Modeling of photovoltaic arrays under shading patterns with reconfigurable switching and bypass diodes

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Modeling of Photovoltaic Arrays under Shading Patterns with Reconfigurable Switching and Bypass Diodes

By

Priyanka O Singh

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Electrical Engineering

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The University of Toledo
December 2011
An Abstract of
Modeling of Photovoltaic Arrays under Shading Patterns with Reconfigurable Switching
and Bypass Diodes

By
Priyanka O Singh

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With growing socio-economic and industrial development, the need to examine alternative sources for generating electricity has become very important. Renewable energy sources such as wind energy, solar energy, and tidal energy play an important role to cover for the additional energy demands. Solar energy has the advantages of clean emission free production and continuous supply during day time while being portable and scalable. However, better understanding of the operation of the photovoltaic cells is necessary to improve efficiency of energy conversion.

The modeling of nonlinear current-voltage characteristics of solar cells for performance prediction becomes difficult under the influence of shading. Non-uniform illumination due to shadows casted by the other panels/modules, buildings, clouds, etc. can cause maximum power to change drastically. Partial shading of PV installations has a disproportionate impact on its power production. Moreover, the power losses in the individual shaded cells would result in local heating and create thermal stress on the entire module/array resulting in hot-spot formation. Under extreme cases of shading the
reverse bias on the solar cell might exceed its breakdown voltage and cause irreparable
damage.

In this thesis, a MATLAB model has been implemented for solar cells to predict
its performance under random shading patterns and verified using SPICE simulations.
The developed MATLAB model of the solar cell estimates of power generation are
within 5%-7% of SPICE simulation results. The developed model of solar cells was
integrated to implement a MATLAB model for solar module. Algorithms have been
designed to model the bypass diodes to counter the deterioration of maximum peak
power caused by shading in solar modules. Several shading scenarios have been
implemented and maximum peak power is shown to decrease by up to 85% for the PV
arrays that do not incorporate bypass diodes within the modules. Another contribution of
this research work is to develop an algorithm to study a reconfigurable switch
architecture design for solar arrays. The architecture allows solar cell modules to be
isolated within a solar array to increase the output power under different shading patterns.
MATLAB models show that the maximum power extracted from the solar array increases
by up to 80% when reconfigurable switching architecture is used.
Dedicated to my Late Grand Father and my Family members
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List of Symbols

\( \eta_{\text{max}} \) .......................... Maximum Efficiency
F.F ........................................ Fill Factor
\( I_{BP} \) ................................. Bypass Diode Current
\( I_{BP(\text{max})} \) .......................... Maximum Current through the Bypass diode
\( I_{\text{Illuminated}} \) ...................... Total Current across Illuminated cells
\( I_{OUT} \) ................................. Output Current of the Module
\( I_{\text{Peak}} \) ............................. Current at Peak Power
\( I_{\text{Shaded}} \) ........................ Total Current across Shaded cells
\( I_x \) ...................................... Initial guess of the input cell Current for Newton-Raphson’s method
\( I_{x+1} \) .................................. Calculated Next guess of the input cell current for Newton-Raphson’s method
\( i_{BP} \) ................................. Reverse Saturation Current of the Bypass Diode
\( i_o \) ................................. Solar cell Diode’s Reverse Saturation Current
\( i \) ...................................... Total number of Illuminated cells
\( I_D \) ...................................... Diode Current
\( I_m \) ...................................... Individual cell Current at Maximum Peak Power
\( I_M \) ...................................... Total Output Current of the Module.
\( I_{\text{out}} \) ............................... Total Current across the Six cells in Series/Parallel analysis
\( I_{PH} \) .................................. Photonic Current
\( I_{\text{SC}} \) ................................ Short Circuit Current
\( n \) ...................................... Diode Ideality Factor
\( N_{P} \) .................................. Number of Parallel cells in the respective Series row within the Module
\( N_s \) .................................. Number of Series Rows in the Module
\( P_l \) .................................. Power to the Load
\( P_o \) .................................. Total Output Power across the Six cells
\( P_{\text{OUT}} \) ............................... Output power of the Module
\( P_{\text{max}} \) ............................. Maximum Output Power
\( R_L \) .................................. Load Resistance
\( R_S \) .................................. Series Resistance
\( R_{SH} \) ................................. Shunt Resistance
\( s \) \hspace{1cm} \text{Total number of Shaded cells} \\
\( V_{BP(max)} \) \hspace{1cm} \text{Maximum Voltage through the Bypass Diode} \\
\( V_{BP} \) \hspace{1cm} \text{Voltage across the Bypass Diode} \\
\( V_{IL} \) \hspace{1cm} \text{Voltage across individual Illuminated cell} \\
\( V_{OUT} \) \hspace{1cm} \text{Output Voltage of the Module} \\
\( V_{Peak} \) \hspace{1cm} \text{Voltage at Peak Power} \\
\( V_{SH} \) \hspace{1cm} \text{Voltage across individual Shaded cell} \\
\( V_{m} \) \hspace{1cm} \text{Individual cell Voltage at Maximum Peak Power} \\
\( V_{M} \) \hspace{1cm} \text{Voltage across an individual solar cell} \\
\( V_{OC} \) \hspace{1cm} \text{Open Circuit Voltage} \\
\( V_{t} \) \hspace{1cm} \text{Thermal Voltage (\( \approx 25\text{mV at } 300^\circ \text{ K} \))} \\
\( V_{total} \) \hspace{1cm} \text{Total Voltage across the Six cells} \\

\text{For the Main Array: (From Figure 5-2)} \\
i , j \hspace{1cm} \text{Index used to locate Modules (i: row number, j: position of module in the row).} \\
I_{array} \hspace{1cm} \text{Total Current across the Array.} \\
I_{OUT} \hspace{1cm} \text{Current across each Module.} \\
I_{row} \hspace{1cm} \text{Current through a particular Row which ideally should be the same as } I_{array}. \\
N_{PA} , N_{SA} \hspace{1cm} \text{3 Parallel Modules connected in 4 Series Rows} \\
V_{max} \hspace{1cm} \text{A } N_{PA} \times N_{SA} \text{ array containing the maximum operating Voltage across each module.} \\
V_{row} \hspace{1cm} \text{Voltage at each row (same in each row but different in different rows).} \\

\text{For the Module: (From Figure 4-2)} \\
i_{total} \hspace{1cm} \text{Total Current across the Module.} \\
N_{PM} , N_{SM} \hspace{1cm} \text{20 Parallel cells connected in 10 Series Rows.}
Chapter 1

Introduction

Ever increasing energy demand, owing to population growth, technology development, and industrial expansion, has led to exploring alternative sources for energy generation. Environmental issues with concerns on global warming, greenhouse effects, depletion of natural reserves like fossil fuels, natural gas, coal, etc. is motivating research to invest in technologies that can harvest energy from renewable energy sources like wind, solar, tidal waves, etc. Of these, the solar energy with irradiance levels of up to 1kW/m² is abundant and photovoltaic power is a prime candidate for electrical energy generation [1]. Photovoltaic is the process of converting sunlight directly into electricity using solar cells. It basically comprises of two steps.

