

Analysis of Partial Shading Effects of Solar PV Module Configurations Using MATLAB/Simulink

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Abstract Solar energy is an important aspect of renewable energy because we can easily obtain access to the source. The photovoltaic (PV) cell is the fundamental unit in the power conversion of the solar system. When the PV cells are exposed to partial shading as a result of a multitude of environmental conditions, the performance of the solar PV module is remarkably affected in terms of the efficiency of the system. In many cases, the PV arrays are shadowed, whether completely or partially, by passing clouds, neighboring buildings and towers, trees, or the shadow of one solar array falling on another. This study investigates the effects of partial shading on energy output of different configurations of solar PV modules. In this study, three different solar PV configurations are investigated: 1) Series 2) Parallel, and 3) Series-Parallel. All the considered PV configurations are analyzed using several possible scenarios of shading in order to evaluate their performances and to find a configuration that is comparatively less susceptible to electrical mismatches due to shadow problems. Owing to the practical difficulty of conducting experiments on varied array sizes, the proposed model also includes a general model of a PV module, which was implemented on MATLAB/Simulink and has been developed for any required array size, configuration and different shading patterns. This model is simple and especially useful to calculate the actual performances of the PV modules under various operating conditions.

Keywords: solar energy, photovoltaic cell, PV module, solar radiation, partial shading effects, MATLAB/Simulink

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1. Introduction

With ever-increasing energy demand, a growing research thrust is on the development and utilization of renewable energy resources. Solar photovoltaic (PV) and solar thermal (parabolic trough, solar tower) are the technologies available that allow the capture of solar energy. In particular, because PV converts solar radiation directly to electricity, most solar power plants are developed based on PV technology. The increasing number of PV installations in the recent years serves to confirm the growing contribution of solar energy in power generation. However, a major challenge in using a PV source is to tackle its nonlinear output characteristics, which vary with temperature and solar insolation.

For some series-connected PV cells, even if some the cells are partially shaded, all the cells carry almost the same amount of current. While a small number of cells under shade produce less photocurrent, these cells are also forced to carry the same current as the other fully illuminated cells. Since a diode is reverse-biased, it does not conduct much of the current. At the same time, if the system is not appropriately considered under shading conditions, a hot-spot problem can negatively affect the performance of the solar PV cells, and the system can be

damaged. In order to solve the stress on shaded solar PV cells, bypass diodes are required to the PV modules. In such a case, multiple peaks in power-voltage characteristics are observed under non-uniform illumination. Moreover, in some cases it is difficult to avoid partial shading of array due to the surrounding and environmental conditions, such as buildings, dust, bird droppings, and cloud cover throughout the day and in all seasons. This makes the study of partial shading of solar PV modules a key issue.

In recent years, the effects on partial shading on the solar PV array system performance have been widely discussed [1,2,3,4]. Like in H. S. Rauschenbusch's work [5], the power reduced due to a shadowed panel has already been studied. However, the power yield of PV modules is a function of different weather conditions, including solar irradiance [6], temperature [7], and configuration of PV array and partial shading [8]. It is important to consider all these parameters to determine the performance of a PV system under the various conditions of shading. Notably, Chin [8], in his work did not consider a detailed description of shading effects on the PV parameters. This paper aims to present a detailed study of various shading conditions on PV modules due to presence of clouds, trees and buildings.

R. Ramaprabha and B. L.Mathur [5] investigated the shading effects based on a required array's size, configuration,

shading patterns, and a number of bypass diodes using MATLAB. Various configurations were studied in their research, and a modified configuration was developed that combined the advantages of the other configurations. A limitation to their research is that different random shading patterns were considered; hence, there was no consistency observed for the reason behind selecting particular shading patterns. L. Gao and R. A. Dougal stated that under shading conditions the parallel configuration should be dominant [9]. However, high output current at low voltage in a parallel configuration will have to be properly conditioned to the required level by using a suitable DC-DC converter. It is recommended to opt for other configurations. Therefore, in this report, various other configurations have been considered, and their performance under partial shading is evaluated. In their proposal, M. Abdulazeez and I. Iskender [10] studied the shading effect on series- and parallel-connected PV modules. The shading effect was artificially generated by covering parts of the module with partially transparent gelatin paper, reducing the incoming solar radiation by approximately 90%. This comparative study examined series- and parallel-connected PV modules. When there is a reduction in insolation by 90%, the temperature decreases, possibly resulting in the performance of the PV module to increase. The paper neglected to consider the effect of temperature when there is considerable reduction in irradiation.

In this paper, for different configuration types, generalized MATLAB/Simulink models have been developed. These are capable of simulating any number of modules connected in a series, parallel, or combination for any type of shading patterns. Possible scenarios of shading have been investigated as well as ways this possible shading can be utilized to comprehend and predict likely power output of different PV configurations from various shading patterns. For certain PV modules, the arrangement of the PV array dramatically contributes to changing the values of the maximum power subjected to partial shading conditions [11].

Research conducted by R.J. El-Khozondar and T. Suntio [12] concluded that the addition of the bypass diode becomes very important as the existence of the bypass diodes improves the solar PV performance, particularly in the cases where one of the modules is under fully shaded conditions. Therefore, the Simulink model developed for various configurations have the bypass diodes connected in anti-parallel with the PV module for improvement of the PV performance.

In this study, the main objective is to investigate the effects of partial shading caused by surrounding environmental conditions through the application of predefined configurations of the solar PV module system in series, parallel and series-parallel arrays. Furthermore, comparisons are made of their maximum output power for varying shading patterns based on the predefined layouts with possible scenarios. The study aims to find an equivalent electrical circuit model of the PV module when cells in the module are connected in series and parallel in order to analyze the characteristics of the module under uniform operating conditions.

