"Improved MPPT Methods for PV Array Under Patrially Shaded Condition"

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***Abstract*—** Under partially shaded conditions PV string exhibits complex output characteristics, i.e., the current-voltage curve (I-V) shows multiple current stairs whereas power –voltage (P-V) curves presents multiple voltage peaks. Therefore the use of conventional maximum power point tracking is not beneficial in the case of tracking accuracy or on tracking speed. This paper introduces two global MPPT methods one is search-skip-judge global MPPT(SSJ-GMMPT) and another is rapid global MPPT (R-GMPPT) methods. These two methods proposed helps to reduce searching voltage range based on study of I-V and P-V characteristics of P-V string. The real maximum power under any shading condition can be tracked by SSJ-GMPPT and therefore high accuracy and rapid tracking speed can be achieved without any additional circuits and sensors. The tracking speed of long string having huge PV modules can be improved by R-GMPPT methods which degrades more than 90% of tracking time that is required by conventional global searching method. Comparing these two propose method with other methods highlights that these proposed methods are good and powerful.

Keywords- *Terms*—Photovoltaic generation system, maximum power point tracking (MPPT), partially shaded conditions.

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I. INTRODUCTION

In typical photovoltaic (PV) installations, PV arrays are formed by connecting multiple PV modules in various configurations (i.e., series, parallel, series–parallel, etc.) A bypass or bypass switch is connected in parallel with each PV module to protect the solar cells against efficiency degradation and hot-spot failure effects. Under uniform solar irradiation conditions among the individual PV modules, the power–voltage (*P–V*) characteristic of the PV array exhibits a unique operating point where the PV generated power is maximized (maximum power point, MPP). Many MPP tracking (MPPT) methods have been developed in the past in order to operate the PV array at the MPP point , enabling the maximization of the PV energy production under the continuously changing solar irradiation and ambient temperature conditions. However, in the case in which one or more of the PV modules comprising the PV array are shaded (e.g., due to dust, shading from surrounding buildings, trees or poles, nonuniform solar irradiation incidence on contoured flexible PV arrays in portable and building integrated PV applications, etc.), then the *P–V* characteristic of the PV array exhibits multiple local maxima and only one of them corresponds to the global MPP. Examples of the *P–V* characteristics of a PV array operating under uniform and nonuniform solar irradiation conditions are depicted in Fig. 1. The PV array output power at the global MPP is lower than the sum of the maximum available power levels that the individual PV modules are able to provide As analyzed in under practical operating conditions, the location and magnitude of the local and global MPPs depend on the stochastically varying shading pattern area and geometry, as well as the configuration of the PV modules within the PV array. The connection of PV cells and modules in parallel, which is proposed in order to avoid the effect of partial shading, is applicable only in low-power PV systems (e.g., for portable applications). Using the distributed MPPT (DMPPT) technique, a dc/dc power converter with MPPT controller is incorporated at each PV module of the PV array thus increasing the total available MPP power of the PV array. However, the entire

PV array is usually connected to a central power electronic converter in order to reduce the PV system cost and implementation complexity.

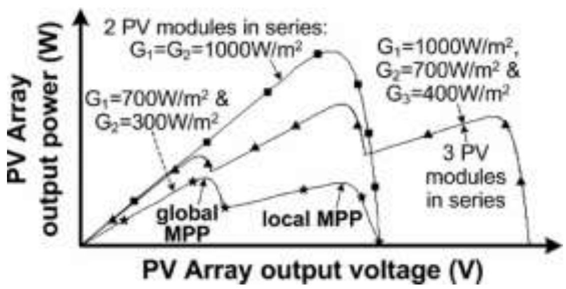


Fig 1. Examples of the *P–V* characteristics of a PV array composed of identical series-connected PV modules with bypass diodes for different irradiations.