The first step is the absorption of solar radiation within the semiconductor. In the second step, transformation to electrical energy is made by generating current and voltage by the incident solar radiation on the solar cells that produces electrons-hole pairs as shown in Figure 1-1. Several such solar cells are connected in different configurations depending on the current/voltage requirements to form Modules and Arrays.
A typical photovoltaic (PV) system, shown in Figure 1-2, comprises of solar arrays/panels, power converter controllers, energy storage systems (batteries and ultra-capacitors) possibly connected to a single-phase or three-phase utility.

A solar module comprises of a number of solar cells that are tied in a predefined architecture to generate enough output power. Several such modules are configured in a single assembly to form a solar array. Solar powered PV systems (For e.g., charging a battery or for grid-connected systems) may either use a single module or an array depending on the total output current and output voltage requirements of the system being powered by it. Stand-alone systems usually require batteries to store power for the times when no sunlight is available while the grid-interface systems use power from the central utility whenever needed and in return supplies surplus generated power back to the utility.

The initial cost of fabrication and installation of a PV system is very high. The goal is to extract maximum power from the installed module under different lighting and operating conditions. However, the solar modules/arrays may be rendered less efficient due to factors such as shading, bird-droppings, hot-spot formation, and cell damage due to extreme temperature and semiconductor material defects.
Maximum Peak Power (MPP) tracking is essential and is used to haul out the highest output power. This is usually done by a power controller or a DC-DC converter. It is a power electronics circuitry that is capable of keeping the output voltage constant at a desired level while the input voltage may fluctuate to match the MPP tracker. This happens by the constant adjustment of the duty cycle ratio of the DC-DC converter design or in simpler words by controlling the turn on ($t_{on}$) and turn-off ($t_{off}$) durations of the switch within the converter. Several MPP control algorithms have been studied and implemented [2] [3] [4] [5]. The output current of a PV system is DC but can be converted to AC (single or three phases) by using additional power circuitry like inverters when integrated to the grid. Battery or super-capacitors are used to charge and save energy.
Chapter 2

Modeling of Solar cells

The chapter gives the overview on the electrical modeling of solar cells. Performance parameters related to these models have been discussed and $I-V$ characteristics with variations in operating conditions are simulated and discussed.

2.1 Solar Cell Model

The ideal 1-D solar cell model is represented by a constant current source and a diode as shown in Figure 2-1. The photonic current, $I_{PH}$, is the amount of current produced by the electron-hole pairs generated by the impinging sunlight. This phenomenon is called photovoltaic effect. $I_{PH}$ depends on the intensity of the incident solar light, characteristics of the solar panel, and the ambient temperature.
Figure 2-1: 1-D Ideal model for a Solar cell

The most important electrical characteristics of a PV cell module/array are:

a) Short Circuit current (I_{SC}): Usually this is associated with the photonic current I_{PH} and is considered the same for normal levels of solar irradiance. It increases slightly with increasing temperature. It is directly proportional to the incident optical power.

b) Open circuit voltage (V_{OC}): It is logarithmically dependent on the solar irradiance. With the increase in temperature there is an increase in saturation current and results in reduction of the open circuit voltage [6].

c) Fill factor (F.F): It is dimensionless quantity and is a figure of merit defining the measure of deviation of the real I-V characteristics from the ideal one. It deteriorates strongly with the inclusion of parasitic resistive components like the series resistance and shunt resistance.

\[
F.F = (F.F)_o \times \left( 1 - \left( \frac{R_s}{V_{OC}/I_{SC}} \right) \right) 
\]

(2.1)
where \((F.F)_{o}\) is the fill factor for an ideal PV module/array without parasitic components [6]. Lower than ideal fill factors are caused by the shunt resistance, series resistance, and other non-ideal diode properties [7].

d) Maximum output power\((P_{max})\): This is the maximum power that can be delivered by the modules/array to the load. Commercial systems use this feature to demonstrate the performance of a PV system. It is a function of the fill factor, open circuit voltage, and short circuit current.

\[
P_{max} = (F.F) \ast (V_{OC} \ast I_{SC}) \quad (2.2)
\]

e) Efficiency\((\eta_{max})\): It is the ratio of electrical power the solar cell delivers to the load, to the optical power incident on it. Incident optical power is normally specified as the solar power on the surface of the earth which is 1 mW/mm\(^2\).

\[
\eta_{max} = \left(\frac{(F.F) \ast (V_{OC} \ast I_{SC})}{P_{in}}\right) \quad (2.3)
\]

The overall efficiency of the solar cell is expected to increase logarithmically with incident power. Since the solar cells are not very efficient, high sunlight concentration results in an increased energy loss inside the cell and higher temperature. The increased thermal effects and electrical losses in the series resistance of the solar cell limit the efficiency enhancement that can be achieved. So, efficiency of solar cells peaks at some finite concentration levels.
Each point on the I-V curve corresponds to a load resistance and a power delivered to the load. So, the I-V curve can easily be converted to a power vs. resistance curve. Also, for resistive loads the load characteristics is a straight line with slope $I/V = 1/R_L$ as shown in Figure 2-2 [8]. Figure 2-3 shows the power and voltage characteristics of a typical solar cell. Power delivered to the load depends on the value of the resistance. Maximum power transfer takes place while matching the load resistance to the value that generates peak power results. MPP trackers use different schemes to achieve this goal. Both the $I$-$V$ and $P_L - R_L$ curves are inter-convertible. The information content imparted by both is the same.
Figure 2-3: Power v/s Load Resistance Curve for Solar Cells

Figure 2-1 represents the ideal case solar cell 1-D model. But, there are certain manufacturing defects and parasitic elements added due to solder bonds, emitter and base region resistances, cell metallization, and cell-interconnect bus bars, and resistances in junction-box terminals. This is modeled as the series resistance Rs. The PN junction non-idealities such as metal migration causes partial shorting of the junction near the cell edges of the solar cell and this effect can be lumped as shunt resistance RSH.

Figure 2-4 is the electrical representation of a 1-D solar cell [9] with the following parameters: the photonic current IPH, the diode current ID, the total output current IM, series resistance Rs, and shunt resistance RSH. The developed models have been extended for use as solar arrays and in different patterns of shading.
2.2 Parasitic Elements in the Model

The performance of a PV module/ array is deeply affected by the choice of parasitic elements included in the model. An accurate knowledge of the series resistance and shunt resistance is particularly important for modeling PV modules behavior.