2. Modeling of Photovoltaic Array System Configurations

In field testing, it is difficult to investigate the effects on partial shading because there are many barriers regarding cost, time and weather conditions. Also, it is challenging to uniformly measure the same level of intensity of shading under a number of different configurations of a shaded PV array system. Alternatively, it is convenient to carry out a simulation study with the help of a computer model. In this study, for different configuration types, generalized MATLAB/Simulink models have been developed and are capable of simulating any number of modules connected in series, parallel or combination for any type of shading patterns.

2.1. Mathematical Modeling of a PV Cell and Module

A PV module consists of a number of solar cells, which convert light into electricity. The solar cell mainly depends on a diode, a photocurrent (I_{ph}), an internal resistor (R_s), and a shunt resistor (R_{sh}). Figure 1 shows a photovoltaic equivalent circuit of a single cell.

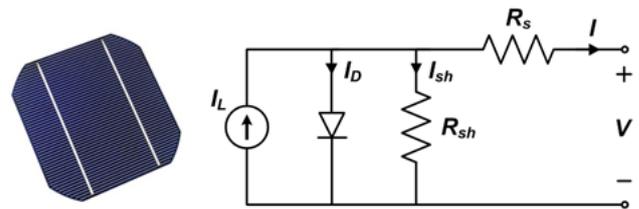


Figure 1. Photovoltaic equivalent circuit of a solar cell

When a PV module collects irradiance energy from the sun by individual solar cells, it is charged with electric energy. The output of electric energy depends on intensity of irradiance ($\frac{W}{m^2}$), temperature (K), material, design of the PV module, and the photocurrent (I_{ph}) in series with the internal resistor (R_s) and parallel with a shunt resistor (R_{sh}), as shown in Figure 2.

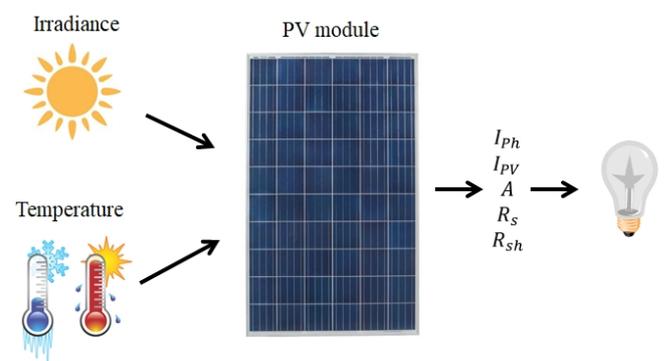


Figure 2. PV module performance with irradiance and temperature

The basic equation of the current at the terminal of the solar cell and the maximum power output are formulated.

[13,14] The photovoltaic panel can be mathematically modeled as:

• Basic mathematical equation of the output current (I) in Eq. (1)

$$I = I_{ph} - I_d \tag{1}$$

I_{ph} is the photocurrent, I_d is the diode current, which is related to the saturation current and is described by Eq. (2):

$$I_d = I_o \left[\exp\left(\frac{V}{A.N_s.V_T.a}\right) - 1 \right] \tag{2}$$

where V is the voltage applied to the diode, then V_T can be expressed by the equation of $V_T = k \cdot \frac{T}{q}$; A is the diode

ideality ranged between 1 and 2; N_s is the number of cells in a series for the output current; a is the diode emission coefficient.

The photocurrent, I_{ph} , is generated from the incident solar irradiation and affected by the temperature (T). It can be expressed by Eq. (3):

$$I_{ph} = \frac{G}{G_{STC}} (I_{ph,STC} + K_I (T - T_{STC})) \tag{3}$$

where $G_{STC} \left(\frac{W}{m^2}\right)$ is the irradiation at STC; $I_{ph,STC}$ is the current produced at STC; K_I is the temperature coefficient of the short-circuit current.

The diode reverse leakage current, I_o , is influenced by the actual temperature and can be expressed in Eq. (4):

$$I_o = \frac{I_{SC,STC} + K_I (T - T_{STC})}{\exp(V_{OC,STC} + K_V K_I (T - T_{STC})) - 1} \tag{4}$$

where $I_{SC,STC}$ and $V_{OC,STC}$ are the short-circuit current and open-circuit voltage at STC; K_V is the temperature coefficient of the open-circuit voltage (V/Kelvin).

In the PV module, the short-circuit voltage (I_{sc}) can be described when V_o across the PV module is equal to zero and I_{sc} , as expressed in Eq. (5):

$$I_{SC} = I_{PV} - I_d \left[\left(\exp \frac{I_{SC} R_S}{V_T \cdot a} \right) - 1 \right] - \frac{I_{SC} R_S}{R_{SH}} \tag{5}$$

• Maximum power point of a PV module in Eq. (6):

$$I_{mp} = I_{PV} - I_d \left[\frac{V_{mp} + I_{mp} R_S}{V_T \cdot a} - 1 \right] - \frac{V_{mp} + I_{mp} R_S}{R_{SH}} \tag{6}$$

The maximum power, P_m , is calculated by $V_{mp} \times I_{mp}$ and described in Eq.(7):

$$P_m = V_{mp} \left\{ \begin{aligned} & I_{PV} - I_d \left[\exp \frac{V_{mp} + I_{mp} R_S}{V_T a} - 1 \right] \\ & - \frac{V_{mp} + I_{mp} R_S}{R_{SH}} \end{aligned} \right\} \tag{7}$$

where shunt resistance of the PV module is expressed in Eq.(8):

$$R_{sh} = \frac{V_{mp} + I_{mp} R_S}{\left(V_{mp} I_{PV} + V_{mp} I \right) - V_{mp} I \cdot \exp \left[\frac{q(V_{mp} + I_{mp} R_S)}{N_s K T a} \right] - P_m} \tag{8}$$

The $I-V$ and $P-V$ characteristics of the PV module operating at various temperatures and intensity of irradiance are determined.

