Maximum Power Point Tracking Algorithm with Turn Round Measurement and Curve Fitting Method for Solar Generation System

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Abstract: - A novel maximum power point tracking (MPPT) algorithm is proposed in this paper. The novel algorithm adopted a round back measurement which makes it easy to avoid misjudge when the irradition varies rapidly, especially comparison to traditional MPPT strategy. What's more, round back measurement makes it possible to imitate PV array's P-U curve with mathematical method which makes it possible to reduce the oscillation near PV's maximum power point (MPP). Lagrange Interpolation Formula is used in this paper to fit PV's P-U curve and a simulation with Matlab/Simulink tool to verify the proposed has been done. The result reveals proposed MPPT algorithm is more accuracy in irradiation variation situation and less oscillation near the MPP. These features make the algorithm a good idea in high-power solar generation system.

Key-Words: MPPT, solar generation system, irradiation variation, oscillation, curve fitting, matlab/simulink

1 Introduction

Photovoltaic (PV) power generation system is widely studied recently for energy crisis and the heavily polluted environment. As the characteristic of PV array is nonlinear and apt to be influenced by ambient temperature and irradiation condition. A maximum power point tracking (MPPT) technology is essential in a PV system to maximize PV's output power. PV system's performance is mostly affected by MPPT controller's stability, efficiency and dynamic characteristic.

Widely used MPPT algorithms can be concluded as perturbation and observation (P&O) and increment conductance (IncCond). These two algorithms failed to track PV's maximum power point (MPP) when the irradiation varies rapidly. The main reason is that traditional MPPT algorithm doesn't take the relationship between power and voltage into account in detail.

To solve this problem, a novel MPPT algorithm using turn round measurement method has been proposed in this paper. What's more, turn round measurement makes it possible to calculate the reference voltage of PV array at MPP which reduces the oscillation near the MPP and the efficiency is prominent improved. The operating principle and simulation result with Matlab/Simulink tool has been given and discussed in this paper in detail.

2 Problem Overview

Fig.1 shows the characteristics of a PV Cell.

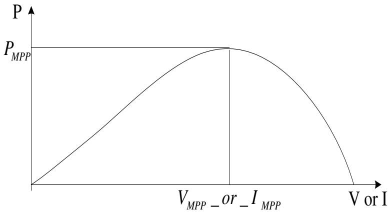

Fig.1 Power curve of PV cell

The problem fixed by the MPPT technique is to find the Vmpp or Impp of PV cell. Maximization output power can be obtained when the PV cell operates at V_{mpp} or I_{mpp} udner specific irradiation and temperature condition. It is noted that partial shading situation resulted multiple MPP of PV cell. However, there is still single true MPP overall. Different MPPT techniques can respond to both irradiance and temperature. But some are apt to deal with irradiance or temperature situations specifically. Some MPPT techniques can be failed when irradiation varies fast.

3 MPPT Techniques

3.1 MPPT principle

According to optical electronic theory, PV array's mathematical module is as Fig2 shown.

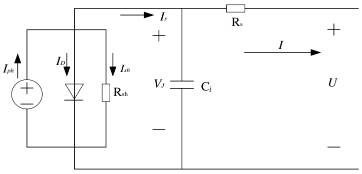

Fig.2 Equivalent circuit model for photovoltaic cell

The relationship between PV’s output current and voltage can be described as equation (1).

$$I = I_L - I_0\left\{\exp[\frac{q(V+IR_S)}{AKT}]-1\right\}-\frac{V+IR_S}{R_{Sh}} \tag{1}$$

PV’s I-U curve and P-U curve are shown as Fig.3 and Fig.4 respectively.