It is preferable to operate PV string at the maximum power point (MPP) to sufficiently extract PV energy. The conventional well-known MPP tracking (MPPT) methods include perturbation and observation (P&O) and incremental conductance (IncCond). Since the power-voltage (*P-V*) curve of PV string has one MPP under uniform irradiance, these conventional methods can track the MPP accurately. With non-uniform irradiance, resulted by trees, buildings and clouds shadow nearby, the *P-V* curve of a PV string exhibits multiple peak-power points (PPPs), in which one is the global MPP (GMPP) and the other are the local MPPs (LMPPs), and the conventional methods hardly differentiate between GMPP and LMPP, therefore reducing the overall efficiency of PV string. A survey reported that the operation of 41% installed PV systems had been affected by shadow, with energy losses of 10%. The searching process within full voltage range can guarantee the tracking accuracy of GMPP, however, the tracking process is time-consuming. So, it is necessary to develop the MPPT method with ability to fast track the GMPP under partially shaded conditions (PSC).

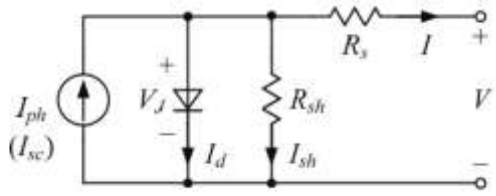
To date, abundant literatures have been published to address the MPPT issue under PSC which are based on hardware and software solutions, respectively. The hardware methods include circuit compensation and reconfiguration. The circuit compensation method uses additional circuit to eliminate the multiple peaks, so the P-V curve exhibits only one peak even under PSC, thus the conventional MPPT methods can be used .However, the additional circuit increases the system complexity and can not be adjusted flexibly corresponding to different PV configurations. The method of reconfiguration has been developed in ,which is using a matrix of power switches to recombine the individual PV modules in a PV array. The target of this reconfiguration is to form the PV modules comprised by the PV array operating under similar solar irradiance conditions. With this method, the complexity of the system configuration and cost are significantly increased .However, the modified incremental conductance is time-consumed for application of PV long string because the method searches all the vicinity of PPPs. Recently a GMPP tracking method, which restricts the voltage window (VW) search range and tracks the GMPP in all shading conditions, is proposed . By means of restricting the voltage window search range the tracking speed is improved. It is a pity for VW method that the characteristic of PV string is not considered and therefore its tracking speed is not fast enough yet. As previously mentioned, the MPPT methods under PSC have more or less disadvantages in terms of tracking accuracy, tracking speed and implementing complexity . The critical issue for PV string MPPT scheme is reducing the searching voltage range by skipping the unnecessary voltage intervals according to the unique P-V characteristic. The improvement of tracking speed mainly depends on the degree of reducing voltage searching range.

This paper proposes two global MPPT under PSC based on the P-V and I-V curve of PV string. The first method can track the real GMPP in any shading pattern with approving tracking speed, and the implementation is simple because it does not require the knowledge of output electrical characteristic of PV string and any additional voltage and current sensors. The second method is designed with very fast tracking speed to apply on long PV string. In these two methods, the searching voltage range is significantly reduced and tracking accuracy is approving as well. The two methods are realized with the specifically improved changes based on the conventional IncCond method. After the vicinity of the GMPP is obtained the conventional IncCond method is used to find real GMPP without oscillation at steady state. This paper is organized as follows. In Section II, the output electrical characteristics (I-V curve and *P-V* curve) of the PV string is investigated, and two relations are achieved. One relation is that the PPP-current is approximately proportional to the short-circuit current (SC-current), *I*sc, and the other is that the PPP voltage is approximately proportional to the open-circuit voltage (OC-voltage), *V*oc. In Sections III, based on the first relation, a search-skip-judge global MPPT (SSJ-GMPPT) method is proposed. The algorithm operating process is analyzed with regard to different shading patterns. Based on the second relation, a rapid global MPPT (R-GMPPT) is proposed in Sections IV.

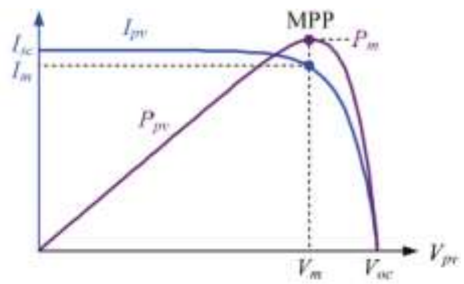
II.OUTPUT CHARACTERISTIC OF PV STRING

A. Output Characteristics of PV String under Uniform Irradiance

Fig. 2(a) shows the equivalent circuit of a PV module, and Fig. 2(b) shows the output characteristics including the *I-V* curve and *P-V* curve As is shown, the *P-V* curve exhibits only one PPP, the MPP. On the left side of the MPP the PV module outputs approximately constant current, while it outputs approximately constant voltage on the right side of the MPP. The current and voltage of MPP (I_m and V_m) can be approximately expressed as