2.2. Solar PV Modules and Array System

A solar PV panel module consists of a number of interconnected solar cells encapsulated into a stable panel module, and an array is constructed with a number of panel modules interconnected in series or parallel. A solar PV array system is comprised of the following components: (1) a number of solar cells, (2) a panel module connected in series, and (3) an array system that includes a charge control system and a storage system based on an AC/DC converter system for transmitting the electricity to a desired place, shown in Figure 3.

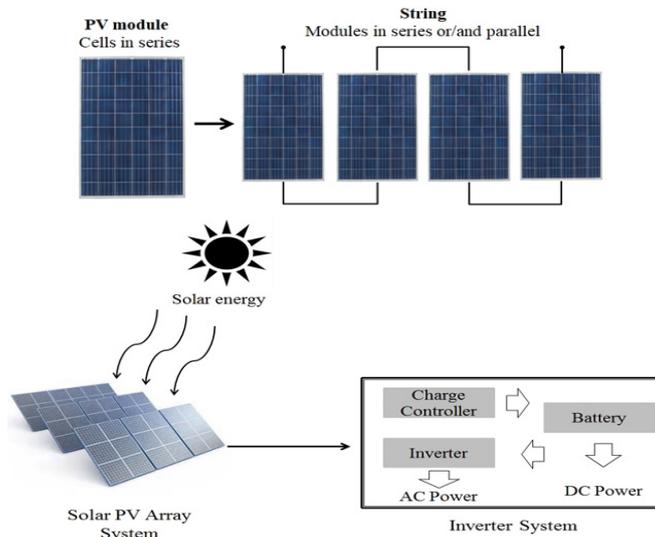


Figure 3. Solar PV array configuration and system

Table 1. Electrical characteristics of MSX-60

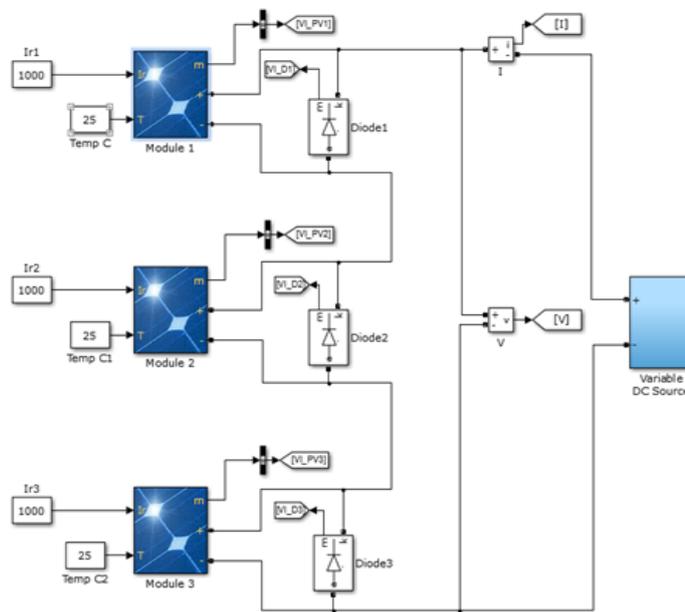
Parameter	Variable	Value
Maximum Power	P_m	60 W
Voltage at P_m	V_{mp}	17.1 V
Current at P_m	I_{mp}	3.5 A
Open circuit Voltage	V_{oc}	21.1 V
Short Circuit Current	I_{sc}	3.8 A
Temperature coefficient of I_{sc}	K_I	0.00065 T/A
Temperature coefficient of V_{oc}	K_V	0.008 T/V

A commercial PV module is interconnected in series, and this standard is used to investigate the effects on maximum power points reached while under partial shading conditions. A single PV module is constructed

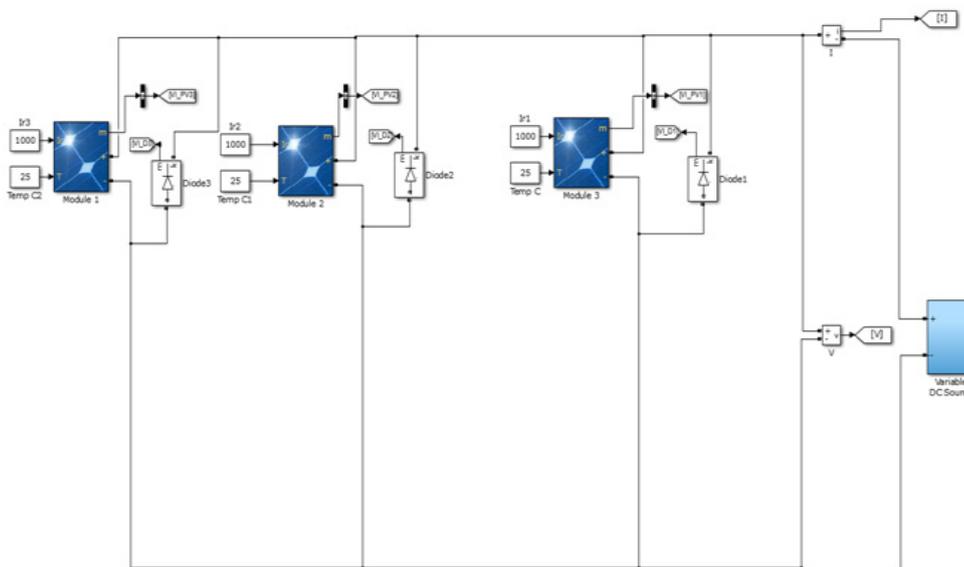
from 36 PV cells derived from a multi-crystalline material. Table 1 shows the electrical characteristics of BP MSX-60 module used in this paper under standard test conditions (STC), indicating that irradiance $G = 1000 \text{ W/m}^2$, temperature = 25°C , and $AM = 1.5$.