A single solar cell schematic has been designed in PSpice and the effect of varying series resistance and shunt resistance has been studied on the \( I-V \) characterization.

For the typical silicon solar cell used in the design here:

- Open circuit voltage (\( V_{OC} \)) = 0.63V
- Short Circuit current (\( I_{SC} \)) = 3.5A (Depends on the area of the solar cell)

2.2.1 Series Resistance

Series resistance occurs due to [7]

a) Movement of current through the emitter and base of the solar cell
b) Contact resistance between the metal contact and silicon
c) Resistance of the top and the rear metal contacts.


d) $R_S$ is also internal to the diode itself within the model [10]

For National Renewable Energy Laboratory, Copper Indium Gallium Selenide (NREL-CIGS) test solar cells, series resistance has a range between 0.2 Ω to 20 Ω [10].

### 2.2.1.1 Simulation of a single solar cell to study variations of Series Resistance $R_S$ on I-V characteristics

The illumination level across the cell is set at maximum with resulting photonic current at 3.5 A. For simplicity sake the short circuit current ($I_{SC}$) is assumed to be the same as the photonic current $I_{PH}$. Parametric analysis is carried out by varying the series resistance $R_S$ from .05 Ω to 0.5 Ω and the load resistance $R_L$ is varied between 0.01 Ω to 3 Ω.

![I-V characteristics for different values of Series Resistance](image)

**Figure 2-5:** $I-V$ Characteristics with Varying Series Resistance and Load at Fixed Illumination
RS does not affect a solar cell at open-circuit voltage because the overall current flow through the solar cell is zero. But, the effect of RS is clearly seen near the short-circuit conditions. The combined load resistance and series resistance are in parallel with the diode in the solar cell model. As the value of RS is increased, the voltage across it increases. This increases the voltage across the diode as well and the current through it. Since the diode current is exponential function of its voltage, a larger portion of the photonic current flows through the diode. So, the output current will decrease. Thus the current flowing through the diode RS is not constant and varies with electrical load and illumination or percentage of shading across the cells [7]. Series resistance is a particular problem at high current densities, for instance under concentrated light.

2.2.2 Shunt Resistance

Shunt resistance mostly arises due to [11]

a) Manufacturing defects, rather than poor solar cell design.

b) Leakage of current through the cell, around the edges of the device and between contacts of different polarity.
2.2.2.1 Simulation of a single solar cell to study variations of Shunt Resistance $R_{SH}$ on I-V characteristics

Similar to the previous case, full illumination level is maintained across the solar cell i.e. the photonic current ($I_{PH}$) is at 3.5A. For simplicity sake the short circuit current ($I_{SC}$) is assumed to be the same as the photonic current $I_{PH}$. Parametric analysis is carried out by varying the shunt resistance $R_{SH}$ from 0.1 $\Omega$ to 10 $\Omega$ in five steps and the load resistance $R_L$ is varied between 0.01 $\Omega$ to 3 $\Omega$.

![I-V Characteristics with Varying Shunt Resistance and Load at Fixed Illumination](image-url)

Figure 2-6: $I$-$V$ Characteristics with Varying Shunt Resistance and Load at Fixed Illumination
As can be seen in Figure 2-6, the effect of shunt resistance $R_{SH}$ is more prominent at the open circuit conditions than at the short circuit. The shunt resistance appears in parallel with the series combination of series resistance and load resistance. As the shunt resistance is reduced it reduces the overall output resistance. Thus the voltage drop across it and the parallel diode in the solar cell model decreases. This causes reduction in the output voltage across the load. The $I-V$ curves deteriorate with decrease in shunt resistance $R_{SH}$.

2.3 Results and Discussion

The above simulations clearly indicate that the $I-V$ characteristics are instrumental in extracting certain important solar cell parameters like the series and shunt resistance. For an ideal solar cell model $R_S$ is zero, and $R_{SH}$ would be very large. Since the effect of $R_S$ is negligible near open circuit conditions, the slope of the IV curve in that vicinity is an indicator of the value of $R_{SH}$. Conversely, since the effect of $R_{SH}$ is negligible near short circuit conditions, the slope of the curve in that vicinity is an indicator of the value of $R_S$. So, in short the variation of $dI/dV$ at short circuit enables determination of $R_{SH}$, whereas the variation of $dI/dV$ at open circuit determines $R_S[12]$.

Degradation in module/array performance is observed by:

a) Increasing $R_S$.

b) Decreasing $R_{SH}$. 

13
Chapter 3

Shading effects on different configurations of solar cells

Performance of a PV system is dependent on temperature, array configuration, solar insolation, and shading across it [3]. Shading can occur when the PV arrays/modules get covered by shadows of passing clouds, buildings, etc., or even by shadows cast by other modules/arrays. As a result the ideal operation of the PV systems is severely affected with deterioration in $P-V$ and $I-V$ characteristics.

Shading of solar cells is a critical issue in their performance because:

a) As the shaded cells can get reverse biased they consume power instead of generating power resulting in loss of total output power.

b) The power losses in the individual shaded cells would result in local heating and increase the temperature affecting surrounding cells. The increase in temperature creates thermal stress on the entire module and cause hot spots and local defects which potentially result in the failure of the entire array [13].
c) Under extreme cases of shading the reverse bias on the solar cell might exceed its break
down voltage. The cell gets fully damaged, develops cracks and an open circuit can occur
at the serial branch where the cell is connected [14].

Typically PV modules/arrays comprise of several solar cells that are interconnected in one of the following forms to attain realizable levels of output voltage and current: purely parallel connection, purely series connection, parallel-series interconnections [15]. A single solar cell operating in isolation when totally shaded may cause significant reduction in generated power. However the increase of irradiation and shadow rate in interconnected array of solar cells causes the shaded cell to dissipate power generated by other cells that would drastically reduce the peak power. Photovoltaic systems are modeled using circuit simulators such as PSPICE as they can accurately predict the behavior. However, these simulations require significant pre-processing to mimic shading conditions.

A readily available solar cell library in MATLAB /SIMULINK has been used by many authors to study effects of shading, but these models are not suited when it comes to integrating PV models for more complex arrays [16] [17] [18]. Instead, the modeling used in this thesis is an attempt to expand the circuit analysis of a single solar cell (as a single unit) for complex shading patterns on different topologies of the entire solar array. However in order to predict the performance of a solar array/modules under shaded conditions, a computer model is essential because testing on field is expensive. Moreover it is difficult to maintain the same level of shading or varying numbers of shaded and fully illuminated cells throughout the experiment [6]. Using higher-level modeling with MATLAB has gained importance in recent years as it provides a better system level
understanding of different interactions [9] [15] [19] [20] [21]. This facilitates a quicker solution to obtain the unique maximum power point (MPP) on its power–voltage ($P-V$) curve.