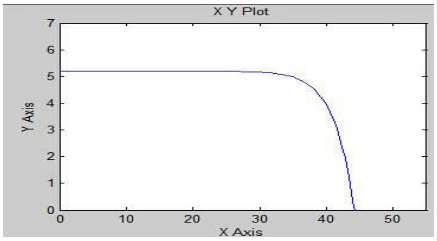

Fig.3 I-U curve of PV cells

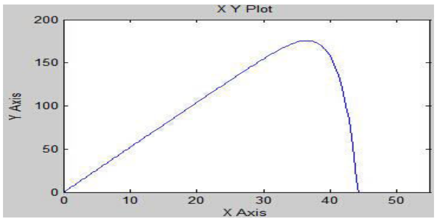

Fig.4 P-U curve of PV cells

PV cell’s model can be simplified as Fig.5. U_{oc} represents the open circuit voltage and resister r can be considered as the output impedance of PV cells. When PV cell’s load resister R equals to output resister r, PV cell’s output power can be maximized. Fig.6 shows the MPPT topology with Boost converter. Equivalent impedance of boost converter and the load R_L can be described as R_{eq}:

$$R_{eq} = (1-D)^2 R_L \tag{2}$$

Among which, D represents boost converter’s duty cycle. PV cell output maximum power when R_{eq} equals to r.

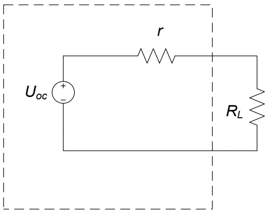

Fig.5 PV cell’s simplified model

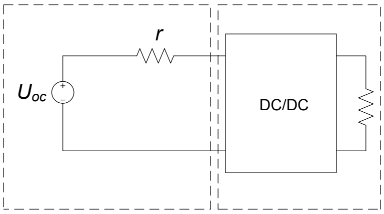

Fig.6 MPPT with DCDC topology

As irradiation varies, P&O and IncCond algorithm failed to response fast. Thus, the MPPT algorithm need to track the MPP again which makes PV’s efficiency reduce significantly under irradiation rapid change circumstance.

Most commonly used MPPT techniques are described in this chapter and the failure principle are analyzed in detail.

3.2 Hill-Climbing/Perturbation and Observation

Hill-Climbing/Perturbation and Observation are most favored MPPT techniques. Hill-climbing method perturbs the duty ratio of the power converter and that results the output current change of PV cell. Perturbation and observation method perturbs the reference of PV cell. When the output voltage of PV cell changes, the output current varies consequenetly. Hill-Climbing and P&O method are different way to envision the same fundamental method.

In Fig.1, it can be seen that increasing(decreasing) the voltage increases(decreases) the power when PV cell operating on the left of the MPP and decreasing (increasing) the voltage decreases (increases) the power when on the right of the MPP. Therefore, next step’s perturbation direction is determined by the output power’s variation. If the power increases, the prior perturbation direction is correct, otherwise reversed the perturbation direction. The relations between changing in power and next perturbation direction are as Table1 shown.

Table1. Summary of hill-climbing and P&O method

Perturbation	**Change in Power**	**Next Perturbation**
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

The perturbation and observation process is repeated periodically until the MPP is reached. The system then oscillates around the MPP. The oscillation wastes PV’s power if the step size is too large. In order to minimize the oscillation near the MPP, the step size should be decreased. However, that will slow down MPPT speed. In some thesis, two stage step size is adopted to track the MPP. A bigger step size is used in first stage to offer fast tracking speed and a finer step size is adopted in the second stage to decrease the oscillation.

Hill-climbing and P&O methods fail under rapidly changing irradiation conditions as shown in Fig.7.

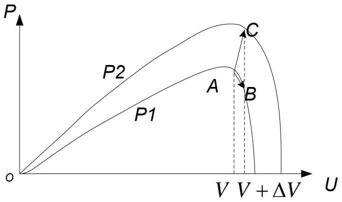

Fig.7 Hill climbing method invalid schematic diagram

Assume the PV cells operates at point A under irradiation P1. The output power will decrease from A to B if the perturbation ΔV is positive. The next step should decrease the voltage of PV cells. The output power will change from A to C if the irradiation changes from P1 to P2. The controller will keep on increasing the operating voltage for the output power increases. It is obvious that the perturbation direction is wrong for the reason of irradiation rapidly changing.