To compare the performance of different configurations under various possible scenarios, uniform operating data under standard test conditions (STC) has been used. These conditions define performance at an incident sunlight of 1000 W/m^2 and temperature of 25°C .

This paper adopts the notions and characteristics of a simplified PV system that a single PV array system is interconnected with three individual PV modules of MSX-60. The Simulink models for the various configurations in series, parallel, and series-parallel combination are shown below in Figure 4:

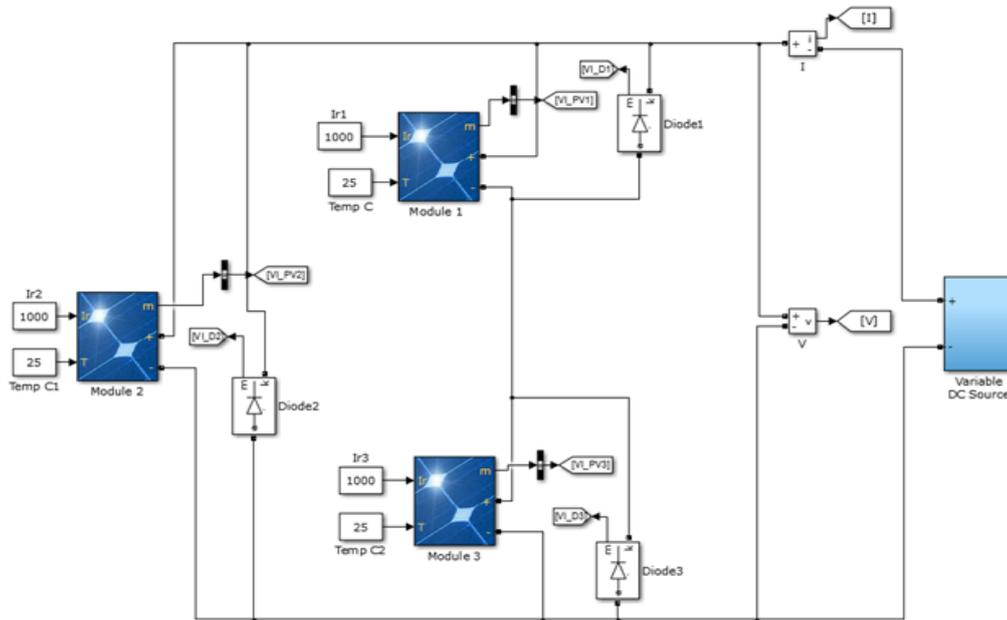


(a) PV module configurations connected in series

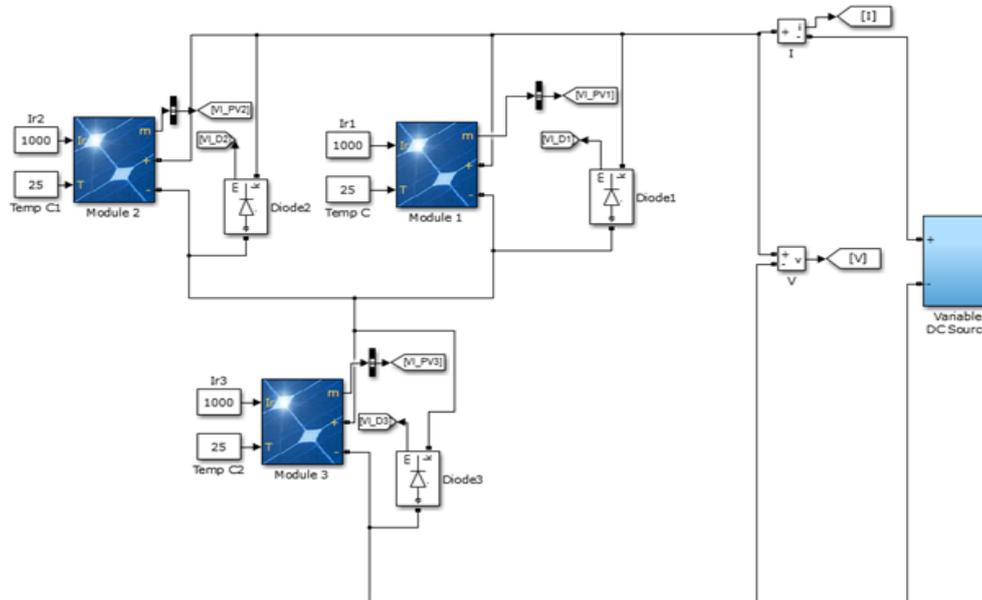


(b) PV module configurations connected in parallel

Figure 4. a,b



(c) PV module configurations connected in series-parallel (combination 1)



(d) PV module configurations connected in series-parallel (combination 2)

Figure 4. Simulink models with respect to PV array configurations

For the sake of comparison and simplicity, three modules have been used for the array configurations. Comparisons to M. Abdulazeez and I. Iskender's [10] work have been made to validate the model developed in this research work.

For comparing the various configurations, several unique possible scenarios have been studied. $I-V$ and $P-V$ graphs for each of these possible scenarios have been simulated, and values of maximum power, voltage, and current obtained from each case have been tabulated in this work.

