Linzhuang Jia, Kan Chen, Guojie Li, Lin Feng, Xiuchen Jiang

Shanghai Jiao Tong University

Output Characteristics and MPPT Research for PV Array under Partially Shaded Conditions

***Abstract**. MPPT(maximum power point tracking) has been one of the hot issues in PV power system all the time. At present, most of MPPT methods are very efficient only under uniform irradiance. However, the output power-voltage curve presents multi-peak characteristics under PSCs (partially shaded conditions), which is one challenge of the MPPT technology. In this paper, the segment characteristics of PV array, which is made by PV modules in series-parallel (SP) connection, was analyzed in details under PSCs. And then a GMPPT (global maximum power point tracking) algorithm was proposed based on the segment model. The MPPT controller using this algorithm can rapidly locate the segment where the GMPP(Global Maximum Power Point) is in and then converges the working point to GMPP using an improved InC (Incremental Conductance) method. A Matlab/SIMULINK model verifies that the proposed algorithm is efficient under both uniform irradiance and PSCs.*

***Streszczenie.** System śledzenia warunków maksymalnej mocy MPPT jest powszechnie stosowany w systemach fotowoltaicznych. Systemy te w większości działają w warunkach jednorodnego nasłonecznienia. W artykule zaproponowano system śledzenia mocy w warunkach częściowego nasłonecznienia. (**System śledzenia mocy MPPT dla układów fotowoltaicznych w warunkach częściowego zacienienia**).*

Keywords: Partially Shaded Condition(PSC), Global Maximum Power Point Tracking(GMPP), Attracting Region, Segment Model
Słowa kluczowe: układy fotowoltaiczne, system śledzenia maksymalnej mocy MPPT

0. Introduction

Solar PV power generation is one of the most important directions in the field of new energy development. In PV power generation system, the working point has considerable impact on the conversion efficiency of PV systems, and thus the research on maximum power point tracking (MPPT) algorithm has been one of the hot issues all the time.

In actual PV power generation system, high voltage and power output is required, so PV array with multiple PV modules in series or parallel connection is generally adopted in the majority of systems. Modeling and simulation studies suggest that power-voltage (P-V) curve is likely to present multiple peaks under PSCs(Partially Shaded Conditions) if multiple PV modules are in series connection [1,2].

At present, conventional MPPT algorithms are valid for the single-peak case[3-9], but very difficult to track the global maximum power point for multiple-peak situations. Meanwhile, there are still some shortcomings in the algorithms specific to multiple-peak situation. The method proposed in literature [10] is basically a method for full domain scan, in which it is not easy to determine a reasonable step size. A large step size will miss GMPPT, while a small step size will result in low tracking efficiency. The most important idea in the 2-stage tracking method mentioned in literature [11] is to make the working point directly move to the vicinity of GMPP bypass other local extremum through MPP(Maximum Power Point) load line $R_{mpp}=V_m/I_m$; where V_m is 0.8 times that of open-circuit voltage of PV array, and I_m is 0.9 times that of short-circuit current. An in-depth analysis on the output characteristics of PV array under PSCs in this paper shows that this method cannot actually track the real GMPP in many situations. The same fault exists for the method proposed in literature [12], though the convergence rate is fast. Although the GMPPT algorithm based on Extremum Seeking Control (ESC) in literature [13] can accurately converge to GMPP, oscillation occurs repeatedly in the process of convergence, and the problem of slow convergence rate exists in practical application. There is another kind of MPPT strategy which is based on improved circuit topology or an increase in the number of measuring circuits[14-17]. This kind of strategy depends on specific hardware system, therefore increasing the complexity and cost of hardware.

