Exploration of Partial Shading Condition in Photovoltaic Array

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Abstract **Photovoltaic (PV) power generation is the most promising renewable energy source. Photovoltaic module has dynamic characteristics with respect to irradiance and temperature. To extract maximum power from PV module maximum power point tracking algorithms are used. These algorithms are trained according to dynamic characteristics of PV module. Array of Photovoltaic modules has distinct behavior than a single PV module under partial shading condition. PV array characteristics has multiple peaks under partial shading condition and maximum power point algorithms are need to trained to find peak with maximum power. Examination of PV array characteristics under normal irradiance and under partial shading is essential to extract maximum power from PV array. This paper explores various traits of Photovoltaic array under partial shading condition and proposes a model to select region on array characteristics for tracking global maximum power point.**

Keywords Photovoltaic Array, Partial shading condition, global MPP , local MPP , shading patterns

I. INTRODUCTION

Photovoltaic (PV) systems are foremost solution for current energy crisis. Photovoltaic system convert sunlight in to electricity. Prime element of PV system is PV cell. Cluster of PV cells is a PV panel. Series parallel connection of PV panels forms a PV array for achieving desired electricity demand. PV devices have nonlinear I-V characteristic and this become more erratic with dynamic irradiance level and temperature. Maximum power point (MPP) is point on I-V curve at which maximum power can be drown from PV panel. Maximum power point tracking (MPPT) algorithms are used to track the MPP on I-V curve [1]. Hill climbing, Incremental conductance, perturb and observe (P&O), Fractional open circuit , Fractional short circuit current are well known conventional MPPT algorithms. Fuzzy Logic control, Neural Network , Particle swarm optimization , Artificial bee colony are Artificial Intelligence based MPPT algorithms [2-4] .All these algorithms are trained to track one MPP on I-V curve. When all PV panels of a PV array have uniform irradiance then it has one MPP on I-V characteristics like PV panel characteristics however PV array has distinct characteristics than PV panel under Partial shading condition (PSC). When some panels of PV array comes under shading and get less irradiance than other PV panels is called as Partial shading condition. Shaded panels act as load instead of generating power and there is power loss. Shaded panels take power generated by unshaded panels and this may permanently damage the shaded PV panels. Bypass diodes are connected in parallel with PV panel. Bypass diodes are used to bypass the current generated from shaded panels and thus mitigates effect of partial shading condition. Bypass diodes makes the P-V and I-V characteristics of PV array distinct than PV panel and it make multiple peaks on it. Under partial shading condition there are many local maximum power points and one global maximum power point are present on P-V characteristics. Conventional MPPT algorithms get trapped at local peak and causes significant power loss. [5]. Algorithms like particle swarm optimization (PSO), Artificial Neural Network (ANN) are competent track the global MPP (GMPP) [6-8]. Detection of partial shading condition followed by improved incremental conductance and improved P & O algorithms are applied to track the GMPP [9-10]. Extremism seeking control (ESC) method [11] and three scanning and storing technique [12] are segment based search methods to track the GMPP. Methods and Algorithms [6-12] are designed to track the GMPP without locating GMPP position and scan maximum area of PV curve. Shading patter affects position of GMPP on P-V characteristics. Prediction of GMPP position can reduce the tracking area thus increases tracking speed and tracking efficiency. Here investigation of different shading patterns under varied irradiance is done to predict GMPP position.

II. CHARACTERISTICS OF PV ARRAY UNDER UNIFORM IRRADIANCE

PV array of six PV panels connected in series is used here for analysis of characteristics of PV array .Figure 1 shows a PV array with six PV panels and bypass diode in parallel with each PV panel. Table 1 gives the specification of PV panel used in this paper.

TABLE I. SPECIFICATION OF PV PANEL

Parameter	*Variable*	*Value*	*Unit*
Short Circuit Current	Isc	5.45	Ampere
Open Circuit Voltage	Voc	22.2	Volt
Current at Pmax	Impp	4.95	Ampere
Voltage at Pmax	Vmpp	17.2	Volt

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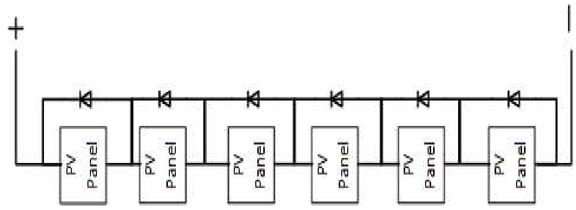

