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# Improved perturb and observe maximum peak power tracking for solar satellite systems

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**Abstract.** The aim of this work is to solve partial shading problem in solar panels to detect the global peak power point that can be used in satellite systems. This can be done by proposing a modified perturb and observe control algorithm depends on comparing all the local peak power points in photovoltaic system to detect the global one, by making initial estimation to the duty cycles of the corresponding local peak power then using perturb and observe to make fine tuning to reach the exact local peak points when oscillations happen. Also to detect the oscillations theory of operation of incremental conductance algorithm is used depending on the difference between incremental conductance and the instantaneous conductance values. The idea of operation is verified using boost converter applied in Matlab/Simulink showing good results. Also variable duty cycle is used to solve the problem of oscillations in output power.

## 1. Introduction

Photovoltaic systems are applied in street lighting, load power supply and satellites power systems, where CubeSats are small satellites sorted by standard size and weight for volume of 1U its size is about 10x10x10 cm, power not greater than 2.5 Watts, increasing up to 20 U[1]and[2]. CubeSat's subsystems consist of attitude determination and control (ADCS), communication control and data handling (C&DH) and electrical power supply (EPS). [2], [3] and [4]. Electric power system function is to supply the satellite the power it needs to do its mission and keep working. EPS is divided into four units, Solar Power Unit, Power Conditioning Unit, power storage and Power Distribution Unit. The solar power produces the required electric power where to change it to the necessitated bus voltage the power conditioning unit is used then to change it to the various voltage levels of the satellite subsystems the role of power distributions come here. Also power storage contains batteries used to generate power in case of eclipse periods and it is recharged by battery charger during sunlight periods by battery charger. In space the solar power intensity is about 1366 w/m<sup>2</sup>, so it is required 1m<sup>2</sup> area of solar panel to generate 1366 watt according to the American society for testing and materials at 1 astronomical unit [5] and [4]. There is only one point on power voltage curve works on maximum power called MPP (maximum power point). This point varies with temperature and irradiance change. there should be a technique to be used to track the maximum power[6]. First direct energy transfer where unused power is dissipated through shunt resistors to avoid internal dissipation, second MPPT (maximum peak power tracker), it extracts exact power a load requires up to the array's peak power so it is non-dissipative system better than direct energy transfer. We used here MPPT method with a dc-dc converter controlling its duty cycle by peak power tracking algorithm to match



the load resistance with the source one. So when irradiance and temperature change, features of photovoltaic system changes as a result the duty cycle should vary to match the source impedance to work at peak power. Many methods are used to track the peak power, first Indirect methods where they work on preset calculations of the operating points for the position of maximum power point with use of database of PV panels, like open circuit voltage coefficient, look up table and curve fitting method. Second direct methods where it always takes immediately voltage and current values to calculate MPP like perturb and observe, incremental conductance, fuzzy logic control and sliding mode control [7], [8], and [9]. In [10] artificial neural network is used, this method is precise, but needs fast processors to be applied physically or it will run slowly, In [15] a good enhanced P&O method using maximum power trapezium, for partial shading containing all GMPPs but this method is complicated and is used when connecting the load to the grid using inverter. In [11] and [12] partial shading problem hasn't been solved, so the proposed method can solve the partial shading problem with straightforward method with short time and simplicity.

## 2. PV MODEL

### 2.1. Equivalent circuit and mathematical model of PV

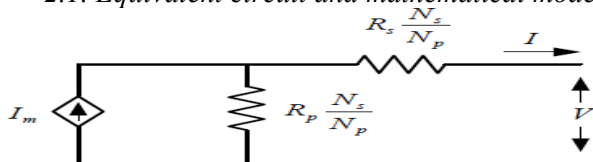


Figure 1. Equivalent circuit of PV module [10].

