

Validation of Shadow Effects on Solar Photovoltaic Modules Based on Module Positioning



Revathy Subbiah Rajaram, Kirubakaran Victor

Abstract: Solar Energy is one of the cleanest forms of energy harnessed from the sunlight using semiconductors through photoelectric effect. This paper reviews the existing models to study the effect of partial shading conditions or varying irradiance on the solar modules. In this paper a PV module is simulated in Matlab/ Simulink using solar cell block from Simelectronics Library to study the effect of shadows on the output power under different panel positioning under different load conditions. The simulation results have been validated against the real time study and measurements. Both the simulation and experimental results confirm that the power loss due to shading effects in a solar photovoltaic module is influenced by the topology and the interconnection of the PV cells.

Keywords: Solar Cell, Solar Photovoltaic, Shadows, Maximum Power, Matlab.

I. INTRODUCTION

The growth in energy demand and erratic availability of energy sources like coal, oil and natural gas is pressing us to focus on renewable energy technologies like solar energy, wind energy, hydro power, bio-energy, ocean & tidal energy, geothermal energy etc,. Among the renewable energy technologies, solar energy seems to be most promising because it can be implemented anywhere because sunlight is easily available and at free of cost. Moreover, it is more suitable and prominent solution for both domestic and industrial power needs. [1]

Solar cells or photoelectric cells are semiconductor based electrical devices that convert the sunlight falling over it into current and this process of converting the energy in the photon into electricity is called photo electric effect. Solar cells are combined to form a solar panel or module to increase the power production.

The power produced by the solar cell is directly proportional to the incident irradiance.

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The power output of solar modules exhibits a non-linear relationship with the irradiance and Temperature. Under the partial shadow conditions, the maximum power point decreases with respect to the incident irradiance.

Several PV cells are connected in strings to increase the overall output voltage.

When one of the cells in the string is shaded, hotspot heating occurs in it. If the string current exceeds the short circuit current of the shaded cell, then the overall current of the whole string is limited by the shaded cell.

This is because, the extra current produced by the unshaded cells are forward biased along the string while the shaded cell is reverse biased. Hence a detailed study on the effects of shadows on the PV modules is necessary. Many models have been developed over time to study the PV module / array performance under the partial shading conditions. [2]

II. MODEL OF A SOLAR CELL

Photovoltaic cells exhibit exponential characteristics due to their diode like behaviour. In Matlab solar cells can be implemented in three possible ways.

Firstly, as a mathematical model using any instrument that implements differential equations. Secondly, electrical model using components like resistor, capacitor, inductor, diodes etc through Simscape.

Thirdly, using solar cell block in the SimElectronics library of Matlab/Simulink [3]. Solar cell block acts as a current source, which includes solar-induced current and temperature dependence. The electrical characteristics of solar cell block are given in Table - 1. [4, 5]

Table – I: Solar Cell Block Specifications

Parameter	Value
Short-circuit current [A]	$I_{sc} = 7.34$
Open-circuit voltage [V]	$V_{oc} = 0.6$
Series resistance [Ω]	$R_s = 0$
Quality Factor	$N = 1.5$
First order temperature coefficient for $\frac{1}{K}$ phi	$TI_{PH1} = 0$
Temperature exponent for I_s	$TX_{IS1} = 3$
Temperature exponent for R_s	$TR_{S1} = 0$
Parameter extraction temperature [$^{\circ}C$]	$T_{meas} = 25$
Fixed circuit temperature [$^{\circ}C$]	$T_{FIXED} = 25$

A. Solar Induced Current:

The block represents a single solar cell as a resistance R_s that is connected in series with a parallel combination of a current source, two exponential diodes and a parallel resistor R_p . The output current of the solar cell is given by equation (1).

$$I = I_{ph} - I_s \left(e^{\frac{V+IR_s}{N_1V_t}} - 1 \right) - I_{s2} \left(e^{\frac{V+IR_s}{N_2V_t}} - 1 \right) - \frac{V+IR_s}{R_p} \quad (1)$$

Where I_{ph} is solar induced current is given by equation (2)

$$I_{ph} = I_{ph0} \frac{I_r}{I_{r0}} \quad (2)$$

Where I_r is irradiance than falls on the surface of the cell; I_{ph0} is measured solar generated current for the irradiance I_r , W/m^2 ; I_s is the saturation current of the first diode; I_{s2} is the saturation current of the second diode; $V_t = kT/q$ is the thermal voltage, V_t depends on the device temperature, k is the Boltzmann constant and q is the elementary charge of the electron; N is the quality factor (the emission coefficient for the diode) of the first diode; N_2 is the quality factor (the emission coefficient for the diode) of the second diode; V is the voltage at the terminals of the solar cell.

