Improvement inPower Efficiency of Photovoltaic ArrayUnder Shading Condition Using Bypass Diode

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Abstract- In this paper, we have studied and analyzed the shading effect on solar photo voltaic (SPV) modules connected in series using four 75 WSPV modules for three different shading conditions: (1) one module is fully shaded, (2) two modules are fully shaded and (3) three modules are fully shaded. The performance of the modules which decreased due to shading effectare improved in each case using bypass diodes connected in parallel with each of the modules. This analysis is done by using the simulation model in PSCAD and an outdoor experiment is also performed to validate the simulation results for the same configurations. An improvement in open circuit voltage (V_{oc}), short circuit current (I_{sc}), maximum power (P_{max}) and power efficiency are observed when bypass diodes are used.During an outdoor experiment when one panel is shaded the power efficiencies are17.96 % and 12.79 % with and without bypass diodes respectively. In case of two modules are shaded these values are 14.50 % and 9.63 % respectively. When three modules are shaded the power efficiency is 3.59 % in case of without bypass diode, which is increased to 6.87% with bypass diodes.

Keywords: Solar photovoltaic,irradiation, bypass diode, simulation, efficiency, PSCAD.

1. Introduction

The conventional energy resources, which are limited in quantity, are getting exhausted due to extensive use.This alsoenhances the rate of change inclimate rapidly. Today the world is looking for alternative energy resources. Renewable energy is the remedy to this situation. The solar photovoltaic (SPV) system is playing the key role in the renewable energy sector [2] [3].Since solar energy is available to the most part of the globe, it's suitable for the distributed energy system in which we can generate and employ the electric power with minimum transmission and distribution losses.Apart from this, a PV system can instantly convert the solar energy to electric energy without having any intermediate energy conversions.But PV system also suffers from different types of faults which reduce performance of the PV system. Two major types of faults are incorporated in PV systems- Non recoverable faults and recoverable faults [7]. Non recoverable faults take placedue to micro-cracks, PV degradation and breaking of solar panels. In this type of faults, the PV cells or modules need to be replaced. Recoverable faults arecaused by dust or any type of shading due to cloud or tree [8]. Theincrease in temperature of PV panels also reduces the efficiency of the system. Another type of fault associated with PV system is ground fault. A ground fault is the condition where the current flowing through the grounding conductor. The cause of this fault is a short circuit between a current-carrying conductor in the PV system and the equipment grounding conductor. These faults degrade the performance of the SPV connected in an array and also reduces the overall power efficiency [9] [10].When we come into a PV system connected in an array, suffer from unavoidable shading which reduces its efficiency below an unacceptable degree. In this paper, we have demonstrated the analysis of the decrement in power efficiency of the solar photovoltaic arrays connected in series due to shading effect and also provided a preventive solution using bypass diodes which increase overall power efficiency [13]. The analysis and solution both were done by simulation using PSCAD and experimentally in real time environment [4].

2.Solar Photovoltaic (SPV) Model

Two diodes model of a solar cell is defined by Fig. 1 [12] [14].

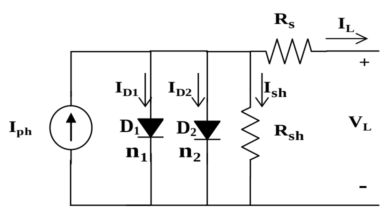


Fig.1. Two diodes model representation of a typical solar cell

$$I_L = I_{Ph} - I_{D1} - I_{D2} - I_{sh} \qquad \text{.......................(1)}$$

I_L **:** Terminal Current,

I_{Ph} **:** Photocurrent,

I_{D1} **:** First diode current,

I_{D2} **:** Second diode current,

I_{sh} **:** Shunt resistor current.