Fig. 1. PV Array of Six PV Panels

Maximum power point (MPP) is observed for five cases of Uniform irradiance as given in Table I. Perturb and observe (P&O) algorithm [2] is used to track the MPP on P-V curve .Power and voltage at tracked MPP is listed in Table I. As per Open circuit voltage method the relationship between open circuit voltage (Voc) & operating voltage (Vop) of PV-module at MPP, this relationship is given by equation 1

$$Vop = K1 * Voc \tag{1}$$

In this equation K1 is a proportional constant and it is depend on the characteristics of the PV array. The factor K1 is about 0.76 (within ±2%) [2] [13-14]. Operating voltage of PV panel and PV array at MPP as per equation 1 is gives as

$$Vop\_panel = 0.76 * Voc = 0.76 * 22.2 = 16.872 \text{ volt} \tag{2}$$
$$Vop\_array = Ns * 0.76 * Voc = 6*0.76*22.2 = 101.232 \text{ volt}$$

P-V characteristics of PV array is examined with respect to six important point relevance to Vop of PV array . These six Vop Point are as follow

$$\begin{aligned} &P1 \text{ (Point 1)} = 20\% \text{ of } Vop\_array = 20.246 \text{ volt} \\ &P2 \text{ (Point 2)} = 40\% \text{ of } Vop\_array = 40.492 \text{ volt} \\ &P3 \text{ (Point 3)} = 60\% \text{ of } Vop\_array = 60.738 \text{ volt} \\ &P4 \text{ (Point 4)} = 80\% \text{ of } Vop\_array = 80.986 \text{ volt} \\ &P5 \text{ (Point 5)} = 100\% \text{ of } Vop\_array = 101.23 \text{ volt} \\ &P6 \text{ (Point 6)} = 120\% \text{ of } Vop\_array = 121.478 \text{ volt} \end{aligned} \tag{3}$$

TABLE II. UNIFORM IRRADIANCE CASES

Case	*Uniform Irradiance in W/M² at all PV Panels*	P_{MPP} *(watt)*	V_{MPP} *(volt)*
1	1000 W/m²	510.84	103.2
2	800 W/m²	410.63	102.91
3	600 W/m²	307.47	105.66
4	400 W/m²	198.35	108.38
5	200 W/m²	106.31	106.31

Observing figure 2 for maximum power point and from calculated values of Vmpp as given in Table I, it can be concluded that for uniform irradiance MPP lies between Vop point P4 to Vop point P6. For uniform irradiance the segment for MPP tracing can be defined between these two points.

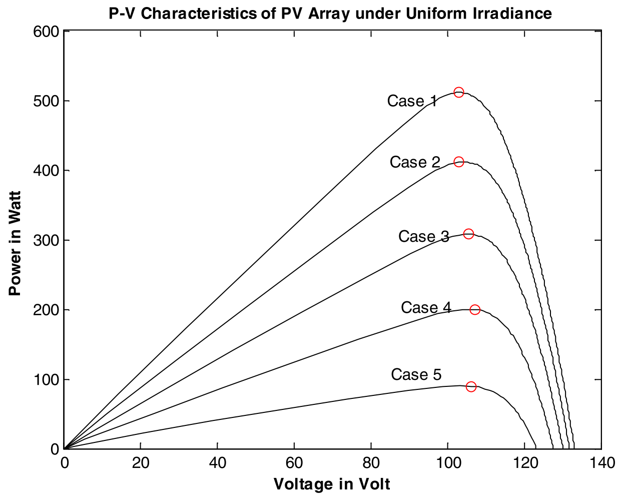

Fig. 2. P-V Characteristic of PV Array under Uniform Irradiance as per Table II

III. CHARACTERISTICS OF PV ARRAY UNDER PARTIAL SHADING CONDITION

In Partial shading condition (PSC) PV panels of PV array has distinct irradiance on it and thus it has multiple MPP. Maximum power point tracking algorithms has to track the global MPP (GMPP) to minimize the power losses under PSC. There can be any indecisive shading pattern and position of GMPP will be swing accordingly. Shading pattern are classified according to the irradiance level and irradiance difference among PV panels and grouped as below

- Shading pattern with high irradiance level and small irradiance difference among PV panels
- Shading pattern with low irradiance level and small irradiance difference among PV panels
- Shading pattern with high irradiance level and large irradiance difference among PV panels
- Shading pattern with Low irradiance level and large irradiance difference among PV panels
- Shading pattern with random irradiance among PV panels

Here P-V characteristics of PV array are examined for all these shading patterns and it is correlated with six Vop Points.