The solar cell block in the Simscape Library allows choosing one of two models: a model with 8 parameters in which the previous equation describes the output current, and a model with 5 parameters where the equation (1) can be simplified with following assumptions: the impedance of the parallel resistor is infinite and the saturation current of the second diode is zero. The 5 parameters model allows optimization of the solar cell block according to the equivalent circuit model parameters or by short circuit current and open circuit voltage.

B. Temperature dependence:

The solar cell parameters like the solar-induced current, the saturation current of the first diode, the saturation current of the second diode, the series resistance and the parallel resistance depends on temperature. Photovoltaic cell temperature is specified by value of the fixed circuit temperature parameter, T_{FIXED} . The relation between the solar-induced current I_{ph} and solar cell temperature T is given below in equation (3).

$$I_{ph}(t) = I_{ph}(1 + T1PH1(T - T_{meas})) \quad (3)$$

Where, $T1PH1$ is the first temperature coefficient for I_{ph} and T is the parameter extraction temperature [4, 5, 6].

III. SIMULINK MODEL OF A SPV MODULE

The Simulink Model in Figure - 1 represents a PV cell array connected to a variable resistor. The module has 36 cells of which two strings of 18 cells each are connected in parallel. This structure can be built in any configuration by adding or removing any number of cells. A signal builder block is used to provide irradiation as input to the solar cells. The ramp input varies the resistance in steps unto 30 steps. The subsystem containing the 36 solar cells is given in Figure - 2.

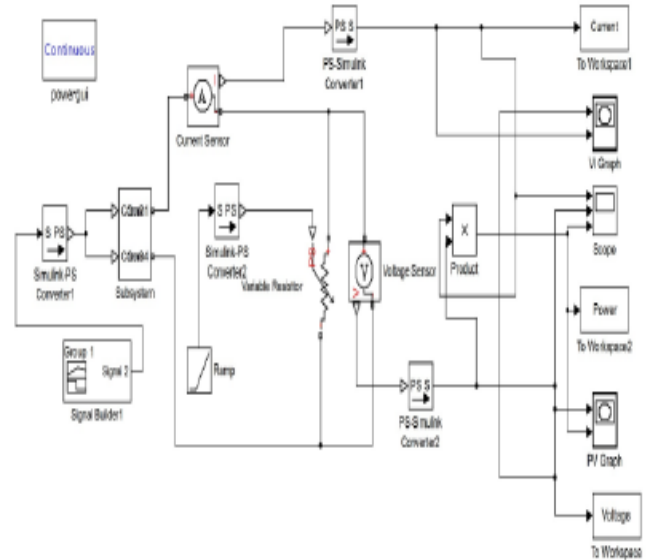


Fig. 1. Simulink Block Model of the PV System

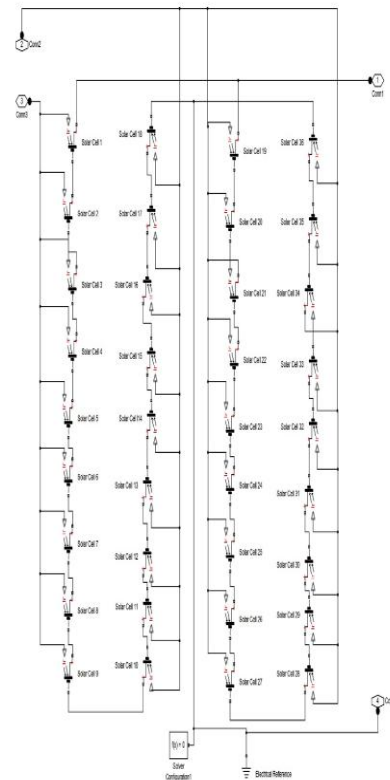


Fig. 2. Connection of solar cells in SPV Module Subsystem

The developed model is validated by simulating it with irradiance of $1000W/m^2$ at a temperature of $25^{\circ}C$ (standard operating conditions). The current, voltage and power output of the model under standard operating conditions are depicted in Figure - 3.