To attain the desired output power solar cells are connected in series and parallel, the array parallel and series resistances are  $R_p, R_s$  while  $N_s, N_p$  are the number of series and parallel modules respectively, the voltage and current output of the array are  $V, I$  and the module current is  $I_m$ . Fig.1 displays model of photovoltaic module.[10][13] and [14].  $I_m$ , is achieved from the following equation.

$$I_m = I_{pv}N_p - I_oN_p \left[ \exp \left[ \frac{V + IR_s \left( \frac{N_s}{N_p} \right)}{V_t a N_s} \right] - 1 \right] \quad (1)$$

$$V_t = \frac{N_{cs}KT}{q} \quad (2)$$

$V_t$ : Thermal voltage of the array,  $A$  is diode ideality factor,  $N_{cs}$  is the number of cells connected in series,  $k$  is the Boltzmann constant  $= 1.3806503 \times 10^{-23}$  J/K,  $q$  is the electron charge  $= 1.60217646 \times 10^{-19}$  C,  $I_{pv}$  is the photovoltaic current as in equation

$$I_{pv} = (I_{pvn} + K_i \Delta T) \frac{G}{G_n} \quad (3)$$

Where  $I_{pvn}, G_n$  are photovoltaic current and irradiance at standard test conditions,  $K_i$ : current temperature coefficient.  $G$ : Irradiance. The reverse leakage current of the diode is  $I_o$  and can be calculated from

$$I_o = \frac{I_{scn} + K_i \Delta T}{\exp \left( \frac{V_{ocn} + K_v \Delta T}{a V_t} \right) - 1} \quad (4)$$

$V_{ocn}, I_{scn}$ , are open circuit voltage and short circuit current at nominal conditions,  $T$  is the variance between actual and nominal temperature in kelvins, the voltage temperature coefficients is  $K_v$ . [10]

### 2.2. PV MODEL simulation

Matlab/ Simulink is used to model the PV mathematical module. The PV system used is Triple-Junction Solar Cell for Space Applications (CTJ30) with boost converter as in table.

**Table 1.** Specifications for (CTJ30) PV solar cell average electrical output parameters @AM0, T=25°C.

parameter	value
Rated output power, $P_m$ (W)	1.2
Open circuit voltage, $V_{oc}$ (V)	2.61
Short circuit current, $I_{sc}$ (A)	0.538A
Current at the maximum power point, $I_{mp}$ (I)	0.517 A
Voltage at the maximum power point, $V_{mp}$ (V)	2.33 volt

**Table 2.** Parameters of boost converter.

parameter	value
Input capacitor, $C_{in}(\mu f)$	47
Output capacitor, $C_o$ ( $\mu f$ )	70
Inductance, $L$ (mH)	3
Switching frequency, $f$ (kHz)	5
Input capacitor, $C_{in}(\mu f)$	47

### 2.3. Irradiation and Temperature effect on PV system

At constant temperature, increasing irradiance causes current to increase whenever voltage increase is small. So higher irradiance results in higher maximum power. With constant irradiance current increases or decreases slightly with temperature depending on the physics of the module [15], but voltage decreases, so the power decreases too. PV systems have nonlinear relations depending on the changes of environment of temperature and irradiance. [16] Fig 2 shows the effect of changing temperature and solar irradiance on PV's output power. [10] [17].

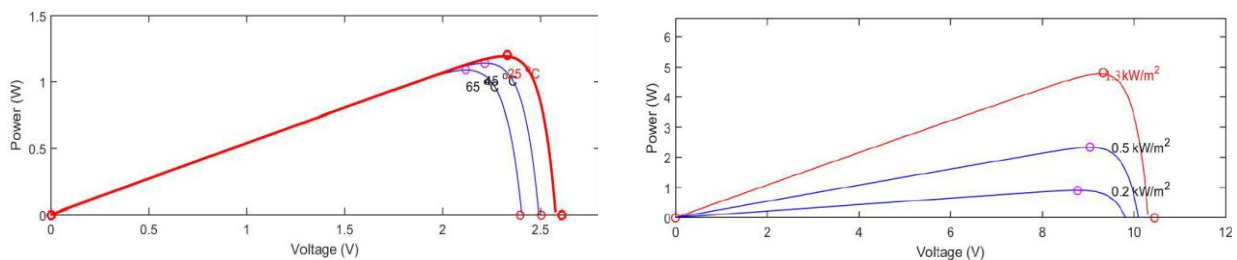


Fig. 2(a) Effect of temperature changes on P-V curves

(b) Effect of solar irradiance changes on P-V curves.