2.3 Case Studies

The series, parallel and series-parallel configurations of modules have been simulated. To study and compare these configurations, a certain basis is required. In order to

compare the different configurations, the following possible scenarios are proposed:

- Case I: One module is under partial shading effect, and the other is exposed to full irradiance.
- Case II: Two modules are under partial shading effect, and the other is exposed to full irradiance.
- Case III: All three modules are under partial shading effect.

Partial shading conditions of the PV array system affect power output. In this study, partial shading conditions are classified into four categories: 1) buildings, 2) snowy weather, 3) clouds, and 4) trees.

2.3.1. Buildings

C. Deline [15] proposed that the relative performance of one system versus the other could be averaged using a

weighted average based on survey data that was collected for representative rooftop installations. There are three different shading conditions caused by buildings, and they were simulated by classifying levels of intensity: “light” shading (7% annual irradiance reduction), “moderate” shading (15%–19% irradiance reduction), and “heavy” shading (25% irradiance reduction). These shading conditions were to provide the basis for a weighted-average annual performance score of different solar PV systems. For this research, these three shading conditions have been used to compare the different solar PV array configurations. Table 2, Table 3 and Table 4 give a description on the various cases of shading caused by shade due to building over three PV modules with the corresponding irradiance values.

Table 2. Light shading condition with 7% irradiance reduction

Case	Module 1 Irradiance(W/m ²)	Module 2 Irradiance(W/m ²)	Module 3 Irradiance(W/m ²)
I	1000	1000	930
II	1000	930	930
III	930	930	930

Table 3. Moderate shading condition with 17% irradiance reduction

Case	Module 1 Irradiance(W/m ²)	Module 2 Irradiance(W/m ²)	Module 3 Irradiance(W/m ²)
I	1000	1000	830
II	1000	830	830
III	830	830	830

Table 4. Heavy Shading condition with 25% irradiance reduction

Case	Module 1 Irradiance(W/m ²)	Module 2 Irradiance(W/m ²)	Module 3 Irradiance(W/m ²)
I	1000	1000	750
II	1000	750	750
III	750	750	750

2.3.2. Snowy Weather

In order to identify the relationship between a low-performing module and snowy weather or dust, historical climate condition data from a third party reference was collected. R. French [16] uses the solar PV performance ratio (PR), which is a measure of PV module output at a given incident power from sunlight, as an indicator of a modules’ working effectiveness. The PR of the modules was small or equal to zero even when irradiance was not very low, which indicates that the module may experience snow coverage. Historical climate condition data from a third party website was collected for evaluating the performance. Low PR appears only during or after snow or fog-snow days. For this research, we are taking into account the average PR value, which is 0.4 - 0.3. With this, the amount of irradiance that is incident on the PV module can be calculated. It is also worth considering the fact that snowy weather is marked with a decrease in temperature. For this research, the average temperatures of the months of January, February and March in Cleveland, Ohio were used. The average temperature collected from a third party website was found to be 4.26°C for those 3 months in Cleveland. Table 5 describes values of irradiance when the PV modules are covered with snow.

Table 5. Effect of Snow on PV modules

Description	Module 1 Irradiance (W/m ²)	Module 2 Irradiance (W/m ²)	Module 3 Irradiance (W/m ²)
When all three modules are under snow	400	400	400

2.3.3. Clouds

P. Burgess [17] discusses how solar irradiation intensity varies with cloud cover and different seasons. According to Burgess, there is around 25% loss even when the sky is clear, and this is due to scattering of light and other phenomena. It was stated that these losses may be quantified as high as 75% when the cloud cover density is heavy. For instance, during a dark, thundery sky, only 5 to 10% of the potential radiation is received. In this work, the effect of cloud cover causing partial shading on the PV array has been considered. Specifically, high cloud density eventually leading to partial or full shading on the PV module has been considered. Seasonal data of New Delhi, India, a city that has an average temperature of 15°C during winters, was examined. Table 6 indicates the values of irradiance when the PV modules are covered with clouds.

Table 6. Heavy cloud condition with 50 % irradiance reduction

Case	Module 1 Irradiance (W/m ²)	Module 2 Irradiance (W/m ²)	Module 3 Irradiance (W/m ²)
I	1000	1000	500
II	1000	500	500
III	500	500	500

Table 7 (given below) describes the various cases of shade possible from heavy rains. For this study, seasonal data of New Delhi, India from a third party website was collected for consistency. In instances of rain when there is little or no trace of sun, minimum irradiance is captured by the PV modules. Therefore, there can be a drastic reduction in irradiance values. The average temperature of New Delhi was estimated to be 32.5 °C during heavy rain season.

Table 7. Heavy rains condition with 90% irradiance reduction

Case	Module 1 Irradiance(W/m ²)	Module 2 Irradiance(W/m ²)	Module 3 Irradiance(W/m ²)
I	1000	1000	100
II	1000	100	100
III	100	100	100

2.3.4. Trees

G.M. Heisler [18] carried out research on how the effect of individual trees would be on the irradiance incident on a PV array. The significance of the irradiance reductions for a PV array was tested by using physical models of representative tree crowns (similar to maple) and a PV array to evaluate shadow patterns. The paper concluded that, on clear days, the average reduction in the shade of trees in leaf ranged from 65% to 85%.

The following research and results were obtained during analysis and experiments conducted in U.S.A. Table 8 describes values of irradiance when PV modules

are under the effects of shading conditions caused by the trees.

Table 8. Effect of tree-blockage condition with 50 % irradiance reduction

Case	Module 1 Irradiance(W/m ²)	Module 2 Irradiance(W/m ²)	Module 3 Irradiance(W/m ²)
I	1000	1000	250
II	1000	250	250
III	250	250	250

3. Numerical Results

In this section, solar PV module $I-V$ characteristics are investigated to find maximum performance with respect to various configurations of solar PV modules interconnected in series, parallel, and a combination of serial-parallel strings. In order to compare the power output of the different configurations, the possible scenarios are shown as Case I, II, and III.