A. Shading Pattern with High Irradiance Level and Small Irradiance Difference among PV panels

Four cases of shading pattern with high irradiance level with small irradiance difference among PV panels are listed in Table III. Figure 3 is a plot P-V characteristics for cases in Table III and Table IV gives the Power at six Vop points with respect to each shading Pattern given in Table III .

TABLE III. SHADING PATTERN WITH HIGH IRRADIANCE LEVEL AND SMALL IRRADIANCE DIFFERENCE AMONG PV PANELS

Case	*Irradiance in W/M² at PV Panels*					
	Panel1	Panel 2	Panel3	Panel 4	Panel 5	Panel 6
6	1000	1000	1000	900	900	900
7	1000	1000	900	900	800	800
8	900	900	800	800	700	700
9	700	700	600	600	900	900

TABLE IV. POWER OF PV ARRAY WITH RESPECT TO VOP POINTS FOR CASE 6 TO CASE 9

Case	*Power in watt at Vop points*					
	P1	P2	P3	P 4	P 5	P 6
6	112.55	215.75	300.56	388.83	474.48	308.39
7	110.06	201.18	292.58	350.91	426.55	291.52
8	98.72	177.09	258.84	307.15	371.27	259.34
9	100.94	153.79	225.94	262.93	318.40	231.59

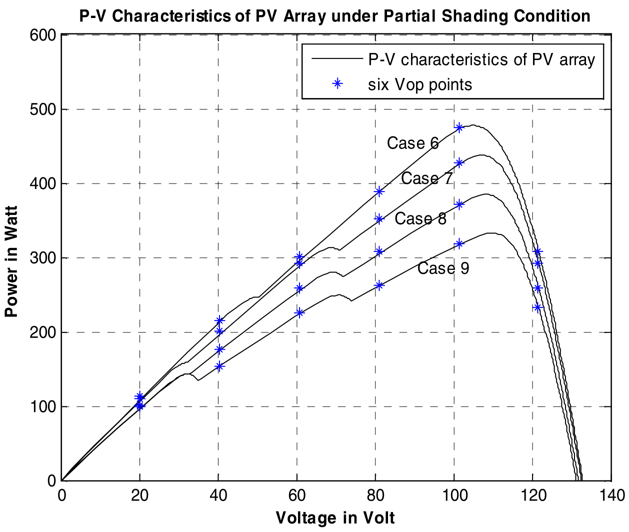

Fig. 3. P-V Characteristic of PV Array under Partial Shading Condition as per Table III

As per the observation of figure 3, global maximum power point (GMPP) is present on the region between Vop point P5 and P6 for cases 6 to 9 .

B. *Shading Pattern with Low Irradiance Level and Small Irradiance Diffe rence among PV panels*

Three cases of shading pattern with low irradiance level with small irradiance difference among PV panels is listed in Table V. Figure 4 is a plot P-V characteristics and Table VI gives the Power at six Vop points with respect to each shading Pattern for cases in Table V. As per observation of figure 4, global maximum power point is present on the region between Vop point P5 and P6 for cases 10 to 12.

TABLE V. SHADING PATTERN WITH LOW IRRADIANCE LEVEL AND SMALL IRRADIANCE DIFFERENCE AMONG PV PANELS

Case	*Irradiance in W/M² at PV Panels*					
	Panel1	Panel 2	Panel3	Panel 4	Panel 5	Panel 6
10	400	400	400	500	500	500
11	500	500	400	400	300	300
12	200	200	300	300	400	400

TABLE VI. POWER OF PV ARRAY WITH RESPECT TO VOP POINTS FOR CASE 10 TO 12

Case	*Power in watt at Vop points*					
	P1	P2	P3	P 4	P 5	P 6
10	56.06	105.56	129.54	134.73	153.75	108.41
11	54.36	87.72	125.67	133.80	153.61	103.53
12	43.00	64.27	92.10	89.018	98.78	55.93