Two diodes currents are represented by Shocley equation as expressed in Eqs (2) and (3).

$$I_{D1} = I_{SD1}[\exp(\frac{q(V_L + I_L R_S)}{n_1 KT}) - 1] \qquad \text{………………(2)}$$

$$I_{D2} = I_{SD2}[\exp(\frac{q(V_L + I_L R_S)}{n_2 KT}) - 1] \qquad \text{………………(3)}$$

$$I_{sh} = \frac{V_L + I_L R_S}{R_{sh}} \qquad \text{………………..(4)}$$

$$I_L = I_{Ph} - I_{SD1}[\exp(\frac{q(V_L + I_L R_S)}{n_1 KT}) - 1] - I_{SD2}[\exp(\frac{q(V_L + I_L R_S)}{n_2 KT}) - 1] - \frac{V_L + I_L R_S}{R_{sh}} \qquad \text{..(5)}$$

$$I_{ph} = I_{ph,ref}(\frac{G}{G_{ref}})[1 + \alpha_T(T - T_{ref})] \qquad \text{……………….(6)}$$

$I_{ph,ref}$: Photo current at standard reference condition,

α_T : Relative temperature coefficient of the short-circuit current.

G : Irradiation on the SPV module,

G_{ref} : Reference irradiation (1000 W/m^2),

T_{ref} :25°C.

3. Calculation of Power Efficiency

The input power (P_{in}) per unit area to the SPV modules is solar irradiation (G) which is 288 W/m^{2}in each case in our experiment. The output power (P_{out})per unit area is the delivered power from the SPV system.The effective area of each module is .42 m^2. The power efficiency is calculated as,

% efficiency= $\frac{P_{out}}{P_{in}} \times 100$

4. Working Principle of Bypass Diode

In a series connected SPV system when an SPV module comes under shade condition which causes the reduction in irradiation leading to the reduced photo current [15]. Eq (6) depicts the relation between the photo current (I_{Ph}) and irradiation (G) [5]. But the SPV module without shading generates current larger than the shaded module. Due to the difference in the current, the circulating current gets generated through the shunt resistance (R_{sh}) of the shaded module. It causes “hot spots” on the shaded module due to heat dissipation and also reduces the module output voltage [6]. When a bypass diode is connected in parallel to the shaded module in normal condition the diode is reverse biased and remains inactive, but during shading it gets forward biased and bypasses the shaded SPV module improving the performance of SPV system.

5. Outdoor Experimental Setup

Four 75 W SPV modules (Tata BP solar) were connected in series. Four diodes (rating :5A) were connected in parallel to each of the modules. A voltmeter and an ammeter were connected in parallel and series respectively. A rheostat was connected in series to measure the values of output voltage and current in different values of resistance. The zero resistance condition gave the short circuit current and open circuit voltage was measured directly across the output terminals of PV System. Now, the resistance was varied and the corresponding voltage and current were noted down. A lux meter and a pyranometer were used to measure the light intensity and irradiance respectively. In different shading cases the solar panels were completely covered manually.

6. Simulation and Experimental Results

6.1. Simulation Model

PSCAD is used as simulation tool for all the analysis made in this paper [18]. All the simulations and outdoor experiments are done using SPV modules of each 75 W (Standard Testing Condition). Both simulation model and outdoor experimental model are designed such that 4 SPV modules are connected in series, 4 bypass diodes are connected in parallel in reverse with each of the SPV modules [19]. Fig.2 shows the configuration. In normal conditions the diodes are reverse biased and during shading on any SPV module, the respective diode connected in parallel with it becomes forward biased and bypasses the shaded SPV module. The irradiation (G) and temperature (T) of each module can be controlled by individual sliders [1]. A biasing module with slider is incorporated to use variable resistances during the simulation as per need. A diode is connected in forward direction to ensure the protection of the SPV modules from reverse current. A voltmeter and an ammeter are connected in parallel and series respectively, with the system to measure output voltage (V) and current (I) respectively. A multiplier is used to get the output power (P), using output voltage and output current as its inputs.

The simulations and outdoor experiments are done in shade conditions of different SPV modules and respective P-V and I-V characteristic graphs are plotted for each condition [11] [16] [17]. Finally, a comparative study is done with these results for with and without bypass diode condition and the power efficiency in each case is compared. Improved power efficiency is obtained in each casefor bypass diode condition in comparison to the model without having bypass diode.