In this paper, A GMPP tracking algorithm based on segment model is proposed by analyzing the characteristics of series-parallel PV modules. The algorithm first quickly locates the segment where GMPP is in by analyzing the relative size of each local extremum, and then stably track GMPP with an improved InC(Increment Conductance) method. The tracking efficiency of this algorithm is comparable to that of traditional algorithm under uniform irradiance; in cases of irradiance changes or PSCs, this algorithm can response quickly, capable of tracking the latest position of GMPP. The improved InC method enables the working point finally stabilize within a very small range in the vicinity of GMPP. A simulation model is built with Matlab/Simulink for verificaion. The results prove that the algorithm proposed in this paper has the advantage of tracking GMPP accurately and efficiently under PSCs.

1. Output characteristics under uniform irradiance

1.1 Model of PV cell

Much study work has been done on the model of PV cell [18]. Here we only repeat the features of this model in light of output characteristics. An equivalent circuit of a PV cell is shown in Fig.1:

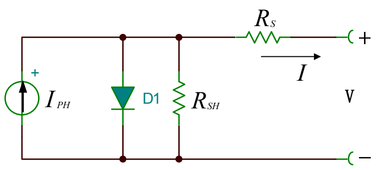

Fig.1 Equivalent circuit model of PV cell

Output current-voltage is described by:

$$I = I_{PH} - I_S\left[\exp\left(\frac{e\left(V + IR_S\right)}{mkT}\right) - 1\right] - \frac{V + IR_S}{R_{SH}} \quad (1)$$

where I_{PH} is photo-generated current; I_s is cell saturation of dark current; R_S and R_{SH} are shown in the equivalent circuit model; characteristic factor m is associated with the manufacture process of solar panel; k is the Boltzmann constant: $k=1.38\times 10^{-23}J/K$; e is the charge of electron: $e=1.6\times10^{-19}C$; T is temperature of the PV cell.

Current-voltage and power-voltage curves are shown in Fig.2:

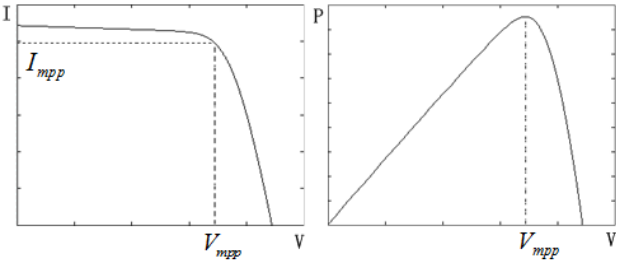

Fig.2 Output characteristics of PV cel

It is clear that the output characteristic is non-linear, and there is a MPP on it. The output characteristic of the PV cell is similar to a current source with the output voltage smaller than the MPP voltage V_{mpp} while it is similar to a voltage source with the output voltage larger than V_{mpp}.

1.2 Model for PV module and PV array

PV module usually consists of series-parallel connected PV cells in practical applications because a single PV cell can only output power of less than 2W and voltage about 0.5V. With superscript M denoting a PV module, superscript C a PV cell, N_p the number of parallel connected PV modules, and N_s the number of series connected PV modules, the output model of PV module under uniform irradiance can be described by Formula (2) [18]:

$$I^M = N_P I_{PH}^C - N_P I_S^C \left[\exp\left(\frac{V^M / N_S + I^M R_S / N_P}{V_t} \right) - 1 \right] - \left(N_P V^M / N_S + I R_S \right) / R_{SH} \qquad (2)$$

where $V_t = \dfrac{mkT}{e}$

Apparently, PV module and PV cell share similar characteristic curve. $0<V<V_{mpp}$ segment can simply be regarded as constant current segment of PV module, while $V_{mpp}<V<V_{oc}$ segment as constant voltage segment, where V_{oc} is the open-circuit voltage of PV module. Fig.3 shows the I-V and P-V characteristics curves of PV module under different irradiance. Without changes of other external conditions, output short circuit current I_{SC} of PV module is approximately proportional to irradiance.