(a)



(b)

Fig. 2. PV module: (a). Equivalent circuit. (b). P-V and I-V curves.

$$I_m \approx 0.9 I_{sc} \quad (1)$$

$$V_m \approx 0.76 V_{oc} \quad (2)$$

Multiple PV modules can be connected in series to constitute one PV string. Under uniform irradiance (UI), these PV modules have the same output characteristics, thus, the output characteristic of PV string is simply obtained by those of PV modules. Likely, the current and voltage of MPP (I_{m_str} and V_{m_str}) can be expressed as:

$$I_{m\_str} \approx 0.9 I_{sc\_str} \quad (3)$$

$$V_{m\_str} \approx 0.76 V_{oc\_str} \quad (4)$$

where, I_{sc_str} is the SC-current and V_{oc_str} is the OC-voltage of PV string.

B) *Output Curves of PV String with Two PV Modules Under PSC*

The PV string with two modules is shown in Fig. 3(a). It is assumed that PV_1 receives more irradiance than PV_2, so the SC-current and OC-voltage of PV_1 are larger than those of

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PV_2. Fig. 3(b) shows the output curves of the PV string. When the string current, i_{str}, is smaller than the SC-current of PV_2, I_{sc2}, both PV_1 and PV_2 generate energy and the string voltage is equal to the sum of voltages of PV_1 and PV_2. When i_{str} exceeds I_{sc2}, diode D_{p2} conducts, and thus, PV_2 is bypassed and does not generate energy. Then, the output of string is equal to that of PV_1.