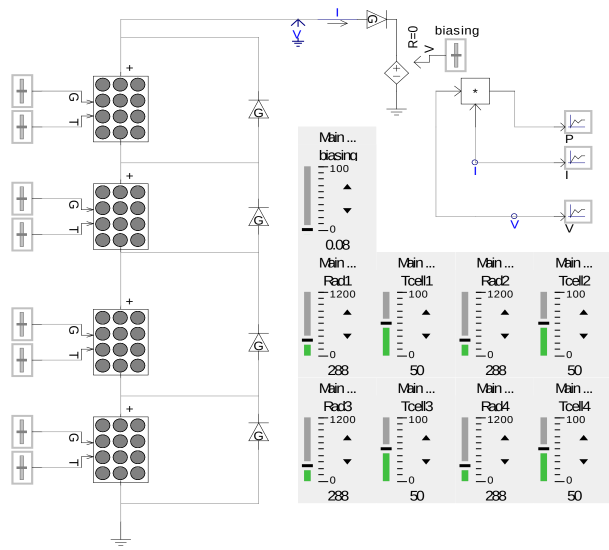


Fig.2. Simulation model of four SPV modules connected in series with four bypass diodes in parallel with each of them designed in PSCAD.

6.2. Without Shading

As there is no shading, so no bypass diode is considered in this case. I, V and P are measured for a single 75 watt SPV moduleat G=288 W/m^2, T=50°Cin both simulations and outdoor experiment and when there is no shading.Then four SPV modules are connected in series and I, V and P are measured at in simulation and also an outdoor experiment at same condition [20]. The results are referred by table 1.Fig. 3 shows the P-V and I-V graphsfor this condition.

Table 1

Output parameters	Simulation results		Experimental results	
	1 SPV module	4 SPV modules	1 SPV module	4 SPV modules
V_{oc}(V)	18.94	75.8	19.1	77.7
I_{sc}(A)	1.82	1.82	2.13	2.17
P_{max} (W)	21.91	87.66	21	80
Powerefficiency (%)	17.87	17.90	17.13	16.33