This chapter deals with studying the effects of shading on series connected solar cells, parallel connected solar cells, and modules with parallel connection of solar cells arranged in series rows (parallel in series architecture). The behavior of solar cells under shading pattern has been modeled in MATLAB and the results are compared with PSPICE.

### 3.1 Series-Connected Cells

Solar cells are connected in series so that voltage across each cell can be accumulated at the output. The cells in series carry the same current irrespective of the fact whether one or more cells under shade produce less photonic current. As the shading increases in a cell, its output voltage starts to fall. Under some shading conditions, in order to maintain the same output current a shaded cell can get reverse biased. Then the shaded cell consumes power instead of delivering power. This power is drawn from illuminated cells and thus reduces the overall power generated by the array. Power losses in the individual shaded cells would increase the temperature creating thermal stress on the entire module and cause hot spots and local defects [9].

To validate the models used between PSPICE and MATLAB, simulations using six series connected solar cells have been carried out. The diode model used in the simulations has the following parameters:
Reverse saturation current ($i_o$) = 8.67e-11A

Diode ideality factor (n) = 1.0

Series resistance ($R_s$) = 0.1Ω.

A fixed load that delivers peak power under no shading conditions has been used. For simplicity sake the short circuit current $I_{SC}$ is assumed to be the same as the maximum photonic current $I_{PH}$. Similar parameters for diode have been used in generating the equations developed for MATLAB.

### 3.1.1 PSPICE implementation for shaded series cells:

Shading has been implemented across a single cell by using the DC point analysis in PSPICE. The photonic current across one cell has been varied and the changes in the output voltage, output current, and power has been tabulated. Six different scenarios with shading ranging from 0% to 100% in steps of 20% have been studied and readings have been included.

![Diagram of six solar cells connected in series with shading ranging from No illumination to Full illumination across the Last cell](image)
Table 3.1: PSPICE results for Total Output Power under varying shading conditions for Six Series connected cells

<table>
<thead>
<tr>
<th>$I_{ph}$ of Shaded Cell (A)</th>
<th>$V_M$ across non Shaded Cells (V)</th>
<th>$V_M$ across Shaded Cell (V)</th>
<th>$V_{total}$ (V)</th>
<th>$I_{out}$ (A)</th>
<th>$P_o$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>0.1726</td>
<td>0.1726</td>
<td>1.034</td>
<td>3.4</td>
<td>3.51</td>
</tr>
<tr>
<td>2.8</td>
<td>0.308</td>
<td>-0.697</td>
<td>0.8344</td>
<td>2.81</td>
<td>2.34</td>
</tr>
<tr>
<td>2.1</td>
<td>0.3943</td>
<td>-1.333</td>
<td>0.6384</td>
<td>2.12</td>
<td>1.35</td>
</tr>
<tr>
<td>1.4</td>
<td>0.4731</td>
<td>-1.933</td>
<td>0.4334</td>
<td>1.44</td>
<td>0.62</td>
</tr>
<tr>
<td>0.7</td>
<td>0.549</td>
<td>-2.517</td>
<td>0.2283</td>
<td>0.76</td>
<td>0.17</td>
</tr>
<tr>
<td>0</td>
<td>0.623</td>
<td>-3.093</td>
<td>0.022</td>
<td>0.07</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The degradation in the output power with varying levels of shading has been noted in Table-3.1. Since the cells are in series the shaded cell can generate negative voltage with increasing level of shading [19].

The output power with full illumination across all the cells is 3.5 W. A voltage 0.17 V is generated across each cell and a total output current of 3.4 A flows through the load resistance. As the percentage of shading on the cell increased the output power starts to reduce and reaches its worst approximately 0.001 W for the 100% shading case. In case of no shading a significant part of photonic current in the solar cell model flows through the diode to generate enough voltage at the output. When the cell gets shaded, the photonic current is reduced. As a result the current that was previously flowing through the diode is also reduced. This allows less current to flow through the output. In order to maintain the same output current across each cell (since the cells are in series), the shaded cell operates under reverse bias and negative voltages are generated across the output voltage as indicated in the third column of Table-3.1. This effect becomes more prevalent as the percentage of shading across the cell under consideration is increased. The
deterioration of power from full illumination across all the cells to full illumination across five cells and 100% shading across the last cell is 99.74% for the given load. As the load is adjusted the deterioration can be mitigated.

### 3.1.2 MATLAB implementation for shaded series cells

Forward and reverse bias conditions are evaluated for determining if the particular cell is shaded depending on the value of the photonic current of the cell. An illumination vector comprising of six values ranging from 0 to \( I_{ph} \) is created for the shaded cell while the other five cells are operated at maximum value as was done in PSPICE. Initially a guess of the output current is passed as a single parameter to the solving function. Depending on whether the cell is shaded or illuminated the code executes the following set of equations for the solar cell and evaluates the output voltage.

For no shading: The following 1-Diode model is used to evaluate the output voltage across illuminated cell:

\[
V_{IL} = \left( n \cdot V_t \right) \cdot \ln \left( \frac{I_{PH} + i_o - I_M}{i_o} \right) - (I_M \cdot R_s) \quad (3.1)
\]

For shading condition: The above equation may not be valid if the device is operating in reverse bias mode. Then the output voltage across a shaded cell, \( V_{SH} \), can be approximated as:

\[
V_{SH} = \left( - \left( \left( I_{out} - i_o - I_{ph} \right) \cdot R_{sh} \right) \right) - (I_M \cdot R_s) \quad (3.2)
\]
The output voltage across the load is the summation of voltages across each series connected cells.

\[ V_{out} = \sum_{1}^{s} V_{SH} + \sum_{1}^{i} V_{IL} \quad (3.3) \]

where \( s \) represents the total number of shaded cells and \( i \) represent the total number of illuminated cells. Depending on the total output voltage, the output current is readjusted and the whole procedure is repeated iteratively. A bisection iterative method is used until the solution converges to appropriate values of output voltage. The results obtained by using this method have been tabulated and discussed in the Table 3.2.