### 3. Cubesat

CubeSats are usually placed in low earth orbit with a distance from 160 km up to 2000 km in an altitude. Period of one orbit increases as the distance the satellite placed increases. This can be detected by Kepler's third law:

$$T^2 = \frac{4\pi^2 R^3}{\mu} \quad (5)$$

$R$  is the distance between centers of Earth and mass of the satellite,  $\mu$  is the gravitational constant for the Earth =  $3.986 \times 10^5 \text{ km}^3/\text{s}^2$ . [21] So the average satellite orbit time is 100 min with 65 min exposed to the sunlight and 35 min in eclipse. For better performance of the satellite cells are placed in

parallel than in series, but we use series to get higher voltage. The power achieved from the solar cell depends on the angle of incident light which is the angle between the light source and solar cell where this angle is changing with the rotation of the satellite and its position to the sun, affecting the performance of solar cells by effectively lowering the total irradiance [18] following the cosine law as in equation:

$$E_s = E_o \cos \theta \quad (6)$$

Where,  $E_s$  is the irradiance fallen onto the solar cell,  $\theta$  is the incidence angle between light source and solar cell, and  $E_o$  is the solar constant which is the power density produced by the sun measured once it reaches earth varying from 1331 to 1423 W/m<sup>2</sup>. [20] Small satellites have few years mission timeline as a result, they operate in LEO (low earth orbit), to reduce the risk of system failure. [19] Incidence angle and Temperature are constantly changing throughout an orbit while radiation causes a constant slow decline. According to the radiation behaviour, when one face of cubesat receives energy the opposite face does not. [21]

#### 4. Dc-Dc converters

DC-DC converter is used to convert the unregulated dc input voltage into a controlled dc output at the required voltage level. By controlling the duty ratio of the converter, the average output voltage can be achieved. [22] buck, boost, buck-boost converter and sepic converters are used in PV systems, since boost converter has the ability of tracking maximum power from the PV array for all solar insolation [23], it has higher sensitivity to variation in duty ratio compared to buck and buck-boost converter [24] also buck converter has lower efficiency than boost but buck-boost has the greater mass ratio, so we used here boost converter. [8]

##### 4.1. Boost converter model

By storing energy in the inductor when closing the switch made step up for input voltage where the output voltage is the sum of the inductor voltage and the input voltage, as closing time of the switch increase the higher output voltage is achieved, equivalent circuit of boost converter is in [25]

The relation between output and input voltage is

$$V_{out} = \frac{V_{in}}{1-D} \quad (7)$$

Where D is the duty ratio, the peak-to-peak inductor current ripple  $\Delta I$  is given by

$$\Delta I_L = \frac{V_{in} D}{f_s L} \quad (8)$$

Also  $\Delta V_o$  is the output capacitor voltage ripple

$$\Delta V_c = \Delta V_{out} = \frac{I_o D}{f_s C} \quad (9)$$

To get the value of the inductance [26]

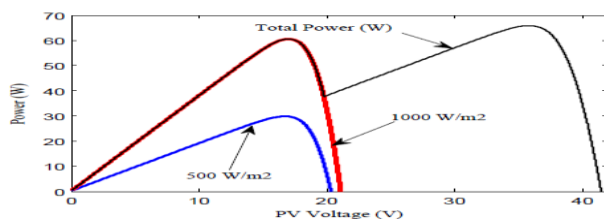
$$\Delta I_L = (0.2 \text{ to } 0.4) I_{out(max)} \left( \frac{V_{out}}{V_{in}} \right) \quad (10)$$

Note that the average inductor current will reach its maximum at D=0.5 and the output current will reach its maximum at D=0.33 [22] parameters calculations of boost converter with an approximation is done in table 2. Maximum Power is transferred to load if load line intersects with  $V_{mpp}$  and  $I_{mpp}$  on I-V characteristics of PV cell, dc-dc converter are seen as a load [9] the load should be in the range of  $1.234R_{mp} < R_L < 100R_{mp}$ .