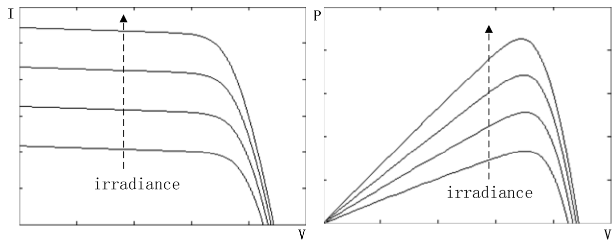

Fig.3 Output characteristics of PV module under different irradiance

Output voltage and power of PV module still cannot meet the requirements of grid-connected inverter in practical applications. So PV modules are used to make up the PV array in series-parallel connection. Similarly, PV array and PV module share similar characteristic curves under uniform irradiance. However, under PSCs the output characteristics of PV array present complex situation. A detailed analysis on output characteristics of PV arrays consisting of series-parallel connected PV modules under PSCs is helpful to find an accurate and efficient algorithm for GMPPT.

2. Analysis of output characteristics under PSCs

There have been many researches on modeling and simulation of output characteristics of PV array under PSCs [1,2,19]. Here we will focus on the distribution features of each local extreme point under PSCs to work out an algorithm of GMPPT.

2.1 Analysis on characteristics of series connection

Consider a simple PV array A formed by series connection of K PV modules with negligible inconsistency. It also can be called a PV string. Then for output voltage and output current, we have:

$$\begin{cases} I^A = I^{M_i}, i = 0,1,\cdots,K \\ V^A = \sum_{i=0}^{K-1} I^{M_i} \end{cases} \qquad (3)$$

To avoid hotspot phenomenon, bypass diode is usually reversely parallel connected to series connected module as shown in Fig.4.

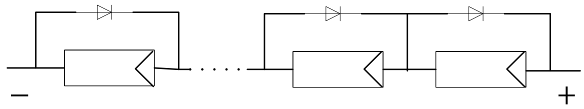

Fig.4 Series-connected PV modules with bypass diodes

Fig.5 shows I-V and P-V curves of PV array formed by series connection of 3 PV modules under PSCs.

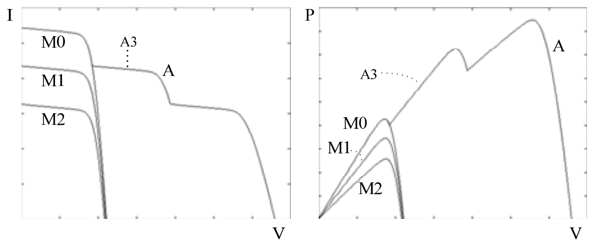

Fig.5 Output characteristics of 3 PV modules and their series connection under different irradiance

With the consideration of generality, PV modules can be ordered logically by decreasing irradiance λ^{M_i} under PSCs, i.e. $\lambda^{M_0} > \lambda^{M_1} > \cdots > \lambda^{M_{K-1}}$,and $I_{mpp}^{M_0} > I_{sc}^{M_1}$. The output characteristics of PV array A are described segment by segment as the output current decreases:

1) When $I_{sc}^{M_0} \geq I^A > I_{mpp}^{M_0}$, bypass diode of M_1~M_{K-1} is switched on. Then M_0 is the only one that output power. Output characteristic curve of PV array for this segment is that of constant current segment of M_0.

2) When $I_{mpp}^{M_0} > I^A > I_{sc}^{M1}$, M_1-M_{K-1} is still bypassed and does not output power. This segment of output of PV array is part of the constant voltage segment of M_0.

3) When $I_{sc}^{M_1} > I^A > I_{mpp}^{M_1}$, M_0 is still in constant voltage segment and its output voltage decreases gradually as output voltage of PV array increases, while M_1 enters the constant current segment and begin to output power. Other modules are still bypassed. For the case where voltage source M_0 and current source M_1 are in series connection, the changes of output voltage of PV array are mainly caused by M_1. Consequently, when there is negligible inconsistency between M_0 and M_1, the changes in output power of PV array A are mainly represented by those of M_1. That is, output power rises rapidly as output voltage rises, forming $A3$ segment shown in Fig.5.

4) When $I_{sc}^{M_1} < I^A < I_{mpp}^{M_2}$, both $M0$ and $M1$ enter constant voltage segment. Output power of PV array decreases

rapidly while output voltage increases.
5) The above procedures are repeated while the working point go through constant current segment and constant voltage segment for all PV modules.