3.3 Incremental Conductance

The incremental conductance method is based on the fact that the slope of the PV array power curve is zero at the MPP, positive on the left of the MPP, and negative on the right, as given by formula (3).

$$\begin{cases} dP/dV = 0, at\_MPP \\ dP/dV > 0, left\_of\_MPP \\ dP/dV < 0, right\_of\_MPP \end{cases} \tag{3}$$

Since

$$dP/dV = d(IV)/dV = I + VdI/dV \cong I + V\Delta I/\Delta V \tag{4}$$

(2)can be rewritten as

$$\begin{cases} \Delta I/\Delta V = -I/V, at\_MPP \\ \Delta I/\Delta V > -I/V, left\_of\_MPP \\ \Delta I/\Delta V < -I/V, right\_of\_MPP \end{cases} \tag{5}$$

The MPP can thus be tracked by comparing the instaneous conductance(I/V) to the incremental conductance ($\Delta I/\Delta V$) as shown in Fig.8 V_{ref} is the reference voltage at which the PV array is forced to operate. At the MPP, V_{ref} equals to V_{MPP}. Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in ΔI is noted, indicating a change in atmospheric conditions and the MPP. The algorithm decrements or increments V_{ref} to track the new MPP.

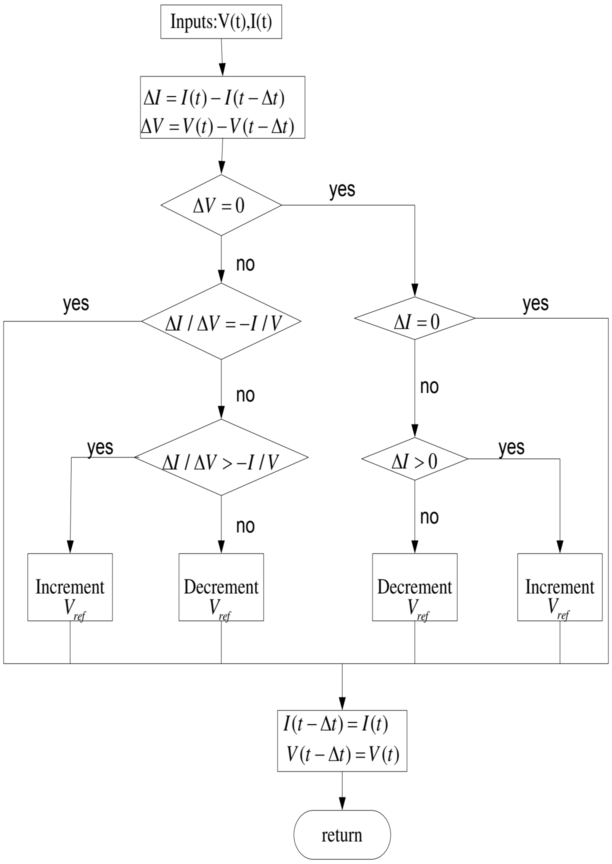

Fig.8 IncCond algorithm flowchat

The increment size determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at the MPP and oscillate about it instead; so there is a tradeoff. References [2] and [3] propose a method that brings the operating point of the PV array close to the MPP in a first stage and then uses IncCond to exactly track the MPP in a second stage. By proper control of the power converter, the initial operating point is set to match a load resistance proportional to the ratio of the open-circuit voltage V_{oc} to the short-circuit current I_{sc} of the PV array. This two-stage alternative also ensures that the real MPP is tracked in case of multiple local maxima.

A less obvious, but effective way of performing the IncCond technique is to use the instantaneous conductance and the incremental conductance to generate an error signal

$$e = I/V + dI/dV \tag{6}$$

as suggested in [5,6]. From (6), we know that e goes to zero at the MPP. A simple proportional integral (PI) control can then be used to drive e to zero. Measurements of the instantaneous PV array voltage and current require two sensors. IncCond method lends itself well to DSP and microcontroller control, which can easily keep track of previous values of voltage and current.

For all other applications not mentioned here, we put together Table.2, containing the major characteristics of all the MPPT techniques. Table.2 should help in choosing an appropriate MPPT method.