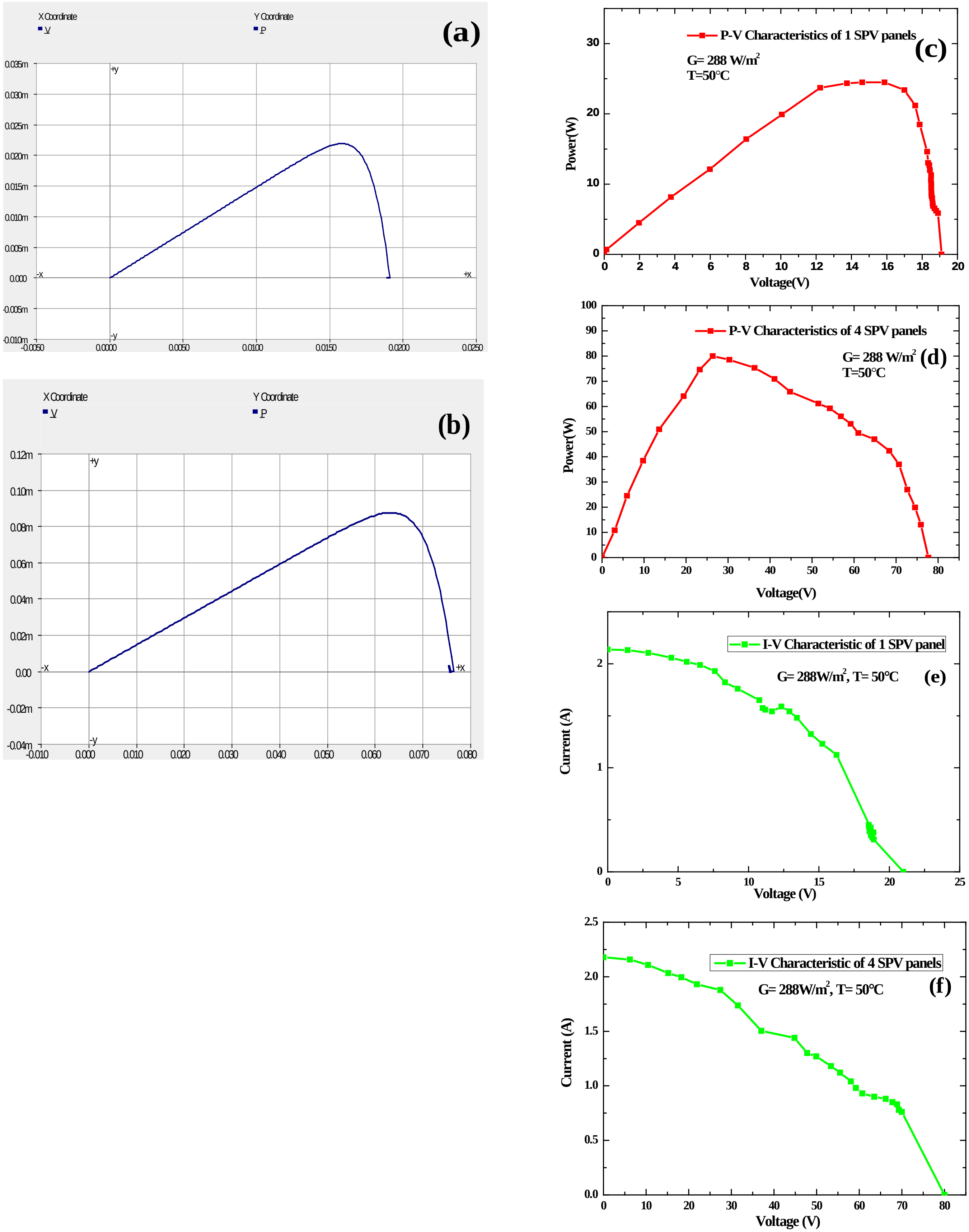

(a)
X Coordinate
V
Y Coordinate
P
+y
-y
-x
+x
(b)
X Coordinate
V
Y Coordinate
P
+y
-y
-x
+x
(c)
P-V Characteristics of 1 SPV panels
G= 288 W/m2
T=50°C
Power(W)
Voltage(V)
(d)
P-V Characteristics of 4 SPV panels
G= 288 W/m2
T=50°C
Power(W)
Voltage(V)
(e)
I-V Characteristic of 1 SPV panel
G= 288W/m2, T= 50°C
Current (A)
Voltage (V)
(f)
I-V Characteristic of 4 SPV panels
G= 288W/m2, T= 50°C
Current (A)
Voltage (V)

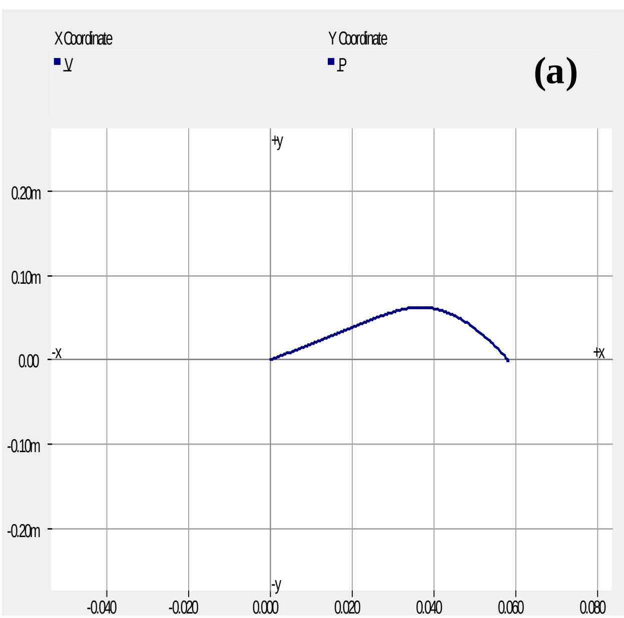
Fig.3 (a) P-V grapah of the single 75 watt SPV module at G=380 W/m^2 and T=50°C and(b) four 75 watt SPV modules connected in series at G=380 W/m^2 and T=50°C in simulation. (c) P-V grapah of the single 75 watt SPV module at G=380 W/m^2 and T=50°C and (d) four 75 watt SPV modules connected in series at G=380 W/m^2 and T=50°C in outdoor experiment. (e) I-V characteristics of the single 75 watt SPV module at G=380 W/m^2 and T=50°C and (f) four 75 watt SPV modules connected in series at G=380 W/m^2 and T=50°C in outdoor experiment.