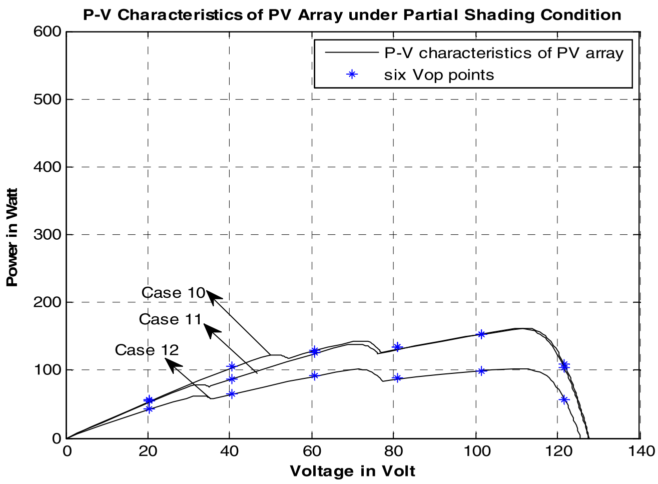

Fig. 4. P-V Characteristic of PV Array under Partial Shading Condition as per Table V

C. *Shading Pattern with High Irradiance Level and Large Irradiance Difference among PV panels*

Four cases of shading pattern with high irradiance level with large irradiance difference are listed in Table VII. Figure 5 is a plot P-V characteristics for cases in Table VII and Table VIII gives the Power at six Vop points with respect to each shading Pattern .

TABLE VII. SHADING PATTERN WITH HIGH IRRADIANCE LEVEL AND LARGE IRRADIANCE DIFFERENCE AMONG PV PANELS

Case	*Irradiance in W/M² at PV Panels*					
	Panel1	Panel 2	Panel3	Panel 4	Panel 5	Panel 6
13	1000	1000	800	800	400	400
14	1000	1000	900	900	400	400
15	1000	100	700	700	400	400
16	800	800	800	800	400	400

TABLE VIII. POWER OF PV ARRAY WITH RESPECT TO VOP POINTS FOR CASE 13 TO 16

Case	*Power in watt at Vop points*					
	P1	P2	P3	P 4	P 5	P 6
13	112.09	177.56	258.59	178.62	211.61	194.71
14	110.06	200.49	293.56	177.82	211.03	200.19
15	109.21	152.58	225.02	167.33	210.42	188.81
16	86.50	175.17	253.89	175.24	209.96	185.22

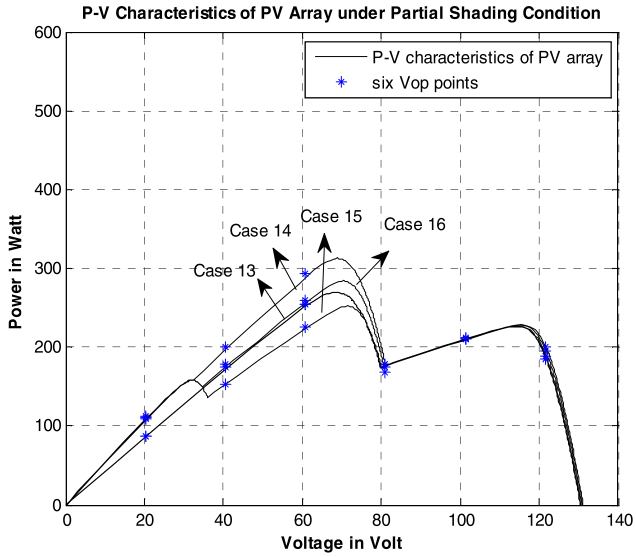

Fig. 5. P-V Characteristic of PV Array under Partial Shading Condition as per Table VII

As per observation of figure 5, global maximum power point is present on the region between Vop point P3 and P4 for cases 13 to 16.

D. Shading Pattern with Low Irradiance Level and Large Irradiance Difference among PV panels

Three cases of shading pattern with low irradiance level with large irradiance difference among PV panels are listed in Table IX. Figure 6 is a plot P-V characteristics and Table X gives the Power at six Vop points with respect to each shading Pattern for cases in Table IX .

TABLE IX. SHADING PATTERN WITH LOW IRRADIANCE LEVEL AND LARGE IRRADIANCE DIFFERENCE AMONG PV PANELS

Case	*Irradiance in W/M^2 at PV Panels*					
	Panel1	Panel 2	Panel3	Panel 4	Panel 5	Panel 6
17	600	600	600	300	300	300
18	600	600	600	200	200	200
19	500	500	500	100	100	100

As per observation of figure 6, global maximum power point is present on the region between Vop point P2 and P3 for cases 17 to 19.