#### 5. Partial shading

To get the desired power PV systems are connected in series for larger voltage and in parallel for larger current, at partial shading modules in the same string will conduct the same current but different voltages [15] if some of these series modules exposed to a lower radiation than others, and as in series the higher radiation modules current will pass in the lower radiation it will cause the voltage terminal of the shaded cells to reverse and act as a load to the unshaded cells. This will increase the shaded cell temperature and may be destroyed causes hotspot. To overcome these phenomena a bypass diode is connected parallel to the cells or a group of series cells so as at partial shading when the voltage is

reversed the bypass diode will be forward biased and the power generated from unshaded cells will pass through the diode. Note that in case of partial shading the total power of the array is lower than the rated power of the individual modules and due to bypass diodes there will be more than one peak power point called local maximum points and only one of them is the global maximum and number of these maximum points is equal to the number of bypass diodes [28][29],[9] a blocking diode can be used in the string to prevent negative current, note that putting a dc-dc converter in each module with MPPT will cause more power switching losses and high cost.[4][15] In Fig. 3 Two series PV cells one is  $1000 \text{ w/m}^2$  and the other is  $500 \text{ w/m}^2$ .



**Figure 3.** The relation between output power and terminal voltage for two series PV cells with bypass diodes. [6]

the power output for shaded PV cells with bypass diodes have local MPPs counting on the number of shaded PV cells and the strength of the shade, conventional algorithms lost in local maximum peak power so modified algorithms are used to search for the only global peak power.[6] If a part of an array is shadowed by cubesat antenna ,deployable panels or other satellite equipment , the voltage-power curve of the array will vary significantly and there will be as many peaks in the curve as the number of radiations[27]

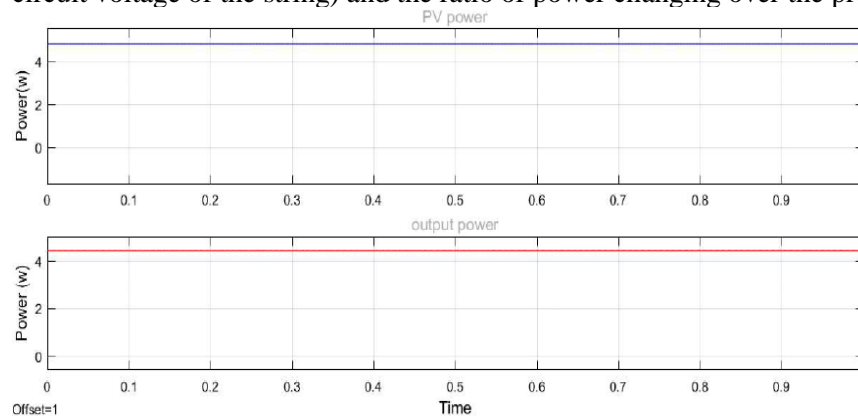
## 6. Perturb & Observe Algorithm

For a given temperature and irradiance PV system has a maximum power point when the load line crosses this point maximum power is achieved, when temperature and irradiance changes maximum power point changes while load line is the same so it doesn't cross the maximum power point so the load line should be transferred to operate at maximum power point this can be achieved by changing the duty cycle of the dc-dc converter [9]This method depends on perturbing the voltage in a specific direction and observing the power if power increase it keeps perturbing in the same direction if not changing perturbation in the opposite direction, if by increasing voltage power increases then the operating point is on the left of MPP otherwise it is on the right. So perturbing will continue until maximum power point is reached and start to oscillate around it. perturbation is done by changing the duty cycle ratio, large step size reaching maximum power point faster but more oscillations, on the other hand small step size results in lower oscillations but more time to reach maximum peak power so an optimization of step size is determined to get the best results for oscillations and time of reaching maximum power. The flow chart of this method is in [24], P&O method can fail under rapidly changing atmospheric conditions, starting from specific operating point with atmospheric conditions are approximately constant, a perturbation  $V$  in the PV voltage will bring to other operating point, and perturbation will be reversed if there is decrease in the power. But if in that moment the irradiance increases that shift the power curve within one sampling period, the operating point will move to wrong point representing increase in power and perturbation is kept same. Afterward operating point will diverges from the MPP and will keep diverging if irradiance is steadily increases. We can make a small modification on P&O to solve the problem of oscillations as in many papers, when the power reaches its peak value we reduce the step size to reduce oscillations achieving smooth output like in Fig. 4. If we have a cubesat with four faces with 1 solar panel on each face, each solar panel consists of four solar cells connected in series to get 9.32 volt and 4.8 watt of type Triple-Junction Solar Cell for Space Applications (CTJ30) as in datasheet [33] which is used in cubesat solar panels for endurosat company[34].For one solar panel attain all the power requirements of the cubesat [5] taking a case study for feeding 11 volt bus voltage with a bypass diode on each cell and a battery with 11 volt is connected in parallel with the bus to fix the bus voltage and one orbit time is 100 minutes taking 10 second as a scale, so if four different irradiance are exposed on each cell  $1366 \text{ w/m}^2$ ,  $700 \text{ w/m}^2$ ,  $450 \text{ w/m}^2$  and  $200 \text{ w/m}^2$  so there are four maximum power points ,one of them is the global maximum, by applying conventional perturb and observe the algorithm will stuck in one of the local