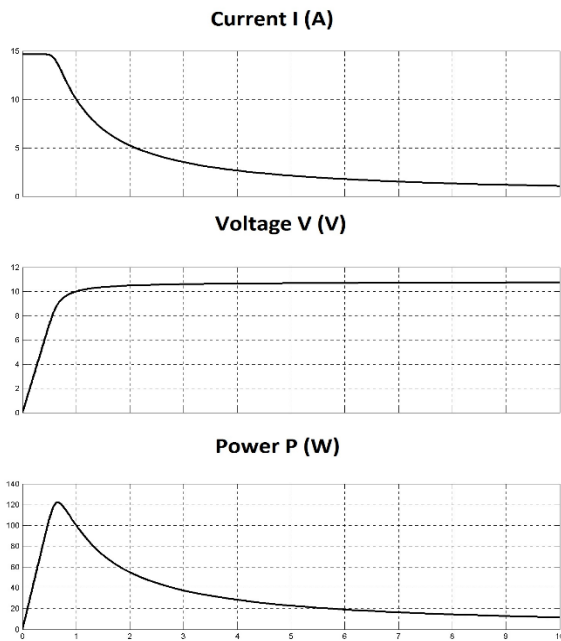


Fig. 3. Current, Voltage & Power curves of PV module in Simulink

The voltage – current characteristics and power – voltage characteristics of the model are depicted in Figure -4. These characteristic curves aids in better understanding the solar cell parameters and the optimal power generated by the SPV module.

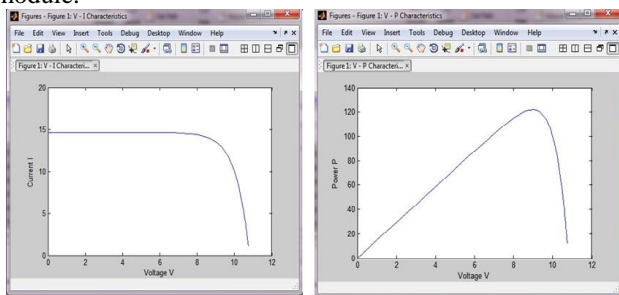


Fig. 4. V-I & P-V Characteristics of PV Module

IV. EFFECTS OF SHADING

The common factors affecting the solar cell performance includes the irradiance falling over it, area of the cell and operating temperature. When a module is shaded, the module does not get uniform or complete irradiance, the shaded area of the cell doesn't produce power instead it acts as load, dissipates heat and becomes a hot spot. This makes shading one of the important phenomena, which affects the performance of the solar photovoltaic modules. The possible sources for shading could be the trees, buildings, poles, clouds or the dust deposited on the SPV module. The common factors affecting the solar cell performance includes the irradiance falling over it, area of the cell and operating temperature [7]. Belhaouas et al., built a PV module based on two diode model using matlab / Simulink to study PV performance under partial shading and have concluded that shadow on a single cell of the module reduces the power output by 50% [8]. The concept of shading factor states that

the power produced is proportional to the illuminated area of the module. Figure – 5 discusses the effects of shading different portions of a single cell in a Luby (LE12P100) 100W panel. Thus, the concept of shading factor could be true in case of a single cell, but does not work well for increased number of cells and shadow position on the module. This paper proposes that, the position of the shadow on the module has a greater influence on the output power.

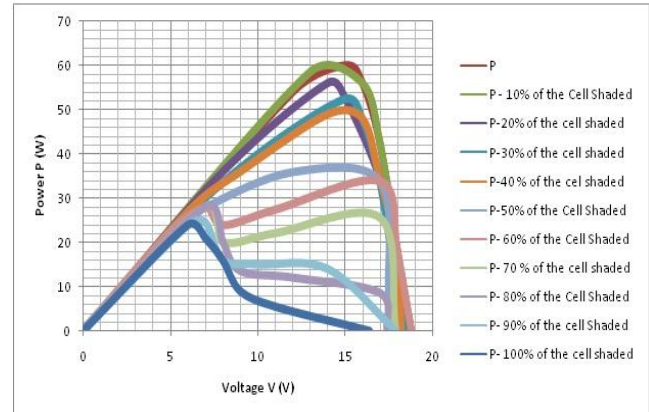


Fig. 5. Effect of Shading a single cell under different percentage in a PV Module

V. METHODOLOGY

To validate the proposed notion four cases are defined in Table -2 and the results are validated experimentally and theoretically using Matlab Simulink model. All the four cases are tested under both fixed load condition and varying load condition.