Table.2 MPPT techniques comparison

MPPT Technique	Converge speed	Sensed Parameters	Irradiation Change?
Hill-climbing/ P&O	Vari es	Voltage, Current	NO
IncCond	Varies	Voltage, Current	NO
Fractional Voc	Medium	Voltage	NO
Fractional Isc	Medium	Current	NO
Fuzzy Logic Control	Fast	Varies	YES
Neural Network	Fast	Varies	YES
Current Sweep	Slow	Voltage, Current	NO
DC Capacitor Droop Control	Medium	Voltage	NO
Linear Current Control	Fast	Irradiation	NO

4 Proposed MPPT algorithm with turn round measurement and curve fitting calculation

4.1 Turn round measurement operating principle

Control system detects the open-circuit voltage U_{oc} of photovoltaic (PV) cells. The initial MPP reference voltage is set as $0.8U_{oc}$ according to papers related. Record PV's current voltage and power as (U_b, P_b) . A perturbation voltage $\Delta U_{ref} = 0.01U_{oc}$ is given to achieve two different operation point $U_a = U_b - \Delta U_{ref}$ and $U_c = U_b + \Delta U_{ref}$. The data is recorded as (U_a, P_a) and (U_c, P_c) respectively. The next perturbation direction is determined by the relation between P_a, P_b, P_c and U_a, U_b, U_c . Given $P_a < P_b < P_c$ and it means U_c is the proximal point to the MPP. Gradient e1 can be obtained as $\left|\frac{P_c - P_b}{U_c - U_b}\right| = e_1$ and after a PI controller we get the fresh perturbation voltage ΔU_{ref} . PI controller is designed to make the perturbation voltage a self-adaption value which makes the tracking process faster when it is far away from the target value. What's more, PI controller decrease the perturbation step near the MPP and that reduce the oscillation near the MPP. After confirmation the new perturbation step, U_c is set as the new voltage starting point. The new tracking process is the same as before. A turn round measurement creates more operating steps for the control system. However, it is essential to take this step to avoid misjudge when the irradiation varies rapidly. Traditional perturbation and observation algorithm failed under this situation. It is explained as Fig.9.

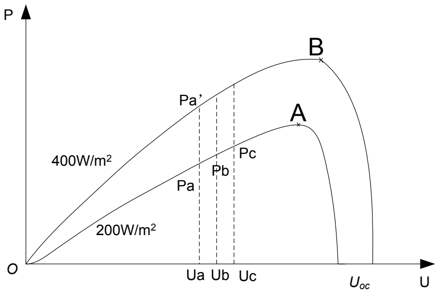

Fig.9 Photovoltaic array's output power and voltage

The origin point of PV is (U_b, P_b). U_a and U_c are obtained with the perturbation voltage ΔU_{ref} . Suppose the irradiation increases at U_a point and the P-U curve of PV transfer from A to B. The output power of PV at U_a point is $P_a^{'}$. If tradition P&O algorithm is used here, $U_a < U_b$, $P_a^{'} > P_b$, and that means the U_a is on the right side of MPP and the controller should decrease PV's output voltage. It is obvious that the tracking direction is wrong. The turn round method proposed in this paper can obtain three operating points at the same moment. A criterion is used in this paper to judge the irradiation situation. MPPT algorithm adopts the latest PV output point if irradiation varies. A new tracking process is initiated after the irradiation. The criteria proposed in this paper are shown as Table3.

Table 3 MPPT tracking direction criteria

PV voltage	PV power	Tracking direction
Ua<Ub<Uc	Pa<Pb<Pc	Increase voltage
Ua<Ub<Uc	Pa<Pc<Pb	Curve fitting
Ua<Ub<Uc	Pb<Pa<Pc	Irradiation varied
Ua<Ub<Uc	Pb<Pc<Pa	Irradiation varied
Ua<Ub<Uc	Pc<Pa<Pb	Curve fitting
Ua<Ub<Uc	Pc<Pb<Pa	Decrease voltage

As the table showed, $P_b > P_a > P_c$ or $P_b > P_c > P_a$ reveals the MPP is located at the section (U_a, U_c) . When this condition is satisfied, turn-round method is stopped and Lagrange Interpolation Formula is used to find the MPP. Curve fitting has been done to simulate PV's P-U curve with Lagrange Interpolation Formula. According to the derived P-

U curve equation, MPP is calculated and the reference voltage for PV is given.

4.2 Curve fitting near the MPP

When the PV's operating point is near the MPP, for the reason of turn round measurement method, three points of PV cells are obtained at the same moment. That makes it possible to restore PV's P-U curve when it is near the MPP and the error will be decreased significantly. With Lagrange Interpolation Formula, PV's P-U curve are fitted by three operating point near the MPP.