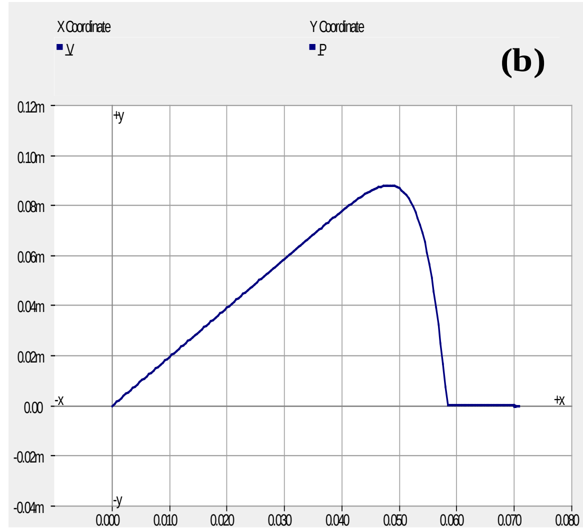
6.3. Case-I: one SPV Module is Shaded

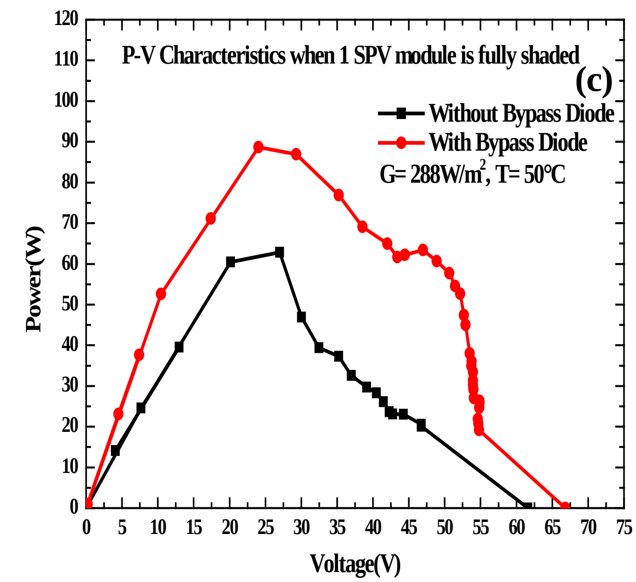
Four SPV modules are connected in series with G = 288 W/m^2 and T = 50° C, where one module is fully shaded. In this case,the simulations and outdoor experiments are carried out for both,with bypass diode (wbpd) and without bypass diode (wobpd)conditions. Improved V_{oc}, I_{sc} and $P_{max}$are measuredin both simulation and experimental results when bypass diodes are connected as the diode bypasses the shaded module. The results of these conditions are described in Table 2.The P-V and I-V graphs obtained in this case are represented by Fig. 4.

Table 2

Output parameters	Simulation results		Experimental results	
	wbpd	wobpd	wbpd	wobpd
V_{oc}	70	57.95	66.83	61.59
I_{sc}	1.95	1.95	2.4	2.1
P_{max}	88.11	62.74	87.97	62.65
Power efficiency (%)	17.99	12.81	17.96	12.79