3.1. PV Module Characteristic Curves When Cells Are Connected in Series

The characteristic $I-V$ curve indicates that there are two regions in the curve: one is the current source region and another is the voltage source region. In the voltage source region (in the right side of the curve), the internal impedance is low, and in the current source region (in the left side of the curve), the impedance is high. When the

$I-V$ characteristic and effects of both factors are considered for evaluating performance of the solar PV array system, irradiance temperature plays a key role in designing the PV system. Whereas irradiance affects the power output, temperature mainly affects the terminal voltage.

The results of the performance of the PV module in series and parallel using MATLAB/Simulink are shown in [Table 9](#).

Table 9. Performance evaluation when cells are connected in series and parallel in terms of maximum power, voltage, and current.

Configuration	Max. Power (W)	Max. Current (A)	Max. Voltage (V)
Series	63.2982	3.5561	17.800
Parallel	40.2551	125.7971	0.3200

From the above table, it can be interpreted that cells provide higher power output when connected in series in a PV module. Therefore, it can be assumed that commercial PV cells and modules are predominantly connected in series.

3.2. Performance of the Various System Configurations

Performance of various configurations under different shading scenarios has been discussed. The simulation results were obtained by using the model that was developed for various configurations using Simulink.

In [Table 10](#), the peak power, voltage, and current for the three configurations under different possible scenarios has been tabulated and compared.

Table 10. Scenario 1: Comparison of the various configurations under shading due to buildings

Scenario	Case	Configuration	Max. Power (W)	Max. Current (A)	Max. Voltage (V)
a) Size of Shade due to Building (Light Shading)	I	Series	173.4	3.345	51.84
		Parallel	175.4	10.25	17.11
		Series-Parallel	130.2	3.604	36.12
	II	Series	170	3.291	51.65
		Parallel	171.3	10.01	17.11
		Series-Parallel	130	3.604	36.06
	III	Series	167.2	3.256	51.36
		Parallel	167.2	9.771	17.11
		Series-Parallel	121.4	3.354	36.19
b) Size of Shade due to Building (Moderate Shading)	I	Series	159.7	3.011	53.05
		Parallel	169.5	9.904	17.11
		Series-Parallel	129.8	3.605	36.02
	II	Series	154.1	2.955	52.14
		Parallel	159.5	9.31	17.13
		Series-Parallel	129.1	3.602	35.85
	III	Series	149.5	2.907	51.44
		Parallel	149.5	8.717	17.15
		Series-Parallel	108.4	2.994	36.19
c) Size of Shade due to Building (Heavy Shading)	I	Series	146.8	2.725	53.87
		Parallel	164.7	9.626	17.11
		Series-Parallel	129.5	3.604	35.93
	II	Series	140.4	2.665	52.69
		Parallel	150.0	8.755	17.13
		Series-Parallel	128.3	3.601	35.62
	III	Series	135.3	2.628	51.46
		Parallel	135.3	7.886	17.15
		Series-Parallel	97.88	2.706	36.17

It is observed that for any configuration, as the number of modules under shading increases, the power decreases, confirming that shading has a negative effect on the power output of an array. It is also observed that for each of the three cases of shading (light, medium and heavy shading), the parallel configuration gives the best performance. It is worth noting that parallel configuration gives better results only when a part of an array is shaded while in

cases of uniform shading (where all the modules are shaded), parallel and series configuration give the same output. Figure 5 shows variations with respect to levels of partial shadings in series, parallel, and series-parallel.

Table 11 shows the results of the maximum power output with maximum current and voltage for partial shading effect from snow with respect to the various PV module configurations.