TABLE X. POWER OF PV ARRAY WITH RESPECT TO VOP POINTS FOR CASE 17 TO 19

Case	*Power in watt at Vop points*					
	P1	P2	P3	P 4	P 5	P 6
17	65.71	127.17	99.30	127.60	151.78	110.6
18	64.65	128.55	68.94	83.48	97.11	68.98
19	53.74	104.90	43.77	39.29	41.99	13.93

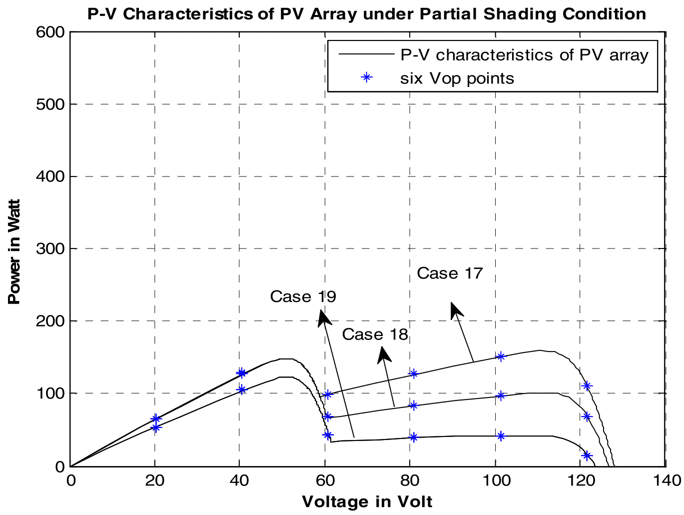

Fig. 6. P-V Characteristic of PV Array under Partial Shading Condition as per Table IX

E. Shading Pattern with Random Irradiance Level

Two cases of shading pattern with high irradiance level with small irradiance difference is listed in Table XI. Figure 7 is a plot P-V characteristics for cases in Table XI and Table XII gives the Power at six Vop points with respect to each shading Pattern given in Table XI .

TABLE XI. SHADING PATTERN WITH RANDOM IRRADIANCE LEVEL

Case	*Irradiance in W/M^2 at PV Panels*					
	Panel1	Panel 2	Panel3	Panel 4	Panel 5	Panel 6
20	1000	800	600	400	300	100
21	1000	300	900	500	700	200

TABLE XII. POWER OF PV ARRAY WITH RESPECT TO VOP POINTS FOR CASE 20 AND CASE 21

Case	*Power in watt at Vop points*					
	P1	P2	P3	P 4	P 5	P 6
20	91.39	134.00	132.41	129.38	119.00	46.68
21	102.17	152.94	163.59	131.75	128.19	105.24

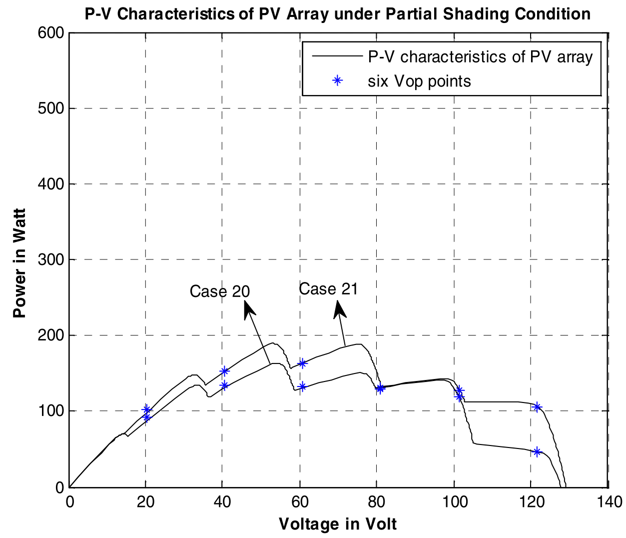

Fig. 7. P-V Characteristic of PV Array under Partial Shading Condition as per Table XI

As per observation of figure 7 , global maximum power point is present on the region between Vop point P2 and P3 and region between P3 and P4 for cases 20 & 21.

IV. PROPOSED SIX VOP POINT MODEL TO DEFINE SEARCH REGION FOR GMPP

In [13][14] 0.8Voc model is used to predict GMPP position . In [14] GMPP position is predicted based on equation which includes variable based on irradiance. In [15] partial shading is detected based on array voltage, current and irradiance. Irradiance sensing makes the system expensive. Here simple and inexpensive six Vop point model is proposed to locate region for GMPP tracking.

Various shaded patterns are examined in previous section and power at six Vop points are observed for these patterns. For uniform irradiance Operating voltage (Vop) is in the neighborhood of 0.76*Voc but it is not applicable to partial shading condition. Under high and low irradiance level if irradiance difference is large then GMPP shift to the right side of 0.76*Voc.

