this paper, a new partial shading determinant (PSD) algorithm is proposed. Conventional PSD algorithms focus on detecting all partial shading occurrences and triggering GPSs. According to an analysis of the P-V curve, an area that does not require a GPS to trigger the GMPP is identified and an adaptive threshold level is proposed. By utilizing this concept, energy waste due to unnecessary GPSs can be reduced. The proposed algorithm exploits the PV power level adaptively to determine proper GPS triggering. In addition, it clearly distinguishes between partial shading and global shading. Thus, it provides for efficient utilization of solar modules. The operation of the proposed algorithm is simulated and tested using two series PV modules under complex partial shading patterns.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2017R1A2B4005488).

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