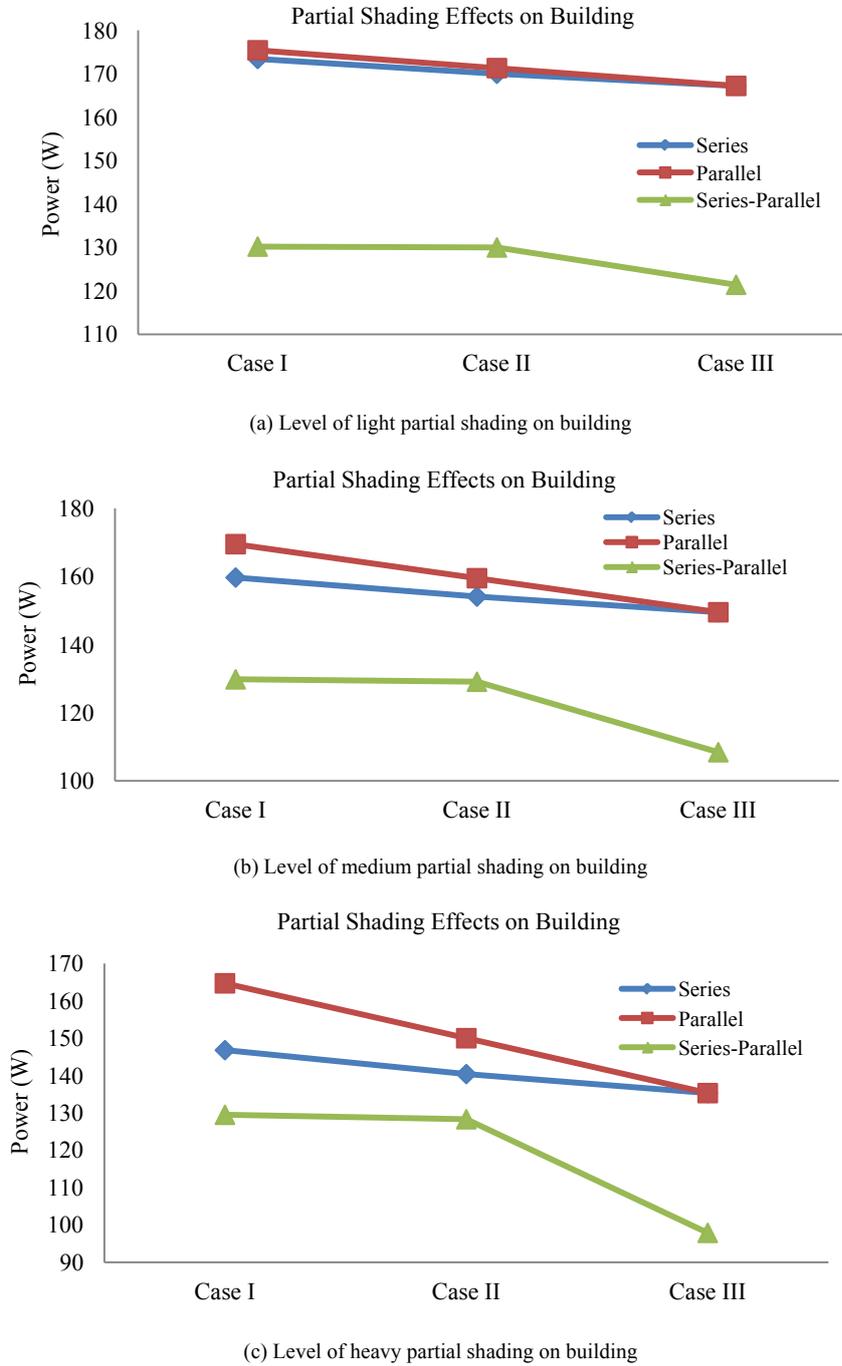


Figure 5. Comparison of power variations with respect to levels of partial shadings

Table 11. Scenario 2: Comparison of the various configurations under shading due to snow

Scenario	Case	Configuration	Max. Power (W)	Max. Current (A)	Max. Voltage (V)
Shade due to snow	All the modules are covered with snow	Series	78.55	1.393	56.4
		Parallel	78.55	4.178	18.8
		Series-Parallel	56.08	1.427	39.31

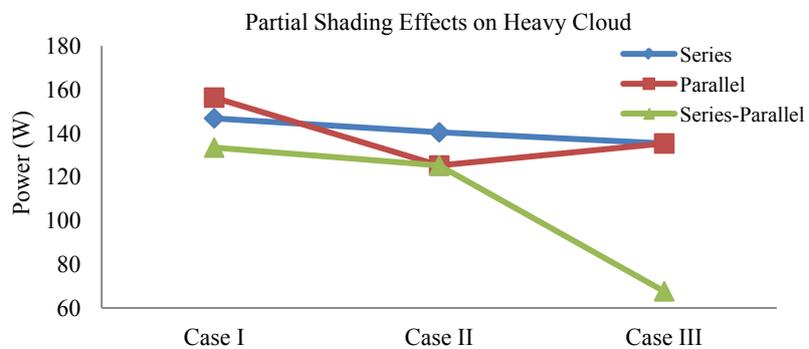
Table 12. Scenario 3: Comparison of the various configurations under shading due to cloud

Scenario	Case	Configuration	Max. Power (W)	Max. Current (A)	Max. Voltage(V)
Shade due to Cloud Cover(Heavy Cloud Cover/Winter)	I	Series	146.8	2.725	53.87
		Parallel	156.3	8.714	17.94
		Series-Parallel	133.4	3.58	37.26
	II	Series	140.4	2.665	52.69
		Parallel	125.2	6.982	17.94
		Series-Parallel	125.2	3.491	35.87
	III	Series	135.3	2.628	51.46
		Parallel	135.3	7.243	17.96
		Series-Parallel	67.57	1.794	37.66
Shade due to Cloud Cover(Rainy Season)	I	Series	113.2	3.503	32.3
		Parallel	120.9	7.374	16.39
		Series-Parallel	118.9	3.588	33.15
	II	Series	52.9	3.487	15.17
		Parallel	68.44	4.218	16.23
		Series-Parallel	55.36	3.498	15.83
	III	Series	16.45	0.3525	46.67
		Parallel	16.45	1.058	15.55
		Series-Parallel	11.84	0.3633	32.58

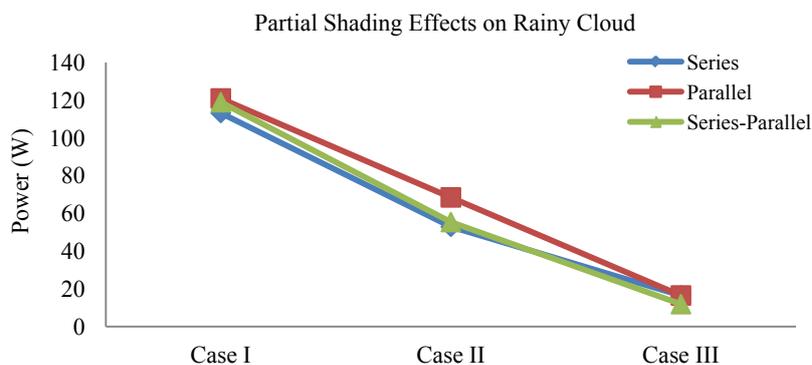
It (Table 11) is observed that snow adversely affects the performance of the PV array. While the power output can be as high as 180 W on a clear sunny day, it decreases to just about 80 W when facing snowy conditions. Under such conditions, series or parallel configurations will

provide a better power output than the combination of series-parallel configuration.