It follows from the analysis above that if $I_{mpp}^{M_0} > I_{sc}^{M_1}$, segment 2 will have the features: output power of M_0 begins to decrease as voltage increases, while there is no output power from M_1. What happens in segment 1 and 2 results in the first local extremum, whereas the second local extremum is formed due to the increasing of output power in segment 3 and segment 4.

If $I_{mpp}^{M_0} < I_{sc}^{M_1}$, M_1 has entered constant current segment when M_0 has not yet entered constant voltage segment. Thus, segment 2 above does not appear. So the occurrence of two local extremum can be avoided. Therefore, the condition for two local peaks to occur in PV array formed by series connection of two PV modules under PSCs is $I_{mpp}^{M_0} > I_{sc}^{M_1}$, where the relationship directly reflects the non-uniformity level of irradiance.

2.2 Output characteristics of PV array with series-parallel(SP) connections

SP topology was employed in most PV arrays, as shown in the Fig.6.

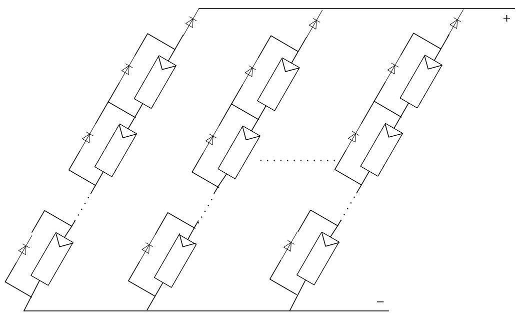

Fig.6 Series-parallel(SP) solar PV array

Let's consider a PV array consists of L strings parallel connected. Then the output current and voltage is given by the following equation:

$$\begin{cases} I^A = \sum_{i=0}^{L-1} I^{S_i} \\ V^A = V^{S_i}, i = 0,1,\cdots,L-1 \end{cases} \tag{4}$$

where superscript S denotes PV string.

According to this equation and the segment model of the PV array in series connections as shown in Fig.5, the output current of the PV array simply equal to the sum of the L PV strings segment by segment. As a result, PV array with SP topology has similar segment characteristic with PV array which only consists of PV modules in series connection. Therefore, series-parallel connection of PV modules can be reduced to series connection when output characteristics of PV array are concerned under PSCs.

3. Conventional algorithms' failure under PSCs

3.1 Traditional HCS and constant voltage method

The most widely used and well-known MPPT algorithm is undoubtedly hill-climbing search (HCS) algorithm, the representatives of which are perturb and observe method (P&O) and incremental conductance (InC) method. In InC method, when $dI/dV > -I/V$, the moving direction of working point is the direction along which the voltage increases; when $dI/dV < -I/V$, the moving direction of working point is the direction along which voltage decreases. It is obvious that HCS method enables the working points, which are initially located at each monotonous segment on two sides of MPP on *P-V* curve respectively, to gradually move towards MPP. As long as the step size δ is small enough, the working point can move infinitely close to MPP. The domain consisting of monotonous segments on the two sides of MPP can be called attracting domain of MPP under HCS, strictly described as:

If the voltage of initial working point is V, for arbitrary $\varepsilon>0$ and step size $\delta<\varepsilon$, there is always a positive integer k that satisfies the relationship $|V(n)-Vmpp|<\varepsilon$ for any $n>k$ under the closed-loop system of HCS. Then the domain comprised of all these initial working points is called the attracting domain of MPP under the HCS system.

According to the previous analysis on output characteristics of series connected PV modules and the concept of attracing domain of extremum point, we draw the following conclusions:

When multiple local extremum occurs on *P-V* curve of PV array, if the step size δ is small enough, the working point will finally converge to the local extremum point whose attracting domain is just where the initial position is in. Therefore, HCS will be invalid if the working point is not initially located in the attracting domain of GMPP.