Table – II: Case Description

Case	Case Description
Case - 1	The vertical portion of the module including cells 28 to 36 are shaded (9 cells in a column)
Case - 2	The horizontal portion of the module including cells 9,10,27,28 are shaded (4 cells in a row)
Case - 3	The vertical portion of the module including cells 10 to 18 are shaded (9 cells in a column)
Case - 4	The horizontal portion of the module including cells 6,13,24,31 are shaded (4 cells in a row)

A. Experimental Setup

The effect of shading on SPV module based on the predefined cases was studied in the laboratory through series of experimental measurements. A 100 Watts Poly crystalline panel was taken for the study. The panel has 36 cells where two strings of 18 cells are connected in parallel. Figure - 6 shows the experimental setup. The electrical specifications of the panel are given in Table – 3. The PV panel was illuminated artificially through lighting system with 21 halogen lamps each 150 watts. Desired irradiance can be achieved by adjusting the power knob in the lighting system. Temperature was measured using digital thermometer attached behind the panel. Keithley 2700 data acquisition system was used to measure and log voltage, current to the PC. A 50-ohm rheostat was used as load and Fluke 289 digital multimeter was used to measure the resistance value applied as load.

Shading was done by blocking the concerned cells with black acrylic paper. The voltage and current measurements were made for all the four cases under varying load (0 ohm to 50 ohms) and fixed load of 35 ohms. To eliminate the effects of temperature, water was sprayed on the panel to maintain the temperature at 25°C.

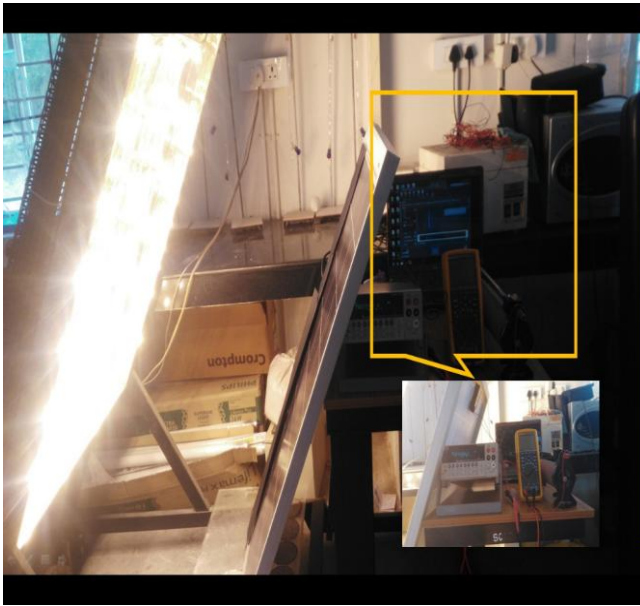


Fig. 6. Experimental Setup

Table – III: Specifications of LE12P100 module

Parameter	Value
Short-circuit current [A]	$I_{sc} = 6.2$
Open-circuit voltage [V]	$V_{oc} = 21.5$
Maximum Power [W]	$P_{max} = 100$
Maximum Voltage [V]	$V_{max} = 17$
Maximum Current [A]	$I_{max} = 5.88$ A
Maximum System Voltage for UL [V]	600
Maximum System Voltage for IEC [V]	1000

B. Simulation

Simple equivalent circuit with complex parameters like the SPV module / arrays can be easily implemented using Simulink. The Matlab Simulink model of the single diode equivalent circuit of the SPV Module built with the solar cells block from Simscape library was used to evaluate the four pre-defined cases. The V_{oc} and I_{sc} values of the solar cells are set to 0.5 V and 6.2 A, so as to match the panel used in experimentation. The cases were tested for the irradiance of 1000W/m² and temperature of 25°C under fixed and varying load conditions. The fixed load of 10 ohms was achieved by replacing the variable resistor with a resistor in the Simulink structure discussed above. Also, the shaded cells were fed with irradiance of 0 W/m² using a separate PS Constant block connected to the respective cells.

VI. RESULTS & DISCUSSION

The results of the shading effects based on the panel position are discussed in this section. The P_{max} values for all the cases are presented in Table - 4. Fig- 7 (a) & (b) shows the simulation results for case 1 (vertical shading) and case 2 (horizontal shading) under varying load condition. The

maximum power at no shade condition is 82 watts, whereas the P_{max} values in case 1 is 50 watts and case 2 is 37 watts. The simulation results for case 3 (vertical shading) and case 4 (horizontal shading) under varying load condition are shown in Fig – 7 (c) & (d). In these two cases the P_{max} values are 50 watts for case 3 and 38 watts for case 4.