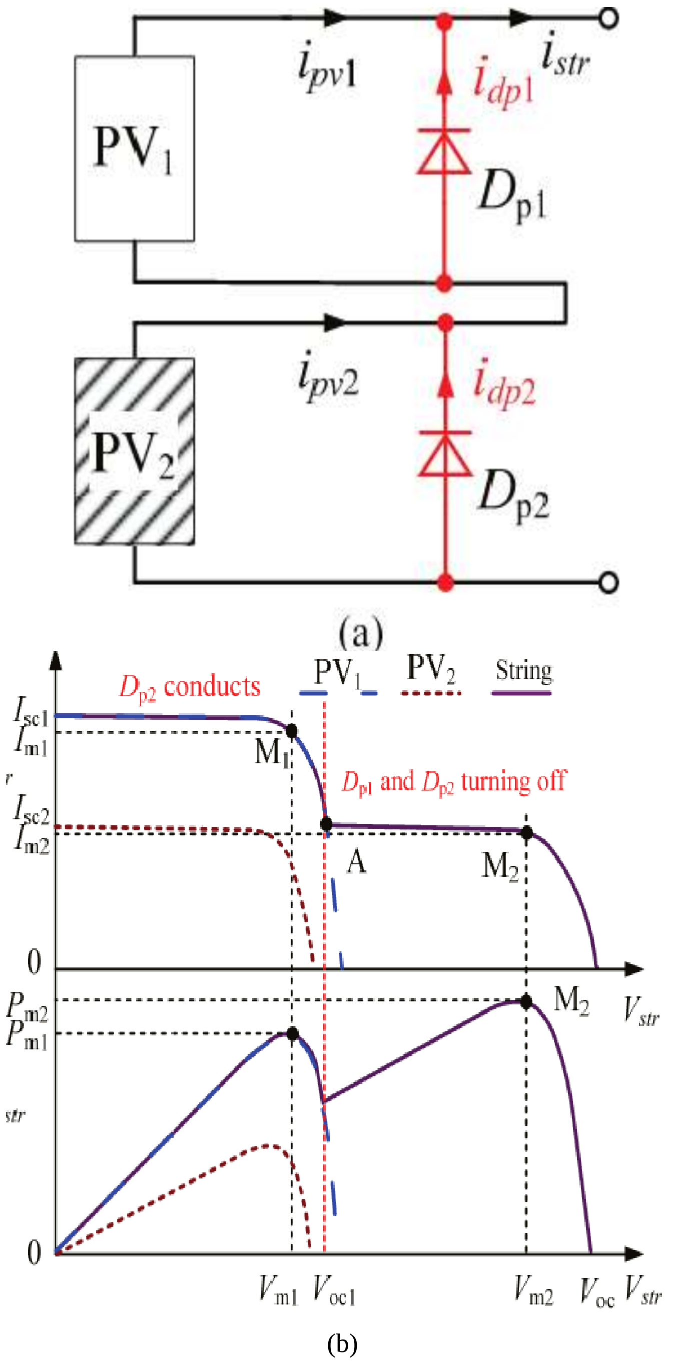

Fig. 3. Two PV modules in series under PSC. (a) Circuit configuration. (b) Output characteristic curves.

As seen in Fig. 3(b), the *I -V* curve of PV string presents two stairs and the *P- V* curve of PV string has two PPPs, i.e., M_1 and M_2. Point A is the dividing point. On the left of point A, only PV_1 works, and the PPP-current I_{m1} is approximately equal to 0.9· I_{sc1}, and the PPP-voltage V_{m1} is ap proximately equal to 0.76· V_{oc1}. On the right of point A, PV_1 and PV_2 work together. Because PV_1 generates approximately constant voltage and the turning point of *I-V* curve is mainly affected by PV_2, the PPP-current I_{m2} is approximately equal to 0.9· I_{sc2}, and the PPP-voltage V_{m2} is approximately equal to the sum of V_{oc1} and 0.76· V_{oc2}. The OC-voltage is proportional to the natural logarithm of illumination intensity so V_{oc1} is approximately equal to V_{oc2}, which is equal to half of the OC-voltage of PV string, V_{oc}. That is, V_{m1} = 0.76· $V_{oc}/2$, V_{m2} = (1+0.76)· $V_{oc}/2$. Similarly, for the *n* PV modules connected in series under PSC, the *I-V* curve has *n* stairs, and the P-V curve shows *n* divided intervals, and every interval has one PPP. Thus, the *P-V* curve has *n* PPPs. The PPP-current and PPP-voltage of *No.j* (j = 1, 2, …, n), I_{mj} and V_{mj}, are expressed as:

$$I_{mj} \approx 0.9 I_{scj} \tag{5}$$

$$V_{mj} \approx (j-1+0.76)V_{oc}/n = (j-0.24)V_{oc}/n \tag{6}$$

where I_{scj} and V_{ocj} are the SC-current and OC-voltage of PV module, respectively.

III. SEARCH-SKIP-JUDGE GLOBAL MPPT METHOD

For the conventional global MPPT method, it is necessary to scan the full voltage range from zero to the OC-voltage to obtain the GMPP. However, the searching voltage range should be reduced by utilized the characteristic of PV string under PSC. In this section reducing the searching voltage range is realized by skipping the vicinity of the LMPPs . This method is the search-skip-judge global MPPT (SSJ-GMPPT) method which fast tracks the real GMPP without additional circuit and voltage or current sensor (only one pair of voltage and current sensors required as the conventional methods).

In order to help understanding the operating principle of the SSJ-GMPPT method, a PV string with three modules is taken as an example to illustrate the whole operating process. The irradiance levels of three modules are intentionally given tobe different, and the P-V curve of string has three PPPs, M1, M2 and M3, as shown in Fig. 4. Fig. 4(a), (b) and (c) show three shading patterns, in which M1, M2 and M3 is the GMPP, respectively.

Fig. 5 gives the block diagram of the SSJ-GMPPT, where *V*oc-mod is the OC-voltage of a single module and it is available in the typical parameters provided by the manufacturer. *P*m is the global maximum power recorded in tracking process and *V*m is the voltage corresponding to *P*m, Δ*V* is the incremental voltage in every perturbation, *n* is the number of module in series, and *I*sc*j* represents the SC-current of the *j*th module, which is exactly the current of section-dividing point (SDP) between current stairs in *I-V* curve . Generally, the number of SDPs and PPPs are both equal to *n*.