For excessively large step size δ, it is also possible that the working point escapes from the attracting domain where it is located. But the final results are unexpected, and the effectiveness of the algorithm also cannot be guaranteed.

Constant Voltage (CV) method [10,20] is also a commonly used method for MPP tracking. According to the output characteristics of PV module, V_{mpp} is always located in 0.72~0.80V_{oc}. Usually 0.76V_{oc} is approximately taken for V_{mpp}. Obviously, this method is no longer suitable for the situation when multiple local extremum occurs.

3.2 Typical algorithm specific to multiple-peak situation

Global scan method: duty cycle of 5% is taken as the step size for local extremum lacks effective theoretical basis in literature [10]. The relative size of power at each scan point is difficult to reflect the relative relationship of local extremum of power in the attracting domain.

Fast tracking method: The method proposed in literature [12] is about tracking GMPP by placing the working point in the attracting domain of GMPP using I_{sc}-V_{oc} linear function and combining with incremental conductance method. The main idea is that PSCs are considered to be detected if the output current of the working point decreases significantly. The voltage value corresponding to new current value on load line I_{sc}-V_{oc} is taken as the new location of the working point, which is in the attracting domain of GMPP. Then with the traditional InC method, the working point can be converged to GMPP.

As in the previous analysis on series connected PV modules, the movement of working point according to I_{sc}-V_{oc} linear function is exclusively determined by irradiance of the last PV module M_{K-1} in logical sequence. The lower the irradiance, the greater the movement of working point will be. So if there is such a situation: the irradiance of M_{K-1} is so low that working point moves to the attracting domain of the local extremum of M_0 segment, though the local extremum of this segment is not GMPP. Then error inevitably occurs. Fig.8 shows one such situation for the simulation results.

With these analysis on conventional algorithms, it is not hard to see that the major difficulty of GMPPT under PSCs is how to make the working point escape from the attracting domain of non-GMPP local extremum without scanning globally, or how to quickly place the working point in the attracting domain of GMPP.

4. Segment scanning and improved InC method

A GMPPT algorithm based on segment scanning in combination with an improved InC method is proposed in this paper by means of analysis of the characteristics of PV array, which is formed by series connection of PV modules. The main idea of this algorithm is to quickly find the constant current segment where GMPP lies using the simplified models of constant current and constant voltage segments described in 1.4. Then the working point is placed into the attracting domain of GMPP and converge to GMPP using improved incremental conductance method.

The priciple can be described in detail as following:

The local extremum of power for each constant current segment can be estimated from the current value:

1) Extremum of segment M_0 is $P_{mpp}^{M0} = \beta V_{oc}^{M} \cdot I^{M0}$

2) Extremum of segment M_1 is $P_{mpp}^{M1} = 2 \cdot \beta V_{oc}^{M} \cdot I^{M1}$

3) Extremum of segment M_{k-1} is

$$P_{mpp}^{M_{K-1}} = (K-2) \cdot \beta V_{oc}^{M} \cdot I^{M_{K-1}}$$

where $\beta = V_{mpp} / V_{oc}^{M}$ is approximately a constant under different irradiances. Only one working point is required for current measurement in one segment because the current is approximately constant in the whole segment. Then extremum of power for each segment are estimated by the formulas above. The segment where the maximum value lies is taken as the constant current segment where GMPP lies.

This algorithm consists of the following steps:

1) Working points for coarse scanning are determined according to the number of PV modules in series connection. Working points are respectively taken as $0.2V_{oc}^{M}$, V_{oc}^{M}, $2V_{oc}^{M}$, … and $(K-1)V_{oc}^{M}$ to ensure that the working points for the scanning are located in the corresponding constant current segment. It should be noted that $0.2V_{oc}^{M}$ is take for M_0 segment to avoid working under a short-circuit condition.

2) In coarse scanning, current of each segment is measured, and the local extremum of power is estimated. The segment where the maximum extremum occur is the constant current segment where GMPP lies.