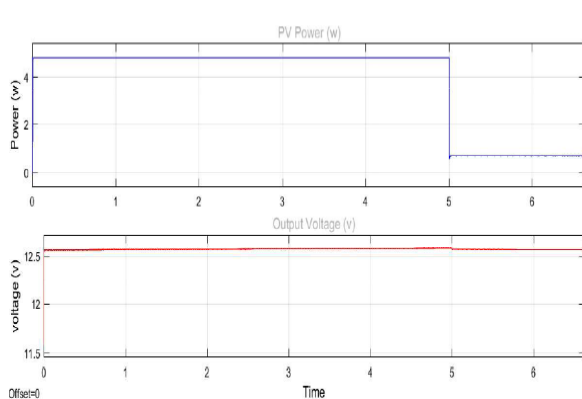
peaks and will not achieve the peak one as in fig.5 . First the system works on full irradiation at 1367 w/m<sup>2</sup> then after 3 seconds the irradiance change causing partial shading. Here the output power is 0.7 watt which is a local peak.

## 7. PROPOSED METHOD

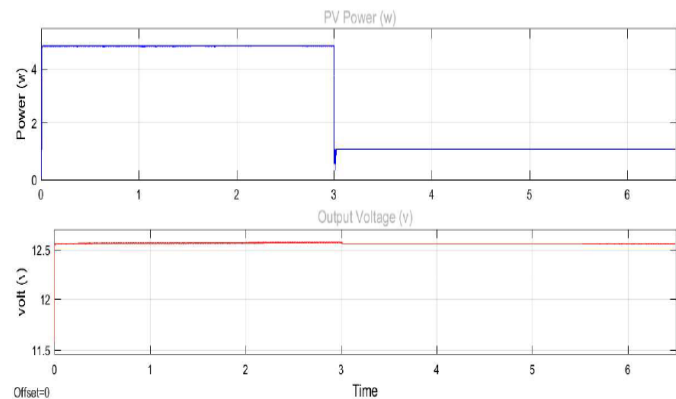
Before applying partial shading algorithm we have to detect first if there is sudden irradiance change, this can be done by putting two conditions as in [3] where if change in voltage is less than 0.005 (open circuit voltage of the string) and the ratio of power changing over the previous power is larger than



**Figure 4.** PV power and Boost converter output power using perturb and observe maximum peak power tracker



**Figure 5.** PV power and output voltage with partial shading with conventional Perturb & Observe



**Figure 6.** PV power and output voltage with partial shading with the proposed algorithm

0.1, so if both is true a large power divergence exists, explaining sudden irradiance change. To overcome this problem a variable step size should be used proportional to the changing rate of irradiance, for large irradiance change large step size is used and then reduced when reaching maximum peak power, also the other problem of this method is tracking local maxima under partial shading, since the voltage at maximum power occurs at 0.78 to 0.85 of open circuit voltage, so there is no maximum power at voltage greater than  $0.9V_{oc}$  so the upper limit for tracking maximum power doesn't exceed this limit and the lower limit shouldn't be less than the voltage occurs at irradiance=100w/m<sup>2</sup> and temperature = 75° c, note that when irradiance decreases and temperature increase the ratio decreases , also the value of voltage at maximum power over temperature range of 25 -75 °C and irradiance from 200-1000 w/m<sup>2</sup> doesn't vary a lot [7][9][24][30], the number of bypass diodes is equal to the number of local maximum points where one of these points is the global one[15], as before we have four cells connected in series to form solar panel of one face of cubesat