The initial operating voltage is set to 60% of *V*oc-mod to guarantee that the first PPP (M1 in Fig. 4) can be found. 90% OC-voltage of the string is set as the ending voltage (Vend) since no MPP will appear when the operating voltage is higher than 90% OC-voltage of the string under any solar irradiance . To begin the SSJ-GMPPT, initializing the operating voltage is necessary which is shown as Os in Fig. 4. Then, the SSJ-GMPPT operates the following three processes.

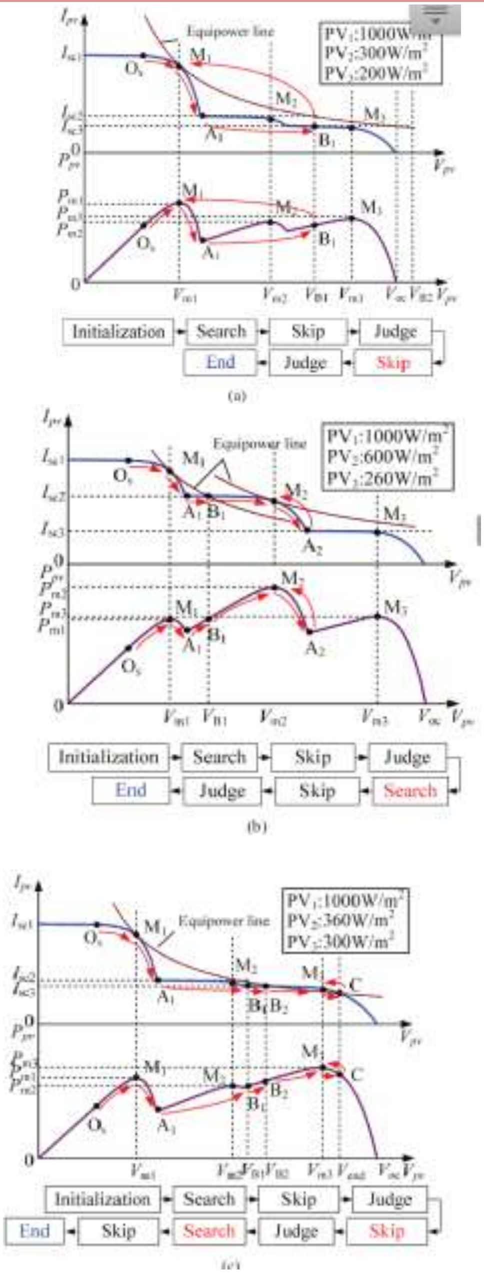

Fig. 4. Tracking process of SSJ-GMPPT method for string with three PV modules under PSC. (a) pattern 1, (b) pattern 2, (c) pattern 3.

Searching Process: With the IncCond method, the first local PPP is found (M_1 in Fig. 4). The power and voltage of the PPP is recorded as P_m and V_m. Then the operating voltage is disturbed in forward direction. When the sign of *dp*/*dv* changes from negative to positive, the corresponding section-dividing point (SDP) after PPP is found (A_1 in Fig. 4). The current of SDP, is the SC-current of (*j*+1)th PV module (I_{sc2} in Fig. 4).

Skipping Process: As shown in Fig. 4, according to the equipower line , the algorithm in this process skips from SDP and sets the quotient of *P*m/*I*sc(*j*+1) as the new operating voltage (B1 in Fig. 4) . The interval between A1 and B1 is unnecessary to scan. That is because, *P*m = *V*B1*I*sc2, the voltage and current between A1 and B1 is smaller than the voltage *V*B1 and current *I*sc2, respectively. As a result, the power of the points between A1 and B1 is less than *P*m. And then, the comparison between the new *Vref* and *Vend* is made. If *Vref* is higher than *Vend*, that means the GMPP has been found. Otherwise, the algorithm turns to next process. The skipping process utilizes the equipower line to skip the interval from A1 to B1, saves the tracking time.