The Fig- 7 (e) & (f) shows the simulation results for case 1 (vertical shading) and case 2 (horizontal shading) under fixed load of 10 ohms. The maximum power at no shade condition is 8 watts, whereas the P_{max} values in case 1 is 7 watts and case 2 is 0.15 watts. The simulation results for case 3 (vertical shading) and case 4 (horizontal shading) under fixed load condition are shown in Fig – 7 (g) & (h). In these two cases the P_{max} values are 7 watts for case 3 and 0.15 watts for case 4.

The Fig- 8 (a) & (b) shows the experimentation results for case 1 (vertical shading) and case 2 (horizontal shading) under varying load condition. The maximum power at no shade condition is 80 watts, whereas the P_{max} values in case 1 is 49 watts and case 2 is 38 watts. The simulation results for case 3 (vertical shading) and case 4 (horizontal shading) under varying load condition are shown in Fig – 8 (c) & (d). In these two cases the P_{max} values are 47 watts for case 3 and 37 watts for case 4.

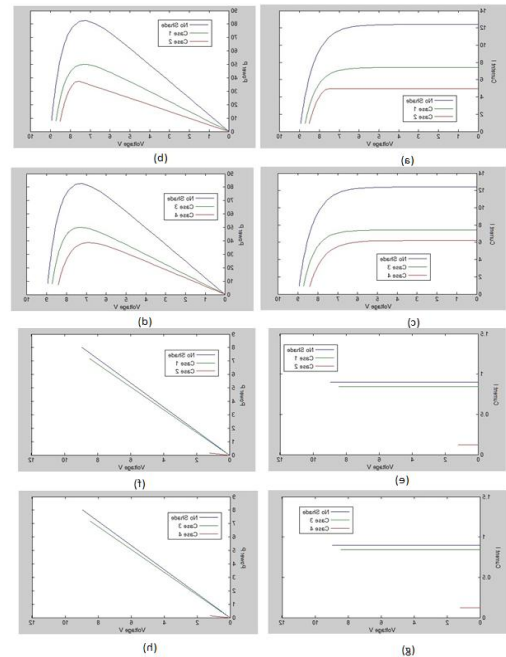


Fig.7. (a) V-I Curves for Case 1 & 2 studied under varying load condition in Simulink model. (b) P-V Curves for Case 1 & 2 studied under varying load condition in Simulink model. (c) V-I Curves for Case 3 & 4 studied under varying load condition in Simulink model. (d) P-V Curves for Case 3 & 4 studied under varying load condition in Simulink model. (e) V-I Curves for Case 1 & 2 studied under fixed load condition in Simulink model. (f) P-V Curves for Case 1 & 2 studied under fixed load condition in Simulink model. (g) V-I Curves for Case 3 & 4 studied under fixed load condition in Simulink model. (h) P-V Curves for Case 3 & 4 studied under fixed load condition in Simulink model

Table – IV: Comparison of simulation and experimental results

Different cases compared	Simulation Results		Experimental Results	
	P_{\max} for Varying Load Condition [W]	P_{\max} for Fixed Load Condition [W]	P_{\max} for Varying Load Condition [W]	P_{\max} for Fixed Load Condition [w]
No Shade	82.65545169	8.05893	80.59067327	7.969159
Case 1	49.96222201	7.15825535	48.93346	6.98323
Case 2	37.28870793	0.153831356	38.75866	0.141428
Case 3	49.97474945	7.15825535	47.871546	7.06775
Case 4	38.62413877	0.153831356	37.46895	0.15011

The Fig- 8 (e) & (f) shows the simulation results for case 1 (vertical shading) and case 2 (horizontal shading) under fixed load of 10 ohms. The maximum power at no shade condition is 8 watts, whereas the P_{\max} values in case 1 is 7 watts and case 2 is 0.14 watts. The simulation results for case 3 (vertical shading) and case 4 (horizontal shading) under fixed load condition are shown in Fig – 8 (g) & (h). In these two cases the P_{\max} values are 7 watts for case 3 and 0.15 watts for case 4. The difference between the simulation and experimental results obtained is around 2%, which is negligible. Based on the simulation and experimental results the power losses under varying load conditions is around 39% for vertical shading and 55% for horizontal shading.