3) Working point is placed in the segment where GMPP lies, and the GMPP is searched by an improved incremental conductance method. It should be noted that step size Δd has to be set larger to quickly approach GMPP, typically 1/10 of a constant current segment.

4) Step size Δd is set as one half of the original value to approach GMPP again after arriving at GMPP. This step is repeated until the step size is shorter than the preset value ΔV_{SET}. Then the system stably operates at GMPP. Here two successive working points satisfy the following condition:

(5) $$\Delta V_{PV} = V_{PV}[n] - V_{PV}[n-1] < \Delta V_{SET}$$

In practical applications, ΔV_{SET} depends on the measurement precision of current and voltage.

5) For two successive working points that meet the conditions above, if output current of PV array satisfies the following condition:

(6) $$\frac{\Delta I_{PV}}{I_{PV}[n-1]} = \left| \frac{I_{PV}[n] - I_{PV}[n-1]}{I_{PV}[n-1]} \right| > \Delta I_{SET}$$ Then it is considered that the irradiance has changed[12] and the steps above are repeated from step 2 until reaching stable situation for a second time.

Setting longer step size in step 3 and repeatedly halving the step size can optimize the traditional incremental conductance method[10]. Compared with traditional InC method, the improved InC method can faster approach the extremum when it is distant away from the extremum. On the other hand, continuously halving the step size when it is in the vicinity of the extremum will improve the efficiency at MPP under stable state.

5. Simulation result analysis

PV array formed by series connection of 4 identical PV modules and a model for GMPPT controller using the algorithm proposed in this paper are established in Matlab/Simulink environment to verify the algorithm. The open-circuit voltage of PV module under irradiance of 1000 W/m^2 is 22.2V, with short-circuit current of 5.45A. The irradiance changes are simulated as follows:

1) When t = 0-2s and uniform irradiation $\lambda^{M_X} = 1000 W/m^2$ (where x=0,1,2,3), I-V and P-V curves of the PV array are shown in Fig.7. It is seen from I-V curve that all the four constant current segments M_0~M_3 connect into a large constant current segment.

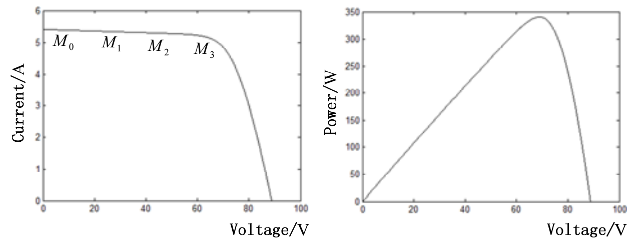

Fig.7 Output curves of the PV array under uniform irradiance 1000 W/m^2

2) When t=2-4s, under PSC, irradiance of the 4 PV modules are $\lambda^{M_0} = 1000 W/m^2$, $\lambda^{M_1} = 600 W/m^2$, $\lambda^{M_2} = 500 W/m^2$ and $\lambda^{M_3} = 50 W/m^2$ respectively, the I-V and P-V curves of the PV array are shown in Fig.8, four constant current segment M_0~M_3 are clearly recognized in I-V curve.

3) When t=4-6s, uniform irradiation of 1000 W/m^2 is restored. Fig.9 (a)~(c) respectively show the curves of voltage, current and power of PV array with the existence of GMPPT controller.

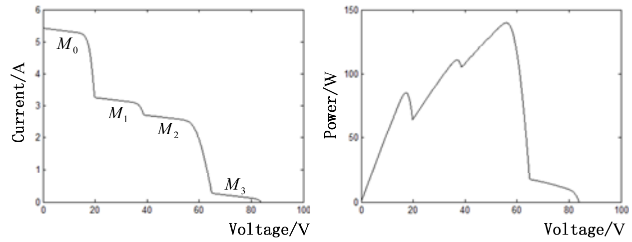

Fig.8 Output curves of the PV array under PSCs

When t=0-2s, i.e., under uniform irradiation condition, GMPPT controller tracks GMPP as the MPPT controller based on the traditional HCS algorithm: in Fig.9 (a), M_0~M_3 segments are scanned first by GMPPT controller. GMPP is located at M_3 segment according to the estimates of all the four local extrema. Then with improved InC method, every time when GMPP is exceeded (sign of $dI/dV + I/V$ changes), the step size is halved so that the working point will be finally stabilized in a very small range in the vicinity of GMPP. The specific range varies with measurement precision of current and voltage of PV array in practical applications.