Judging Process. The judging process utilizes the equation It is important to note that the factor of 0.85 instead of 0.9 in is used, because 0.9 is an approximate factor. To ensure

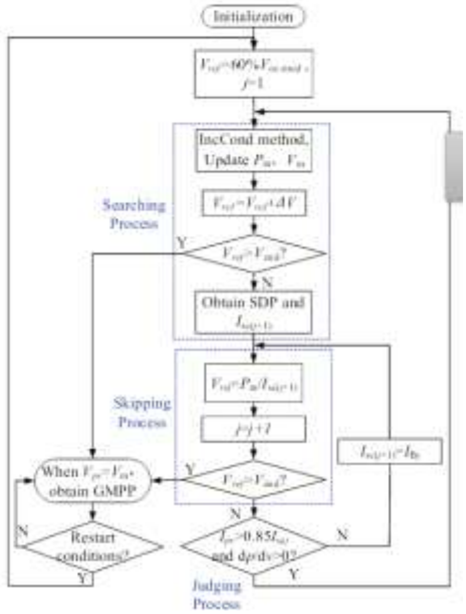

Fig. 5. Complete algorithm flowchart of SSJ-GMPPT.

the tracking accuracy of SSJ-GMPPT method, the factor of 0.85 is carefully selected. But the factor may vary in the practical PV systems accordingly. The necessary conditions to judge including IB1 > 0.85Isc2 and *dp/dv* > 0. The result of the judgment would induct the algorithm to next operating process as follows:

(i) The first condition is to know whether IB1 > 0.85Isc2. According to (5), for PV modules, *I*m is approximately equal to 0.85· *I*sc, so if *I*B1 < 0.85Isc2, IB1 < Im2, point B1 is on the right of M2, which means Pm2 < Pm. The algorithm, then, returns to skipping process again to search the next SDP. Otherwise, *I*B1 > 0.85*I*sc2, which means Pm2 is likely larger than Pm (as shown in Fig. 4(b)). Then, the algorithm turns to the searching process to track M2.

(ii) The second condition is to know whether *dp/dv* > 0. When *I*B1 < 0.85*I*sc2, it is unnecessary to judge the sign of *dp/dv*, because it is obvious that Pm2 < Pm, the algorithm turns to the skipping process. When *I*B1 > 0.85*I*sc2 and *dp/dv* < 0, it is true that point B1 is on the right of M2, as mentioned above, and Pm2 < Pm; Otherwise, B1 is on the left of M2 and Pm2 > Pm, the algorithm will turn to the searching process for M2. The result of the judgment decides the different direction of algorithm. For shading pattern 1, as shown in Fig. 4(a), because *I*B1 < 0.85*I*sc2 and *dp/dv* > 0, the process from A1 to B1 has skipped one or more PPPs (actually skip M2). The result of the judgment would shift the program to the skipping process again. According to the constant-current property of PV module, at this time current *I*B1 can be regarded as SDP current *I*sc3 because *dp/dv* > 0 at point B1. So the algorithm turns to the skipping process and sets the operating voltage equal to the quotient of $Pm/Isc3$. Then, in judging process, the voltage of $Pm/Isc3$ is higher than Vend, so the algorithm is ended and Vm1 is the actual voltage of GMPP. The PV string operates on M1 and successfully tracks the GMPP. The whole scanning process in shading pattern 1 shown in Fig. 4(a) needs two tracking rounds of SSJ-GMPPT method.

For shading pattern 2, as shown in Fig. 4(b), because IB1 > 0.85Isc2 and $dp/dv > 0$, point B1 lies on the left of M2, which means the power of the second PPP (Pm2) is higher than the recorded *Pm*. The algorithm would turn to the searching process again. The newly obtained PPP and SDP are M2 and A2. Because $Pm/Isc3$ is higher than Vend, the second judging result is that M2 is the GMPP and voltage vicinity of M3 is unnecessary to scan. The algorithm would operate on M2 which is actually the GMPP. The whole scanning process in shading pattern 2 spends two tracking rounds of SSJ-GMPPT method.

For shading pattern 3, as shown in Fig. 3(c), because IB1 < 0.85Isc2 and $dp/dv > 0$, the process from A1 to B1 has skipped M2. The program would turn to the skipping process again. The current of B1 is regarded as the current of second SDP. In the skipping process for the second time, the operating voltage changes from B1 to B2 which is achieved by the quotient of $Pm/Isc3$. In the judging process for the second time, because IB2 > 0.85Isc3 and $dp/dv > 0$, point B2 lies on the left of M3, which means the power of the third PPP (Pm3) is higher than the recorded *Pm*. The program would turn to the searching process for M3. Once M3 is obtained and Pm3 is recorded, the disturbance will be done to search the next SDP. However, as M3 is the last one PPP, the operating voltage will reach Vend during the disturbance. As a result, the algorithm will be ended. The obtained GMPP is M3. The whole scanning process in shading pattern 3 spends three tracking rounds of *SSJ-GMPPT*

IV. RAPID GLOBAL MPPT METHOD UNDER PSC

When the voltage of GMPP is lower, the SSJ-GMPPT proposed in Section III needs fewer rounds to track GMPP, But if the voltage of GMPP is very high, and especially for long PV string, the method may be inefficient. For example, if the powers of the PPPs increases one by one, as shown in Fig. 5, the scanning time may be longer because the algorithm must sequentially scans every PPP.