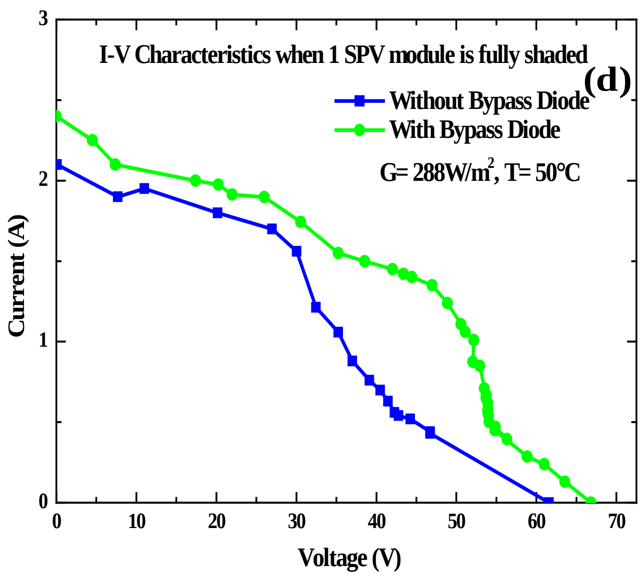


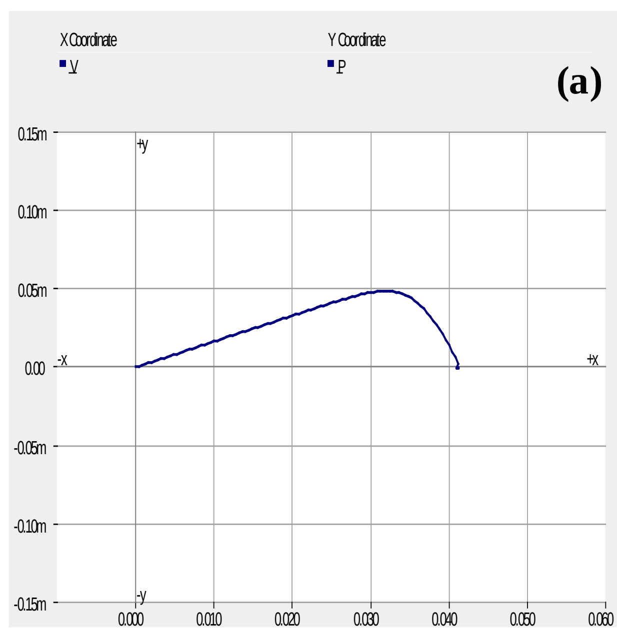
Fig. 4 (a) P-V graph for case 1 in simulation without bypass diode and (b) with bypass diode.(c) P-V graphs and (d) I-V graphs for case 1 in outdoor experiment with and without diode configuration.

6.4. Case 2: two SPV Modules are Shaded

In this case, two SPV modules are fully shaded and G = 288 W/m^2 and T = 50° C. In this case also improved V_{oc}, I_{sc} and P_{max} are obtained with bypass diodes than of without bypass diodes in both simulation and outdoor experimental results. Table 2 describes the results. The P-V and I-V graphs for this caseare shown in Fig. 5.

Table 3

Output parameters	Simulation results		Experimental results	
	wbpd	wobpd	wbpd	wobpd
V_{oc}	53.73	41.1	51.03	43.74
I_{sc}	2.1	2.1	2.2	2.1
P_{max}	73.64	48.56	71	47.15
Power efficiency (%)	15.04	9.91	14.50	9.63