Table 3.2: MATLAB readings for Total Output Power under varying shading conditions for Six Series connected Cells

<table>
<thead>
<tr>
<th>I_{ph} of Shaded Cell (A)</th>
<th>V_M across non Shaded Cells (V)</th>
<th>V_M across Shaded Cell (V)</th>
<th>V_total (V)</th>
<th>I_{out} (A)</th>
<th>P_o (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>0.1963</td>
<td>0.1963</td>
<td>1.17</td>
<td>3.4</td>
<td>4.00</td>
</tr>
<tr>
<td>2.8</td>
<td>0.3056</td>
<td>-0.4805</td>
<td>1.04</td>
<td>2.80</td>
<td>2.94</td>
</tr>
<tr>
<td>2.1</td>
<td>0.3912</td>
<td>-1.2125</td>
<td>0.74</td>
<td>2.12</td>
<td>1.58</td>
</tr>
<tr>
<td>1.4</td>
<td>0.4701</td>
<td>-1.7444</td>
<td>0.60</td>
<td>1.44</td>
<td>0.87</td>
</tr>
<tr>
<td>0.7</td>
<td>0.5454</td>
<td>-2.476</td>
<td>0.251</td>
<td>0.76</td>
<td>0.19</td>
</tr>
<tr>
<td>0</td>
<td>0.6195</td>
<td>-3.0476</td>
<td>0.05</td>
<td>0.076</td>
<td>0.003</td>
</tr>
</tbody>
</table>

The power drop from full illumination across all the cells to full illumination across five cells and 100% shading in the last cell is 99.95%. The voltage across the non shaded/shaded cells in the column 2 and 3 of Table-3.2 is very close to that obtained in the corresponding columns of Table 3-1. Negative voltages across respective shaded cells increase as the percentage of shading is increased. The deviation in the readings of total output power between modeling scheme used in MATLAB and circuit simulations done in PSPICE are between 5%-7%. The error deviation can be further improved by using more efficient iterative techniques that have been discussed in later chapters.
3.2 Parallel Cells

Manufacturers build solar cells with different configurations to obtain appropriate voltages and current across the load. In order to increase the currents, solar cells are connected in parallel. In parallel connection of cells the currents across each cell is summed up while the voltage remains constant across them.

Six parallel connected cells are simulated for their operation under changing shading scenario. Circuit simulations have been carried out in PSPICE and modeling has been implemented in MATLAB to replicate the same.

3.2.1 PSPICE implementation for shaded parallel cells

The circuit configuration used in PSPICE simulations comprises of six parallel cells as shown in Figure 3-2. Shading is carried out by varying the photonic current across the last cell. The pattern of shading is the same as in the series configuration.

Figure 3-2: Six Solar cells connected in Parallel with shading ranging from No illumination to Full illumination across the Last cell
Table 3.3: PSPICE readings for Total Output Power under Varying shading conditions for Six Series connected cells

<table>
<thead>
<tr>
<th>I_{ph} of Shaded Cell (A)</th>
<th>I_M across non Shaded Cells (A)</th>
<th>I_M across Shaded Cell (A)</th>
<th>I_{total} (V)</th>
<th>V_{out} (A)</th>
<th>P_o (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>1.541</td>
<td>1.541</td>
<td>9.246</td>
<td>0.46</td>
<td>4.27</td>
</tr>
<tr>
<td>2.8</td>
<td>1.553</td>
<td>1.456</td>
<td>9.22</td>
<td>0.46</td>
<td>4.25</td>
</tr>
<tr>
<td>2.1</td>
<td>1.57</td>
<td>1.33</td>
<td>9.18</td>
<td>0.46</td>
<td>4.21</td>
</tr>
<tr>
<td>1.4</td>
<td>1.6</td>
<td>1.107</td>
<td>9.11</td>
<td>0.46</td>
<td>4.14</td>
</tr>
<tr>
<td>0.7</td>
<td>1.663</td>
<td>6.50E-01</td>
<td>8.968</td>
<td>0.45</td>
<td>4.01</td>
</tr>
<tr>
<td>0</td>
<td>1.754</td>
<td>-0.01278</td>
<td>8.757</td>
<td>0.44</td>
<td>3.83</td>
</tr>
</tbody>
</table>

Table 3-3 shows the degradation in the output power as one of the cell in parallel is shaded ranging from 0% to 100%. The percentage loss in power from full illumination to no illumination across cell 6 is around 10.20% as compared to 99% in case of series cell. The amount of current across the non shaded cell increases slightly as the percentage of shading is increased but the current across shaded cell falls to minimum as indicated in columns 2 and 3 in Table 3-3. Column 4 sums up the current across all the cells to provide the total output current. The output voltage also remains almost constant over the different range of shading as shown in column 5 of Table-3.3.

Under uniform full illumination across each cell, portion of the photonic current flows through the diode and maintains the required voltage to produce an output current. All these individual currents add up to give the final current while voltage across each cell remains constant.

When one of the cells gets shaded, the amount of voltage at the diode required to produce the same output current is reduced. But in case of parallel cells this effect is very small. As the shading is increased, the photonic current of the shaded diode may not be enough to forward bias its diode. However, this is made up by portions of photonic
current from the five illuminated cells as they are connected in parallel. Thus the output voltage is still maintained constant but at a slightly lower value. However the total output current reduces resulting in reduced output power.

### 3.2.2 MATLAB Simulations for shaded parallel cells

The FZERO method in MATLAB is used to evaluate the roots of the nonlinear equation (8) for the output current. An initial guess for the output current and output voltage across each cell is passed as a starting parametric guess.

\[ I_M = I_{PH} - \left( i_o \ast \left( \exp \left( \frac{V_{IL}}{n \ast V_t} \right) - 1 \right) \right) - \left( \frac{V_{IL} + (I_M \ast R_s)}{R_{sh}} \right) \]  

(3.4)

Using the above equation current through each cell is calculated. Since total output voltage across parallel connected cells remain constant, the total output current across the whole configuration can be mathematically written as follows:

\[ I_{out} = \sum_{1}^{s} I_{SH} + \sum_{1}^{i} I_{IL} \]  

(3.5)

where \( I_{out} \) = total output current, \( I_{SH} \) = total current across shaded cells , \( I_{IL} \) = total current across illuminated cells, \( s \) represents the total number of shaded cells and \( i \) represent the total number of illuminated cells.

Once the output current across each cell is obtained, they all are summed together and passed as a returning value to the main function. Here the convergence condition is checked and iterations are performed by readjusting the values of the output voltage to calculate the output current.
A scenario is created wherein five of the six cells are illuminated at the maximum value of the photonic current (3.5A) and the shading of the last cell is varied as shown in the first column of Table 3-4.