The curve fitting of PV's P-U curve makes it possible to track the MPP with the derived curve which is much easier and faster than traditional MPPT algorithm. The oscillation around the MPP will be prominently decreased with the calculation method rather than perturbation method. Which makes it suit for high-power photovoltaic modules application.

The operating principle of curve fitting is described as follow:

Assume the interpolated point are (U_a, P_a), (U_b, P_b) and (U_c, P_c). The interpolation polynomial of PV's P-U curve is as follow:

$$L_2(U) = P_a \cdot l_a(U) + P_b \cdot l_b(U) + P_c \cdot l_c(U) \tag{7}$$

Among which:

$$l_a(P) = \frac{(U-U_b)\cdot(U-U_c)}{(U_a-U_b)\cdot(U_a-U_c)} \tag{8}$$

$$l_b(P) = \frac{(U-U_a)\cdot(U-U_c)}{(U_b-U_a)\cdot(U_b-U_c)} \tag{9}$$

$$l_c(P) = \frac{(U-U_a)\cdot(U-U_b)}{(U_c-U_a)\cdot(U_c-U_b)} \tag{10}$$

Marix Hishman-Sigmar model of quadratic function can be derived as follow:

$$L_2(U) = x_1 U^2 + x_2 U + x_3 \tag{11}$$

$$x_1 = \frac{P_a}{(U_a-U_b)\cdot(U_a-U_c)} + \frac{P_b}{(U_b-U_a)\cdot(U_b-U_c)} + \frac{P_c}{(U_c-U_a)\cdot(U_c-U_b)} \tag{12}$$

$$x_2 = \frac{P_a\cdot(U_b+U_c)}{(U_a-U_b)\cdot(U_a-U_c)} + \frac{P_b\cdot(U_a+U_c)}{(U_b-U_a)\cdot(U_b-U_c)} + \frac{P_c\cdot(U_a+U_b)}{(U_c-U_a)\cdot(U_c-U_b)} \tag{13}$$

$$x_3 = \frac{P_a\cdot U_b\cdot U_c}{(U_a-U_b)\cdot(U_a-U_c)} + \frac{P_b\cdot U_a\cdot U_c}{(U_b-U_a)\cdot(U_b-U_c)} + \frac{P_c\cdot U_a\cdot U_b}{(U_c-U_a)\cdot(U_c-U_b)} \tag{14}$$

The fitted curve's maximum point is $(-\frac{x_2}{2x_1}, \frac{4x_1x_3-x_2^2}{4x_1})$. Only three points (U_a, P_a), (U_b, P_b) and (U_c, P_c) are needed to fit PV's P-U curve. With the substitution into the formula with three points, the coefficient x_1, x_2 and x_3 are derived. According to the derived P-U parabola curve of PV cells, the referenced voltage at MPP point can be described as $U_m = -\frac{x_2}{2x_1}$. Set the PV's output voltage to $U_{ref} = U_m$ by the controller. PV's output power P_m at operating point U_m need to be recorded. Three maximum power points are selected from (U_a, P_a), (U_b, P_b), (U_c, P_c) and (U_m, P_m). The selected points are marked as (U_1, P_1), (U_2, P_2) and (U_3, P_3). If curve fitting is implemented sequentially with the fresh three points, they must meet the conditions $P_1 < P_2 < P_3$ and $U_1 < U_2 < U_3$. Iteration with the fresh operating points by Lagrange Interpolation Formula as before until the MPP is tracked. PV's current output power P_{now} is compared with the previous cycle's power P_{before}. When the relationship between P_{now} and P_{before} satisfies $\left|P_{now} - P_{before}\right| < \varepsilon$, the MPP is tracked and curve fitting process need to be halted. The algorithm flow chat is as Fig10:

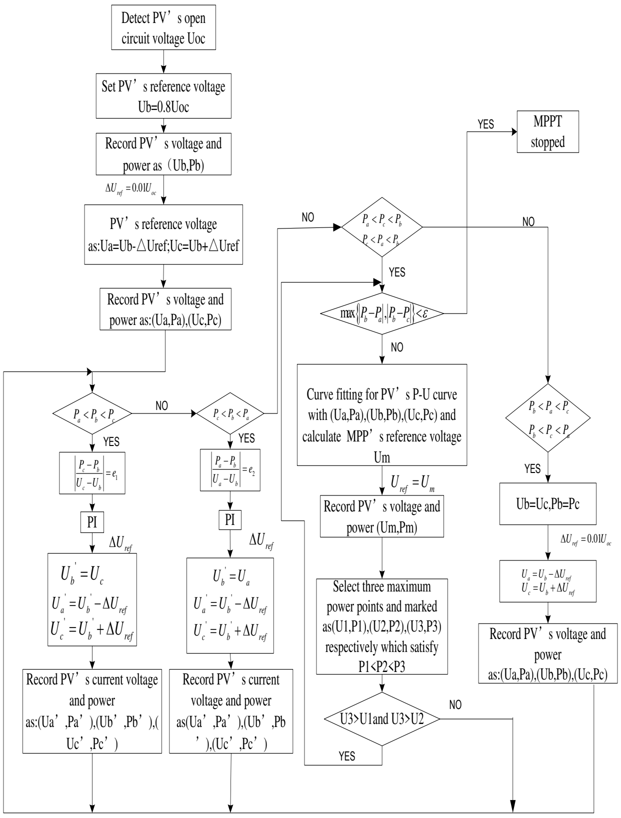

Fig.10 Flow chat of proposed algorithm

5 Simulation and Experiment Results

The simulation and experiment results show the difference between IncCond MPPT control algorithm and proposed MPPT control algorithm.

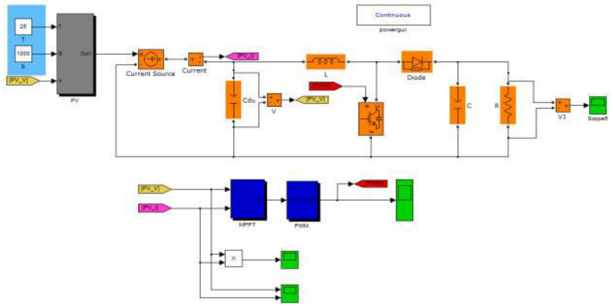

Fig.11 Fig.6 Proposed MPPT model

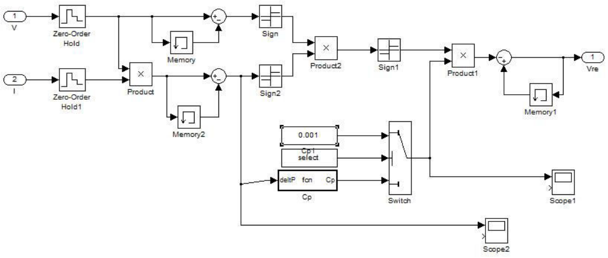

Fig.12 Proposed MPPT algorithm

The simulation conditions are as follow:

Temperature: 25 $^{\circ}C$

Irradiation P1: 600 W/m^2

Irradiation P2: 800 W/m^2

PV cell's key parameters under different irradiation are as Table.4 shows.

Table.4 PV cell's key parameter

Irradiation Condition	P1	P2
Open circuit voltage(V)	42	46
Short circuit Current(A)	4.12	5.67
MPP voltage(V)	34.5	37.5
MPP current(A)	2.75	3.78
MPP Power(W)	95	142

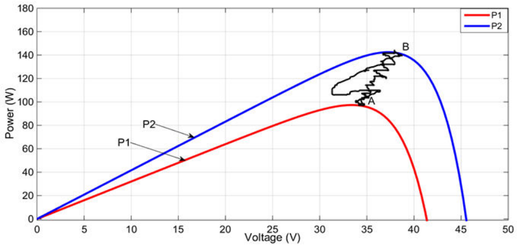

Fig.13 P-U curve with IncCond when irradiation changes

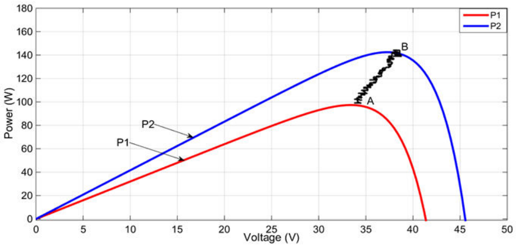

Fig.14 P-U curve with Proposed MPPT algorithm when irradiation changes

Irradiation varies at point A from P1 to P2. According to the simulation model, the irradiation variation process is a continuous process. MPPT algorithm's tracking process are showed as A to B. B point are PV cell's fresh MPP under P2 irradiation. Fig.13 and Fig.14 reveal that proposed MPPT algorithm oscillates lesser near the MPP and it can respond to the fresh MPP point B faster. That means the proposed algorithm is more efficient than IncCond algorithm when irradiation varies rapidly.