In order to overcome the drawback of the SSJ-GMPPT for long PV string under PSC, this section proposes a rapid global MPPT method (R-GMPPT) based on the approximate voltage relationship expressed in .For the string with *n* modules under PSC, there are *n* PPPs in the *P-V* curve. These voltage values Vmj of PPP can be approximately pre-estimated by(). The approximate power values of all PPPs can be pre-estimated by $VmjImj$, as shown in (8), in which Imj can be determined by $Iscj$ during the algorithm initialization based on (5). In the algorithm initialization, the operating voltage is set as 60%Voc-mod, which can make all shaded PV modules operating in short-circuit. So $Iscj$ can be measured by subtracting the current of bypass diode from string current (As seen in Fig. 2(a), $I_{sc1}= i_{str}- i_{dp1}$, $I_{sc2}= i_{str} - i_{dp2}$).

$$P_{mj} = V_{mj} I_{mj} \approx [(j - 0.24) V_{oc} \ \ n] \, 0.9 I_{scj}$$

With the obtained P_{mj}, the approximate global maximum power point (AGMPP) can be distinguished. Then the IncCond method is used to accurately track the GMPP in the local vicinity of the AGMPP. As a result, the accurate GMPP would be obtained. The flow diagram of R-GMPPT is shown in Fig. 6. The initialization, ending condition and restart condition are same as SSJ-GMPPT method. In this method, the voltage interval of scanning is greatly reduced and only the vicinity of the AGMPP is necessary to search which is greatly less than that of the conventional searching method. Therefore, by applying only one local-scanning to replace the global-scanning, the searching time is substantially shortened. It should be noted that the R-GMPPT method needs *n* current sensors to measure the bypass diode current, leading to a increased cost. The OC-voltage of PV string should be updated for every PV system maintenance such as every half a year to eliminate the OC-voltage error by aging.

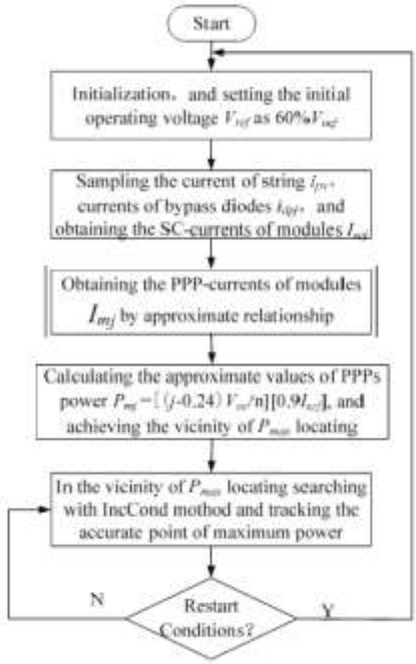

Fig. 6. Complete algorithm flowchart of R-GMPPT.

VI. CONCLUSION

The P-V curve of PV string under partially shaded conditions exhibits multiple peaks. Conventional MPPT methods are not able to achieve either sufficient accuracy or fast tracking speed. In this paper, two global MPPT methods, SSJ-GMPPT and R-GMPPT methods, are proposed in term of reducing the searching voltage range based on comprehensive study of I-V and P-V characteristics of PV string. The SSJ-GMPPT method is capable of tracking the global maximum power point with high accuracy and approving speed without additional circuit and sensor. The R-GMPPT method exhibits very fast tracking speed with 90% time saved compared to the conventional global MPPT method, so it can be used in the conditions of long PV string.. The SSJ-GMPPT method guarantees tracking accuracy with an approving tracking time, while R-GMPPT method performs at a higher speed with acceptable accuracy.

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