Table 3-4: MATLAB readings for Total Output Power under Varying Shading conditions for Six Parallel connected Cells

<table>
<thead>
<tr>
<th>$I_{ph}$ of Shaded Cell (A)</th>
<th>$I_M$ across non Shaded Cells (A)</th>
<th>$I_M$ across Shaded Cell (A)</th>
<th>$I_{total}$ (V)</th>
<th>$V_{out}$ (A)</th>
<th>$P_o$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>1.527</td>
<td>1.527</td>
<td>9.16</td>
<td>0.46</td>
<td>4.21</td>
</tr>
<tr>
<td>2.8</td>
<td>1.54</td>
<td>1.432</td>
<td>9.13</td>
<td>0.46</td>
<td>4.20</td>
</tr>
<tr>
<td>2.1</td>
<td>1.55</td>
<td>1.295</td>
<td>9.04</td>
<td>0.46</td>
<td>4.16</td>
</tr>
<tr>
<td>1.4</td>
<td>1.62</td>
<td>1.064</td>
<td>8.96</td>
<td>0.46</td>
<td>4.12</td>
</tr>
<tr>
<td>0.7</td>
<td>1.69</td>
<td>6.28E-01</td>
<td>8.87</td>
<td>0.46</td>
<td>4.08</td>
</tr>
<tr>
<td>0</td>
<td>1.527</td>
<td>-0.01278</td>
<td>7.62</td>
<td>0.46</td>
<td>3.50</td>
</tr>
</tbody>
</table>

Table- 3.4 gives the readings of total output power obtained for shaded parallel cells implemented in MATLAB. The degradation of output current with full illumination to fully shade is around 16.84%. The amount of current generated by the shaded cell in column 3 of Table3-4 drops as the percentage of shading is increased.

The total output voltage across the six parallel cells remains almost same close to 0.46V for PSPICE and MATLAB. The difference in the total currents for corresponding shading values in PSPICE and MATLAB fall under 7%.

3.4 Random Shading for a $N_s \times N_p$ module

A generic algorithm to understand the effect of random shading pattern on a Parallel in Series architecture has been designed using MATLAB and results are discussed. A module with $N_p$ parallel strings in each of the $N_s$ serially connected strings is considered.
In order to predict $I-V$ and $P-V$ characterization of the module at random shading pattern. The approach has been extended to special shading cases. Additionally the effect of load resistance variation on the maximum power point under different shading patterns is performed.

The algorithm developed is a general case for studying the effects of any pattern of shading across the cells in the array configuration for user defined number of parallel and series cells. Iterative techniques used to solve the nonlinear equations of the model are based on the flowchart given in Figure 3-5. The model is solved to yield the solution for the individual cell currents. The size of the module has been customized to have 45 parallel cells in each of the 26 series rows (to generate approximately 1KW power).
Figure 3-3: Flow Chart for Modeling Shading across Random Solar Cells in a Module
Each cell in the structure is tested for forward bias or reverse bias condition with initial module current estimate. Depending on whether \( I_{PH} > I_M \) or \( I_{PH} < I_M \), the cell is operating in either illuminated or shaded condition. Shading results in reduced photonic interactions in the solar cells and results in reduced power output and is represented in the solar cell model with reduced photonic currents. Depending on the evaluation of the photonic current, (3.6) and (3.7) are used to determine the output voltage for illuminated and shaded cases respectively. For each of the serial strings, the output voltage \( V_M \) across each cell is calculated at respective illumination level and summed over to derive the total output voltage \( V_{OUT} \).

\[
V_{IL} = (n * V_t) * \ln \left( \frac{(I_{ph} + i_o - I_M)}{i_o} \right) - (I_M * R_s) \quad (3.6)
\]

\[
V_{SH} = -\left( (I_{out} - i_o - I_{ph}) * R_{sh} \right) - (I_M * R_s) \quad (3.7)
\]

The negative sign in the first term of (11) accounts for the negative voltage that a shaded cell generates.

### 3.5 Discussion

The results obtained from PSPICE and MATLAB match very well and they show that the power loss under shading is relatively very low for parallel connected cells as compared to for series connected cells. Thus a solar array in parallel configuration has performance which is superior to series cell configuration. But there are some drawbacks to using parallel connected cells. Since excessively high current flow through parallel cells as compared to the series connection; larger currents result in higher \( I^2R \) losses.
which can be potentially hazardous to the capacity of the cell due to overheating [21]. Over-heating results in hot-spot formation. However for rapidly varying shading conditions in low voltage systems for portable applications, a highly parallel-configured PV system operates effectively.

Series or parallel solar cells are unable to provide current and voltage specifications needed to realize an actual deployable PV system. Thus, these cells are inter-connected amongst themselves to obtain higher output voltage or current specifications. The most popular architecture is the one in which the solar cells are connected in series string and several such strings are connected in parallel shown in Figure 3-3.

![Figure 3-4: Module having Series connected Cells in Parallel Columns (Series-Parallel)](image)

Shading on a single solar cell in a particular series string renders the entire column ineffective as the cells carry the same current. The shaded cell in the series string produces reverse voltage and starts consuming power than generating to the load. The output power reduces significantly for the series string. If many cells are shaded in
parallel this causes severe degradation effects. However, researchers have shown that, this architecture is attractive for use when percentage of shading can be kept really low [23]. In that case, it performs very well without the need of protective bypass diodes. Thus it makes a simpler and cost-effective design.

The cells in the solar panel can also be tied in three other configurations. They are the Total Cross Tied (TCT), Bridge Linked (BL), and Honey Comb (HC) as shown in Figure 3-4 (a), (b) and (c) [24]. It is observed that the TCT architecture is superior to the other architectures in terms of its maximum power and Fill Factor performance under shaded scenario [25]. SP has the lowest performance under shading conditions while BL and HC have comparable performance [26].

Figure 3-5: (a)Total Cross Tied (TCT) (b) Bridge Linked (BL) (c) Honey Comb (HC)
This thesis looks into the modeling of a PV system interconnecting the solar cells in the Parallel in Series architecture. In this parallel cells are connected in series rows. This configuration is not very commonly used but has recently started gaining importance [2] [22] [23] [24]

3.5.1 Shading across random cells in $N_S \times N_P$ array design

A typical scenario studied for shading across different cells in the array is shown in Figure 3-5. This is a rather complex illumination pattern to analyze where the voltage and the current across each cell is different depending on the insolation received at the respective cell.

![Random illumination pattern across Random cells in the 26X45 Module](image)

Figure 3-6: Random illumination pattern across Random cells in the 26X45 Module
A 1% difference in the following equation: \( V_{OUT} - I_{OUT} \times R_L \) is used to determine the convergence of the entire module where \( R_L \) is the load resistance, \( V_{OUT} \) is the output voltage of the module and \( I_{OUT} \) is the output current of the module. The process is continued until convergence takes place.

### 3.6 Specific Shading Patterns from the General Model

The following three specific patterns of shading across \( N_S \times N_P \) array of cells have been analyzed in detail.