As per the observation of power at six Vop points for various partial shading conditions, GMPP lies in the region between Vop points. Region for GMPP tracking can be located by comparing power at Vop points.

F. Six Vop point s model to locate region for GMPP tracking.

- Step1: Calculate operating voltage of PV array as per eq. 1 and eq.2 .
- Step2: Calculate Voltage for six Vop points as per eq.3
- Step 3: Set the reference voltage according to six Vop points.
- Step4: calculate power at six Vop points
- Step 5: Compare the powers at these points as per algorithm given in fig. 8 to locate region for GMPP tracking.

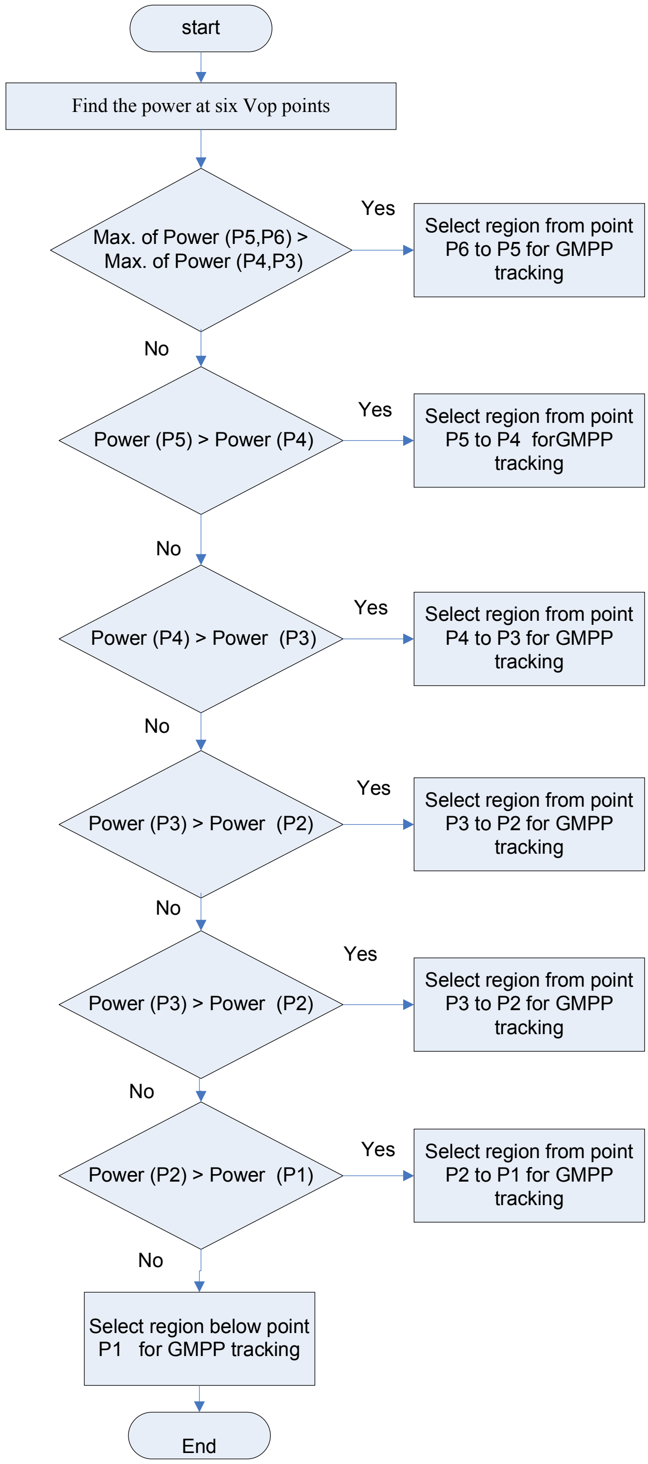

Fig. 8. Algorithm to select region for GMPP tracking

V. Conclusion

Examination of PV array response is done for 5 uniform irradiance conditions and 16 partial shading conditions. GMPP position is observed for various shading patterns. Six Vop points are estimated based on operating voltage (Vop) of PV array. Power at these Vop points is examined for all partial shading condition. Region for GMPP tracking can be estimated by comparing power at Vop points. Estimating region for GMPP tracking will reduce search space hence increases tracking speed and increases tracking efficiency of MPPT algorithm. An adaptive algorithm can be used with six Vop point model for tracking GMPP.

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