with a bypass diode on each cell so there are four maximum power points one of them is the global maximum. Under normal operating conditions the maximum power voltage point of the panel is the sum of individuals maximum power voltage points of each cell [16],[15] so if for one cell  $V_{mpp} = 2.33\text{v}$ . For four cells connected in series  $V_{mpp} = 2.33 * 4 = 9.32\text{v}$  for one panel. As we said that we have 4 maximum local peak powers we can make a start estimation that these points occurs at maximum peak voltage of every cell = 2.33v, 4.66v, 6.99v and 9.32 volt, so we work on four initial duty cycles corresponding to these voltages with perturbation on each point till oscillations happened, storing four local peak powers with duty ratios corresponding to these points. Comparing them to get the global maximum peak power. To get faster performance, after making many simulations on different situations on partial shading with different irradiance values on each cell, the result obtained is that the local peak power points happened on certain voltage ranges shifted from the maximum voltage values, the average of these points in our case are 0.1 volt, 3.1 volt, 6.2 volt and 9.5 volt. So we can take these values as a first initial condition to detect faster the local peak points so as to get the global one in shorter time. From simulation it was found that the third point of 1.09 watt as in fig.6 was the global peak power. Before simulation we should detect first if there is partial shading or sudden irradiance then use the proposed algorithm to do so we first check if with conventional P&O the power reach mpp or not if yes we don't go to the partial shading detection algorithm if not we use it, to do so we compare the difference of output power from the maximum peak power after oscillation happens with a threshold value  $0.07 P_{mpp}$  at STC (standard test conditions) so if it is equal or smaller than this value no partial shading or low irradiance happens as in [11].  $|P_o - P_{mpp-stc}| \leq 0.07 P_{mpp-stc}$  (11)

If not then we go to the partial shading algorithm. We can control the range of operating voltage to reduce time in simulation the lower one which is not smaller than maximum power voltage at  $100\text{ w/m}^2$  with  $75^\circ\text{c}$  and higher one at 0.9 maximum power voltage, if we have four cells in series as in our case. Change in power, voltage and current will be negative only for a decrease in irradiance as shown in [31] note that when we take initial duty cycle to work on and when it reach the local peak value of power which it can be global peak, oscillations happen around this point, so to detect this oscillations we can use the idea of operation of incremental conductance algorithm as it gives better detection performance. [32]

### 7.1. idea of operation incremental conductance

Maximum power is reached when the differentiation of power with respect to voltage is equal to zero

$$\frac{dP}{dV} = V \frac{di}{dV} + i = 0, \quad \frac{di}{dv} + \frac{i}{V} = 0 \quad (12)$$

Where  $di/dv$  represents the incremental conductance and  $i/v$  represents the instantaneous conductance [32] so if we take this equation and compare it to a very small value we can detect the oscillations when it is happened then go to the next duty ratio and do the same thing. Figures 7,8 and 9 show the flow chart of the improved perturb and observe, after simulation we deduced that the global maximum point was reached is 1.06 watt with voltage is 6.53 volt which is greater than the local peak power from the conventional perturb and observe so this method is a combination of perturb and observe and incremental conductance.

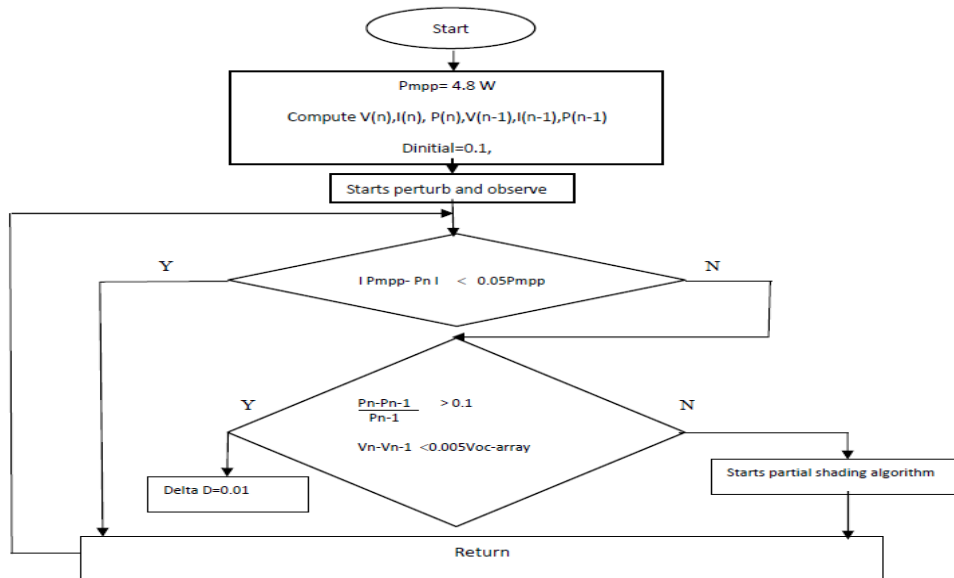
### 7.2. Advantage of the proposed method over others