#### 3.5.1 Row Wise Shading of 26X45 Cell Array

The general model discussed above is used to create a scenario where uniform shading is applied across the first parallel string of the 26X45 array configuration and is shown in Figure 3-7. All other cells of the array are at maximum illumination. Fixed resistive load is maintained at the output to study the degradation in the maximum power transferred. Similar structure is implemented in PSPICE and the results are compared with the model.
3.5.2 Column wise shading of 26X45 cell array

For a fixed load resistance, a second scenario with uniform shading across the first cell of each of the 26 parallel strings and maximum illumination across the other cells is maintained as shown in Figure 3-8. An initial guess of total output voltage is provided which is used to calculate the output current across each cell.
3.6.3 Triangular pattern of shading across 26X45 cell array

In the triangular pattern of shading of the array the assignment of the shading levels to the individual cells is made in such a way so as to shade only the lower left corner portion of the array as shown in Figure 3-9. Fixed resistance at the output is used and degradation in power for different shading levels is noted in proposed model and PSPICE.
3.7 Results and Discussion

A generic code for evaluating the performance of a solar cell module with different levels of shading across random positions in the architectural design has been implemented and applied to cases such as row-wise, column-wise and triangular patterns. All the shading patterns are modeled to observe the degradation in the power delivered to the fixed load resistance and also for varying load values. The results of the reduction in power transferred to the fixed load resistance for different shading patterns across the array is tabulated in Table 3-5.
Table 3.5: Output power for Row, Column and Triangle shading pattern with a Fixed Load.

<table>
<thead>
<tr>
<th>Shading (%)</th>
<th>Column-Wise Shading Pattern</th>
<th>Row-Wise Shading Pattern</th>
<th>Triangle Shading Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output Power from PSPICE (W)</td>
<td>Output Power from MATLAB (W)</td>
<td>Output Power from PSPICE (W)</td>
</tr>
<tr>
<td>0</td>
<td>653.6</td>
<td>607.2</td>
<td>653.69</td>
</tr>
<tr>
<td>20</td>
<td>653.1</td>
<td>606.2</td>
<td>653.03</td>
</tr>
<tr>
<td>40</td>
<td>652.7</td>
<td>606.5</td>
<td>652.01</td>
</tr>
<tr>
<td>60</td>
<td>651.9</td>
<td>600.3</td>
<td>649.86</td>
</tr>
<tr>
<td>80</td>
<td>650.6</td>
<td>600.2</td>
<td>376.57</td>
</tr>
<tr>
<td>100</td>
<td>648.1</td>
<td>601.1</td>
<td>51.48</td>
</tr>
</tbody>
</table>

Under uniform full illumination across each cell, a portion of the photonic current flows through the diode and maintains the necessary output voltage of the cell. The rest of the current serves as the output current of the cell. In the 26X45 cell solar module, all the individual currents of each 45 parallel strings add up to give the final current for the solar array while the voltage across each 26 parallel string remains constant at the output voltage.

For column-wise shading pattern (column 1 of Table 3-5): When the first cell across each 45 parallel strings is shaded, the amount of voltage at the diode required to produce the same output current is reduced resulting in a smaller cell output voltage and a reduced array output voltage. As the percentage of shading is increased, the photonic current cannot keep the diode forward biased. As a result, a portion of the current from the remaining 44 parallel illuminated cells flows through the diode of the shaded cell and voltage is still maintained constant. For the column wise shading, the percentage degradation in the total output power from no illumination to full illumination is 0.8% in PSPICE while that of the proposed model is 1%.
For Row-Wise shading pattern (column 2 of Table 3-5): The parallel strings of solar cells are connected in series rows. The current through each of the series rows should be same. When an entire row gets shaded, the photonic currents may or may not be enough to maintain a constant output current. If the sum of photonic currents in the row is greater than the output current of the module, then the row will generate a positive voltage. However, if the photonic currents are smaller then the entire row gets reverse biased and start dissipating power that is generated by other rows. This explains the extreme degradation of output power when the row is shaded beyond 80% and above.

An error of 5% - 7% in the measured values of power degradation between the proposed model and PSPICE measurements is observed in all the three shading scenarios. One source for this disparity is the condition for convergence is set to less than or equal to ±0.1 V for each cell. When this error is compounded over the entire cells in the array, the cumulative error adds up. In addition, simplified models are used in the proposed model as compared to those used in PSPICE.

3.8 Variation of load resistance to observe maximum power point

The load resistance is varied ranging from 0.01Ω to 3Ω for all the three shading patterns in order to observe the variation of power with load resistance. Figure 3-9 shows the results of output power variation against changing load resistance measured from proposed model in MATLAB and PSPICE.
Figure 3-10: Output Power v/s Load Resistance for Random shading pattern with Random illumination of cells in the 26X45 Array Design

Table 3.6: Variation of Load Resistance for Column-Wise, Row-Wise, Triangle Shading Patterns across 26X45 Array

<table>
<thead>
<tr>
<th>Shading (%)</th>
<th>R_L (Ω)</th>
<th>P_OUT (W)</th>
<th>R_L (Ω)</th>
<th>P_OUT (W)</th>
<th>R_L (Ω)</th>
<th>P_OUT (W)</th>
<th>R_L (Ω)</th>
<th>P_OUT (W)</th>
<th>R_L (Ω)</th>
<th>P_OUT (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.87</td>
<td>1021.6</td>
<td>0.86</td>
<td>1010.8</td>
<td>0.87</td>
<td>1021.1</td>
<td>0.86</td>
<td>1012</td>
<td>0.8</td>
<td>1021</td>
</tr>
<tr>
<td>20</td>
<td>0.86</td>
<td>1007.5</td>
<td>0.85</td>
<td>997.71</td>
<td>0.85</td>
<td>996.3</td>
<td>0.84</td>
<td>988.1</td>
<td>0.8</td>
<td>1000</td>
</tr>
<tr>
<td>40</td>
<td>0.84</td>
<td>983.09</td>
<td>0.83</td>
<td>972.75</td>
<td>0.78</td>
<td>915.1</td>
<td>0.77</td>
<td>909.4</td>
<td>0.8</td>
<td>958</td>
</tr>
<tr>
<td>60</td>
<td>0.80</td>
<td>943.41</td>
<td>0.79</td>
<td>933.66</td>
<td>0.61</td>
<td>722.3</td>
<td>0.61</td>
<td>722.1</td>
<td>0.7</td>
<td>883</td>
</tr>
<tr>
<td>80</td>
<td>0.76</td>
<td>897.14</td>
<td>0.75</td>
<td>887.25</td>
<td>0.35</td>
<td>413.7</td>
<td>0.35</td>
<td>417.2</td>
<td>0.6</td>
<td>792</td>
</tr>
<tr>
<td>100</td>
<td>0.72</td>
<td>850.93</td>
<td>0.71</td>
<td>841.57</td>
<td>0.00</td>
<td>6.5</td>
<td>0.00</td>
<td>1.6</td>
<td>0.5</td>
<td>693</td>
</tr>
</tbody>
</table>
Similarly, the load resistance was varied to study power under uniform shading levels for row, column, and triangle shading patterns. A unique value of load resistance transfers maximum power from the solar cell array to its output [29] [30]. Table 3-6 clearly validates this and shows the peak power is obtained at different load resistance values under the three shading patterns. The peak power load resistance lies within 7% for all the three shading patterns for PSICE and MATLAB simulations.