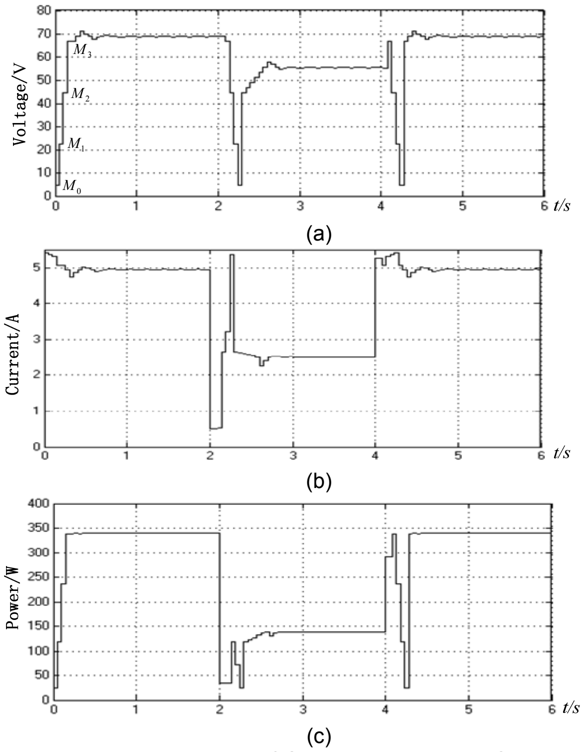

Fig.9 The working process of GMPPT controller (a) Output voltage; (b) Output current; (c) Output power

When t=2s, the irradiance changes, and the measured data of GMPPT controller simultaneously meets the condition (5) and (6), which trigger another scanning and tracking process. When t=2-4s in Fig.9, it is seen that M_3~M_0 segments are scanned in sequence by the controller and local extremum in M_2 segment is considered as global maximum according to local extremum formula(the constant current segment corresponding to irradiance of 500 W/m^2). The values converge to GMPP using improved InC method. The scan time in the Figure corresponds to t=2-2.3s while t=2.3-4S corresponds to the working period of InC method.

When t=4s, the irradiance again becomes uniform, which triggers the scanning and tracking of GMPPT controller once again. The result is almost the same as when t=0-2s.

6. Conclusion

(1) Output characteristics of PV array is first analyzed in this paper and a method for estimating local extremum is proposed according to the simplified model of *I-V* curve, on the basis of which a new GMPPT algorithm is suggested based on segment model;

(2) Simulation verification is performed on the tracking effectiveness of the proposed GMPP algorithm based on segment model by changing the irradiance for the simulation model established. Results indicate that GMPPT controller based on the new algorithm has similar effects with traditional HCS algorithm under uniform irradiation. It can response quickly and accurately capture GMPP when irradiance changes into PSC and multiple local extremum appear on the *P-V* curve of PV array. The working point of the system can converge to extremely small range in the vicinity of MPP by improved InC method. The range is only restricted by measurement precision of current and voltage of the system in practical applications.

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***Authors**: **Linzhuang Jia**. He is currently working toward the Ph.D. degree in the department of Electrical Engineering, Shanghai Jiao Tong University, China. E-mail: jia.linzhuang@sjtu.edu.cn;*

***Kan Chen**. He is currently work toward the master degree in the department of Electrical Engineering, Shanghai Jiao Tong University, China. E-mail: diablosky76@sjtu.edu.cn;*

***Guojie Li.** Prof.Li is a professor at the Key Laboratory of Control of Power Transmission and Transformation, Ministry of Education, China. E-mail: liguojie2000@126.com.*