Table 12 shows the results of the maximum power output for partial shading effects of clouds as they apply to the various PV module configurations in series, parallel, and series-parallel.



(a) Case of heavy cloud cover due to weather conditions



(b) Case of rainy cloud cover

Figure 6. Considerations of cloud cover shaded by weather conditions and seasons

It (Table 12) is observed that temperature can have a negative effect on power output. As the temperature increases, power decreases. Also, when cloud cover is present, irradiation is reduced and, consequently, the power output drops. It is also observed that for both rainy and winter conditions, the parallel configuration gives the best performance outcome. Figure 6 shows variations of the power output with respect to the partial shadings caused by weather conditions and seasons in series, parallel, and series-parallel.

Table 13 shows the results of the maximum power output for partial shading effect of tree blockage as

experienced by the various PV module configurations in series, parallel, and series-parallel.

It (Table 13) is observed that under shade conditions due to tree cover, parallel configurations give the best results. A maximum power of about 134 W is noticed against a value of 117 W, which is an increase of about 14.5%. Therefore, in a site where an array undergoes dense tree cover, parallel configuration should be preferred. Figure 7 shows variations of power output with respect to partial shadings caused by trees and seasons in series, parallel, and series-parallel.

Table 13. Comparison of the various configurations under shading due to trees

Scenario	Case	Configuration	Max. Power (W)	Max. Current (A)	Max. Voltage (V)
Scenario 4: Shade due to Tree cover	I	Series	117.2	3.495	33.53
		Parallel	134.4	7.872	17.07
		Series-Parallel	125.8	3.593	35
	II	Series	54.92	3.497	15.78
		Parallel	89.33	5.259	16.99
		Series-Parallel	64.98	1.807	35.95
	III	Series	44.34	0.8786	50.47
		Parallel	44.34	2.637	16.82
		Series-Parallel	31.84	0.6036	35.24

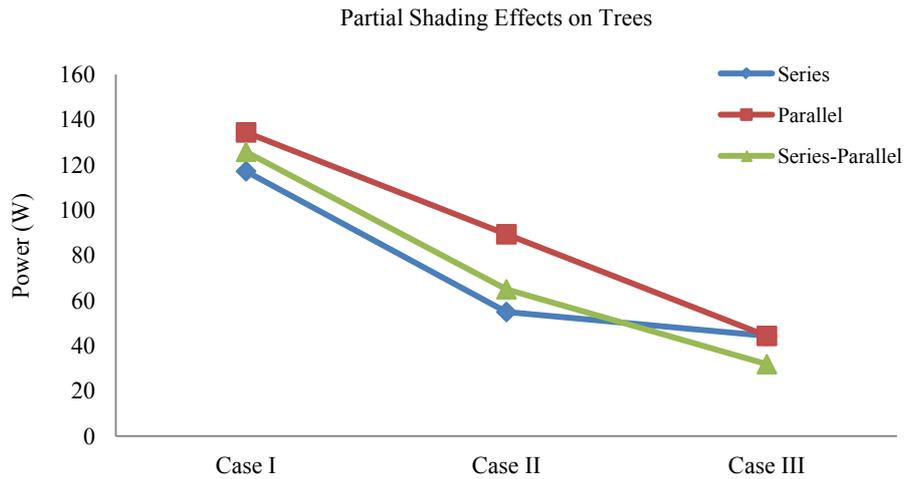


Figure 7. Considerations of tree cover shading

4. Conclusion

Analysis of various SPVA configurations with respect to environmental parameters has been investigated and more realistic models using MATLAB/Simulink have been developed. Two cases wherein cells in a PV module are connected in series and parallel were studied. The results confirmed that cells in a PV module, when connected in series, yield maximum power. Also, a Simulink model has been developed to simulate the behavior of PV modules with different configurations under variable meteorological conditions, in particular the impact of partial shading. In order to collect the maximum possible power output from partial shading caused by environmental conditions, it is recommended that the connection of a bypass diode in anti-parallel with a module or group of cells is required to avoid the stress on the shaded cells. This approach to PV module design

would solve the problem of sensitivity of hot-spot as well as provide a higher power supply when compared to a solar PV module system without considering the configuration of bypass diode. The model developed has incorporated the effects of bypass diodes. An advantage of the presented simulation procedure is that the model developed here can be used for any array size and for any module by simply changing the specifications of the module used in the program. Furthermore, the input parameters (irradiance and temperature) can be changed, making possible the study of different shadow patterns in addition to temperature variations in particular solar modules. After analyzing the various configurations for different possible shading patterns for varied sizes, it is also observed that, in most cases, parallel configuration provides a higher amount of power when compared to the other configurations. Conversely, in some cases in which all the modules received the same insolation, series or a

parallel configuration provided a higher power when compared to the other configurations.

Nomenclature

I_{PV} , V_{PV} - Solar PV module Current (A) and Voltage (V) respectively

I_{ph} - Photocurrent PV module (A)

I_d - Diode reverse saturation current in the equivalent circuit (μA)

R_s - Series resistance in the equivalent circuit of the module ($m\Omega$)

R_{sh} - Parallel resistance in the equivalent circuit of the module (Ω)

R_L - Load resistance

D - Diode used in the equivalent circuit

q - Electron charge ($=1.602 \times 10^{-19} C$)

k - Boltzman's constant ($= 1.381 \times 10^{-23} J/K$)

T - Temperature (Kelvin)

V_T - Thermal voltage ($= nkT/q$)

G - Insolation level (at reference condition $G=1000 W/m^2$)

I_{SC} & V_{OC} - Short circuit current and open circuit voltage of the module respectively

V_{mp} & I_{mp} - Maximum power point voltage and current respectively

P_m - Maximum power

Db - Bypass diodes used in the series array configuration.

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