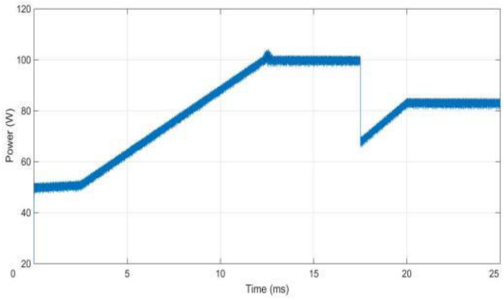

Fig.15 PV's output power with proposed algorithm when irradiation changes

Fig.15 shows the output power of PV cell. According to the result, proposed MPPT algorithm convergence speed is excellent when irradiation varies from time(ms) 15 to time 20. That means the proposed MPPT algorithm can track to the fresh MPP fastly in 5ms which makes it proper to irradiation varies fast circumstance.

Table.5 Theoretical V_{MPP} , I_{MPP} and P_{MPP} of PV cell

Case No.	G (W/m^2)	T (℃)	V_{MPP} (V)	I_{MPP} (A)	P_{MPP} (W)
1	1000	25	33.70	3.56	120.00
2	1000	30	33.72	3.57	120.38
3	2000	25	35.31	7.06	249.29
4	2000	30	35.77	7.11	254.32
5	3000	30	35.84	10.66	382.05
6	3000	40	36.72	10.74	394.37
7	400	30	36.18	14.17	512.67
8	4000	40	36.36	14.27	518.86
9	5000	35	36.09	17.82	643.12

10	5000	45	37.31	17.93	668.97

Table.6 V_{MPP} , I_{MPP} and P_{MPP} of PV cell with IncCond algorithm

Case No.	G (W/m^2)	T (℃)	V_{MPP} (V)	I_{MPP} (A)	P_{MPP} (W)
1	1000	25	32.77	3.47	113.71
2	1000	30	32.90	3.57	117.45
3	2000	25	32.87	6.88	226.15
4	2000	30	33.80	6.94	234.57
5	3000	30	34.04	10.30	350.61
6	3000	40	34.75	10.43	362.44
7	400	30	34.59	13.18	455.90
8	4000	40	35.11	13.71	481.36
9	5000	35	35.78	17.19	615.06
10	5000	45	36.03	17.77	640.25

Table.7 V_{MPP} , I_{MPP} and P_{MPP} of PV cell with proposed algorithm

Case No.	G (W/m^2)	T (℃)	V_{MPP} (V)	I_{MPP} (A)	P_{MPP} (W)
1	1000	25	33.67	3.56	119.87
2	1000	30	33.70	3.57	120.31
3	2000	25	35.01	6.93	242.62
4	2000	30	35.62	7.07	251.83
5	3000	30	36.03	10.37	373.63
6	3000	40	36.76	10.46	384.51
7	400	30	36.31	13.92	505.44
8	4000	40	36.87	13.98	515.44
9	5000	35	36.43	17.41	634.25
10	5000	45	37.11	17.98	667.24

Table.5-7 are data recorded of PV cells respectively under different irradiation and temperature circumstance. These three tables show IncCond method and proposed MPPT method's efficiency and also the data are compared to the theoretical value of PV cell. The data tells that PV cells with proposed algorithm outputs more power than IncCond algorithm.

6 Conclusion

The proposed MPPT algorithm fluctuates less near PV's MPP when the irradiation varies rapidly. Simulation result in Fig.15 shows the proposed MPPT algorithm respond to irradiation change fast. When irradiation varies, proposed MPPT algorithm takes less time to track the new MPP. For the condition of rapidly changing solar radiation, the proposed MPPT algorithm will be very useful.

Acknowledgments

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