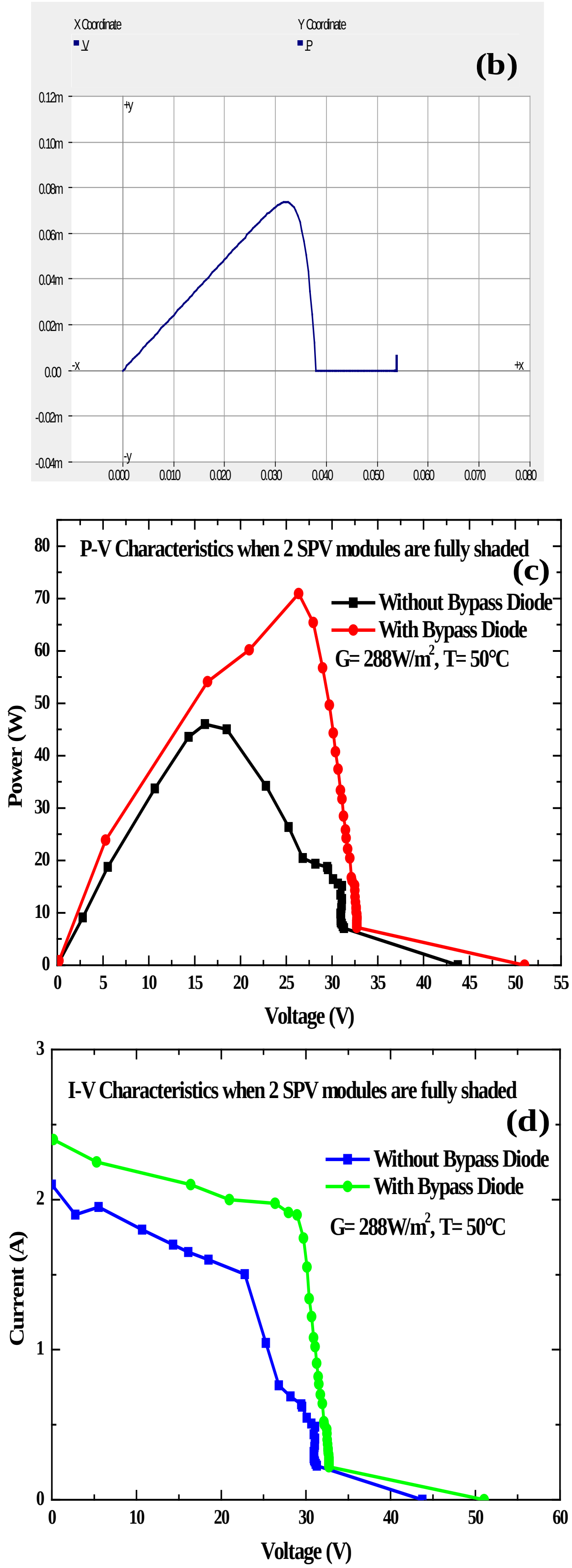


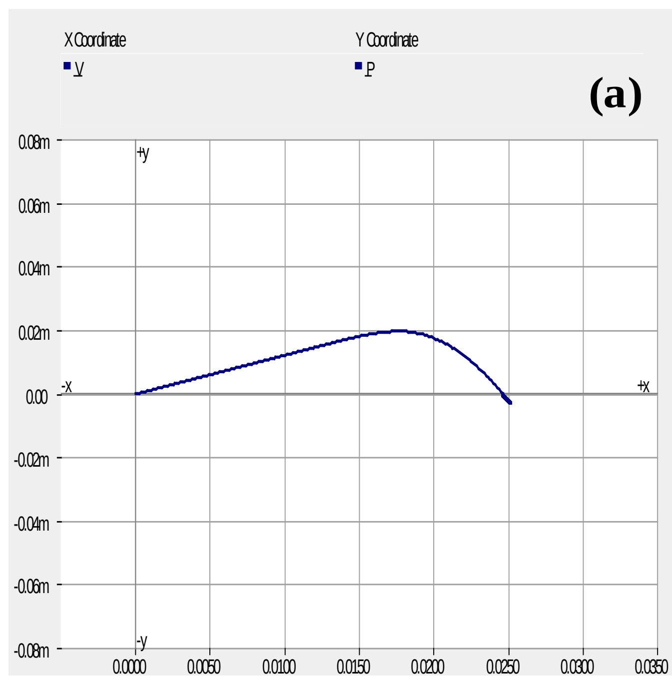
Fig. 5 (a) P-V graph for case 2 in simulation without bypass diode and (b) with bypass diode.(c) P-V graphs and (d) I-V graphs for case 2 in outdoor experiment with and without diode configuration.

6.5. *Case 3: three SPV Module Shaded*

Here, three SPV modules are fully shaded and same simulations and outdoor experiments are done. In this case also improvement in V_{oc}, I_{sc} and P_{max} are recorded for bypass diode in comparison with without diode condition. Table 3 refers the results. The P-V and I-V graphs for this case are depicted by Fig. 6.

Table 4

Output parameters	Simulation results		Experimental results	
	wbpd	wobpd	wbpd	wobpd
V_{oc}	42	24.59	43.74	28.96
I_{sc}	1.95	1.95	2.1	2
P_{max}	32.94	19.86	33.64	17.61
Power efficiency (%)	6.72	4.05	6.87	3.59