So we can deduce that this method doesn't need to scan the whole voltage range so saving time also the modified P&O algorithm will not stuck in local peak point like the conventional P&O, this algorithm is simple and not complicated and doesn't need a lot of sensors.

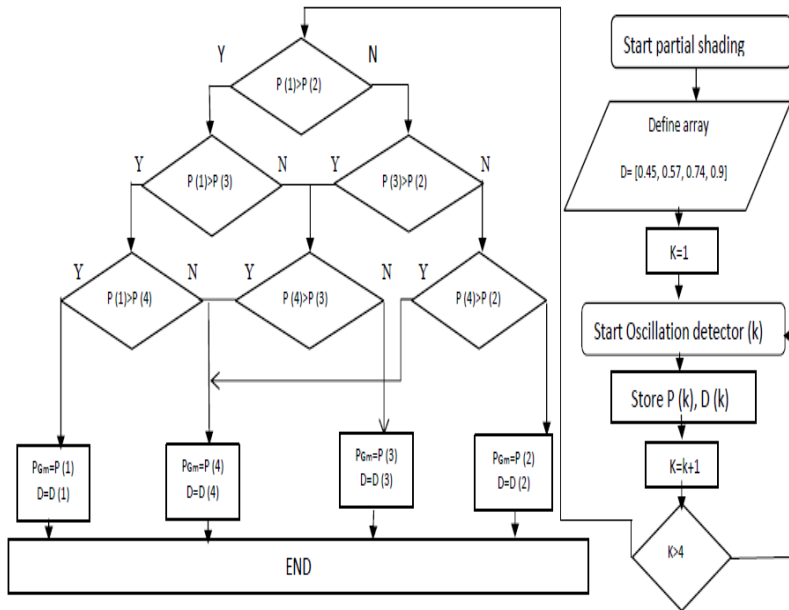


## 8. Conclusion

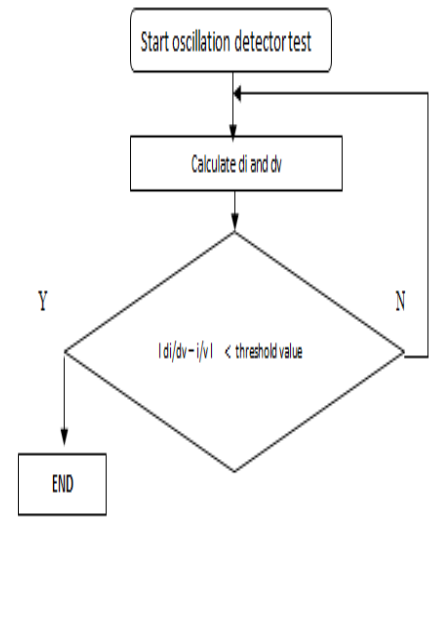
This paper presents a modification of perturb and observe to solve the problem of partial shading using boost converter, so by comparing the power of the local peak power points the global peak power can be detected so avoiding sweeping all the power range so saving time also avoiding sticking in local peak power like conventional perturb and observe, also the algorithm can detect the partial shading when it happens and an oscillation detector is used taking the idea of operation of incremental



**Figure 7.** proposed algorithm of maximum peak power tracking



**Figure 8.** In this case simply justify the caption so that it is as the same width as the graphic.



**Figure 9.** oscillation detector algorithm

conductance comparing it to threshold value to detect oscillation as fast as possible then reducing the duty cycle to avoid oscillations in output power. This method can be used in cubesat satellite systems.

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