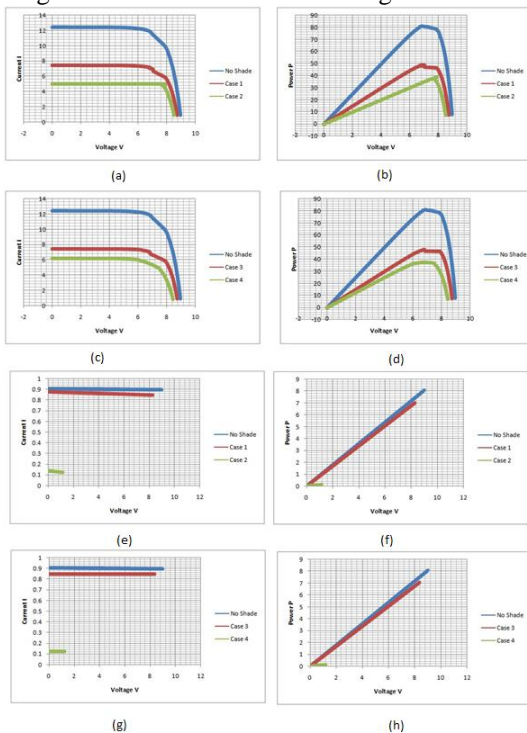


Fig. 8. (a) V-I Curves for Case 1 & 2 studied under varying load condition through experimentation. (b) P-V Curves for Case 1 & 2 studied under varying load condition through experimentation. (c) V-I Curves for Case 3 & 4 studied under varying load condition through experimentation. (d) P-V Curves for Case 3 & 4 studied under varying load condition through experimentation. (e) V-I Curves for Case 1 & 2 studied under fixed load condition through experimentation. (f) P-V Curves for Case 1 & 2 studied under fixed load condition through experimentation. (g) V-I Curves for Case 3 & 4 studied under fixed load condition through experimentation. (h) P-V Curves for Case 3

& 4 studied under fixed load condition through experimentation

In case of fixed load condition, the power reduction is about 12% for vertical shading pattern and 96% for horizontal shading pattern. Although both vertical and horizontal shading patterns contribute to power reduction, high power losses occur under horizontal shading compared to vertical shading irrespective of the number of cells shaded. To further validate this, 4 cells were shaded both vertically and horizontally in LE12P100 panel with an irradiance of 1000W/m² and temperature of 25°C. The power drop values when different numbers of cells are shaded is given in Fig – 9.

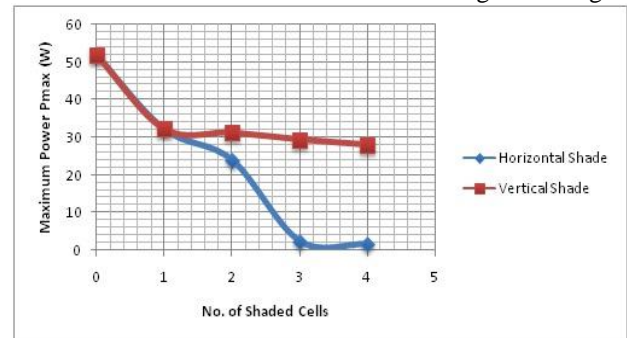


Fig – 9: Power drop with number of shaded cells in different positions

Under no shade condition the panel produces a maximum power of 80 watts. When a single cell is shaded the P_{\max} value drops to 52 watts. The power reduction when 2, 3, 4 cells are shaded column wise (vertically) the P_{\max} values are 31 W, 29 W and 28 W respectively. But when shaded row wise (horizontally) the P_{\max} values are 24 W, 2.4 W and 1.6 W. The above discussion explains that the power loss due to horizontal shading is more than the vertical shading, irrespective of the number of cells shaded or area of the panel shaded. Hence the position of the panel under different shadow conditions becomes a factor of importance to be considered while mounting the panel.

VII. CONCLUSION

This paper has reviewed different SPV models developed to study the effects of shading. A Simulink based model using the solar cell block was designed and used to study the effects of shading based on the panel position. The simulation results are validated across experimental results. Both the results confirm that the power reduction due to horizontal shading is much higher than the vertical shading under both fixed and varying load conditions.

The position of the shadow on the solar module and number of cells shaded also contributes to the power loss. However, from the results it is evident that the connection of the cells in the module conduces the power loss irrespective of the number of cells and shadow area. The module taken for study has two strings of 18 cells each, in case of vertical shading half of the cells in a string produce meagre power whereas, in case of horizontal shading, 4 cells – that is 2 in each string will be shaded dragging down the output power. As a result, the arrangement of cells in the module and their interconnection influences the power output under partial shading conditions. This study can be applied at different stages of PV cells interconnection and also at array level design and installation.

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