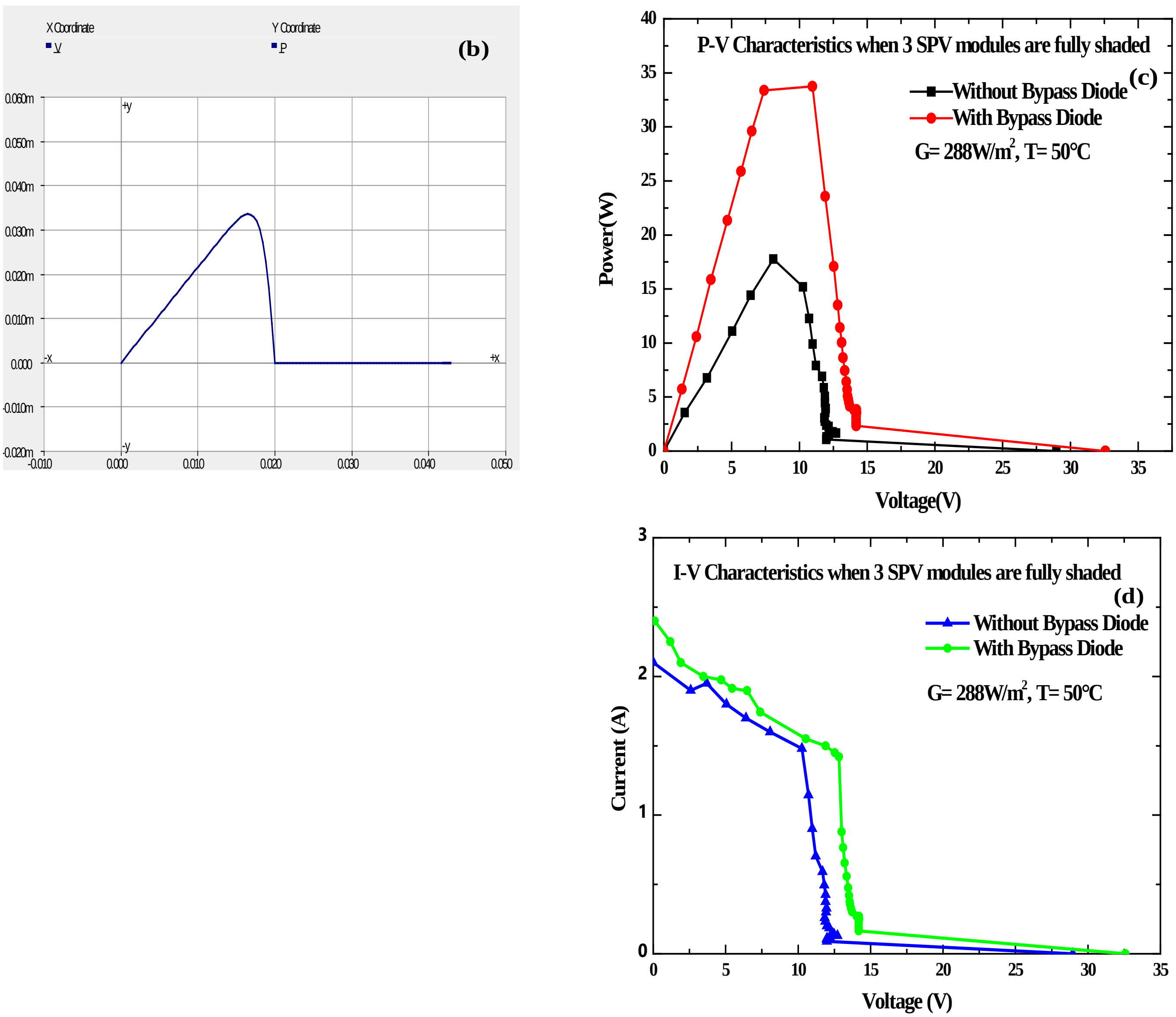


Fig. 6 (a) P-V graph for case 3 in simulation without bypass diode and (b) with bypass diode.(c) P-V graphs and (d) I-V graphs for case 3 in outdoor experiment with and without diode configuration.

7. Conclusion

The effect of shading on SPV modules connected in series was analyzed using simulation and outdoor experiment. The power efficiency, which dropped due to shadow was increased by using bypass diode connecting in parallel in each of the shaded SPV modules. An investigation was done using four SPV modules connected in series for three different shading conditions: (1) one module was fully shaded, (2) two modules were fully shaded and (3) three modules were fully shaded.For each case the analysis was done in simulation and also by outdoor experiment. Improved power efficiency was achieved in both simulation and experimental results in each case using bypass diode. The results obtained from outdoor experiment were in line with the simulation results.

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