For all the three cases, the maximum peak occurs with no shading at a relatively higher value of load resistance. As shading is introduced, the effective value of \( V_{\text{Peak}} \) and \( I_{\text{Peak}} \) is reduced. The maximum extracted power now occurs at a lower value of load resistance.

### 3.9 Advantages of using the proposed modeling technique

Random shading across cells within the modules can be easily evaluated in the proposed model whereas the circuit simulation involves significant preprocessing. Additionally the effect of load resistance variation on the maximum power point under different shading patterns is performed. This type of modeling can be extended to any type of shading patterns.
3.10 Disadvantages of using the discussed Modeling technique

The discussed technique makes use of FZERO function in MATLAB to converge and initial roots are estimated using bisection methods. In terms of faster processing this is not efficient for larger systems (with arrays incorporating modules). In such cases it becomes imperative to derive at the solution of the complex non-linear equations of the solar cells relatively quickly. Also, the accuracy is improved if the convergence criteria are more restrictive but this comes with additional computation time. For this purpose, faster iterative techniques like Newton-Raphson have been used by several researchers to deal with non-linearity of solar cells [20] [31]. The same method has been extended for use in the later sections of the thesis.

3.11 Newton–Raphson Technique to improve the Simulation time and Accuracy

A general description of the Newton-Raphson iterative technique to find a root or solution of a function is given in this sub-section. An initial guess for the root, $x_o$, of the function $f(x)$ is made. The function can be expanded using Taylor Series around this initial value and is given as [32]:

$$f(x) = f(x_o) + f'(x_o)(x - x_o) + \frac{f''(x_o)(x - x_o)^2}{2} + \cdots \quad (3.8)$$

If the initial guess was correct, then the value of $(f(x)-f(x_o))$ will be negligibly small. If the initial guess $x_o$ is close to the actual root $r$ then higher order power terms starting with $(r - x_o)^2$ are negligibly small and the function value at the root $f(r)$ is approximated as given below:
\[ f(r) \approx f(x_o) + f'(x_o)(r - x_o) \]  

(3.9)

Since \( r \) is the root of the equation \( f(r) \) should be zero. Thus the next guess at which the original function \( f(x) \) should be evaluated is as follows:

\[ r = x_o + \frac{f(x_o)}{f'(x_o)} \]  

(3.10)

A good iterative procedure should be able to improve on the initial guess and eventually make the function \( f(x) \) negligible. The non linear current-voltage equation of solar cell \( f(V_{IL}, I_M) \) is given as:

\[ f(V_{IL}, I_M) = I_{PH} - \left( I_o \ast \left( \exp \left( \frac{V_{IL} + (I_M \ast R_S)}{n \ast V_t} \right) - 1 \right) \right) - \frac{(V_{IL} + (I_M \ast R_S))}{(R_{sh})} - I_M \]  

(3.11)

The first order derivative of the above equation is mathematically represented as follows [33]:

\[ f'(V_{IL}, I_M) = \left( \frac{(I_o \ast R_S)}{V_t} \right) \ast \left( \exp \left( \frac{V_{IL} + (I_M \ast R_S)}{V_t} \right) \right) - \frac{R_S}{R_{sh}} - 1 \]  

(3.12)

The next guess for the root is given by:

\[ I_{x+1} = I_x - \frac{f(V_{IL}, I_M)}{f'(V_{IL}, I_M)} \]  

(3.13)

The next value is used to iterate through the equation and this continues until the solution converges to the real root making the function minimum.

Newton’s method is a widely used iterative technique and converges faster with efficient computations. Since it takes comparatively less time to find the roots of an equation it is used for efficient prediction of their operation of PV modules and arrays under complex shading patterns.
Chapter 4

Modeling Solar Modules with Bypass Diodes

This chapter deals with the modeling of the impact of bypass diodes on the protection of solar modules operating under shading conditions. The basic solar cell model from Chapter 3 is used but with an additional feature of a bypass diode incorporated at the module level and is shown in Figure 4-1. The bypass diode is mathematically represented by equation (4.1)
\[ I_{BP} = i_{BP} \exp \left( \frac{-V_{BP}}{nV_t} \right) - 1 \] (4.1)

Two separate set of the codes with and without bypass diodes has been implemented in MATLAB and used for comparing the performances. A module comprising of 10X20 (20 parallel strings in 10 series row each) solar cells is used in the comparison of the results obtained from the two sets of codes. Depending on the illumination levels across the cells in the modules, it is possible to study and predict the performance of both configurations for different shading patterns.

4.1 Without Bypass Diodes:

In shaded solar cells that are not protected by bypass diodes, the reverse voltage developed across them can become very large. Due to these large reverse voltages the cells dissipate power and develop hot spots. If this issue is not taken care of, the hot spot problems can destroy the semiconductor structure of the shaded solar cell leading to failure of the photovoltaic system in the long run.

4.1.1 Modeling a $N_S \times N_P$ module without bypass diodes

Figure 4-2 presents the flow chart used to model the solar cell currents of a module without the bypass diodes. The user can decide the number of solar cells in the parallel rows that are connected in series. In our case, 20 parallel cells are connected in 10 series rows each. An initial guess of voltage across the 10 rows is defined in a column vector $V_{OCN_S}$. Also a total range of operating output currents across the module is assigned $i_{total}$. Summation of the photonic currents in each of the ten rows is evaluated. Two different
conditions are evaluated for comparison between the summed value of the photonic current in a row and the pre-defined range assigned for each value of $i_{\text{total}}$. This is done to distinguish between the forward biases and reverse bias condition. The forward bias condition incorporates Newton-Raphson technique to solve the non linearity relation between the current and voltage relation of solar cells. A set tolerance value is used on photonic current of every cell and respective voltage obtained from the initial guess of $V_{\text{OCNS}}$ of that row. The motive is used to minimize the current-voltage equation given in by iterating through next guess of $I_{\text{out}}$ under the set tolerance value given in (3.11) and (3.12). The value of the voltage $V_{\text{OCNS}}$ for each row is adjusted (increasing or decreasing) in steps depending on whether the error is greater or lesser than the set tolerance value. All the currents for the forward biased cell in each parallel row is added and compared with the initial $i_{\text{total}}$. The whole procedure is repeated unless the error falls within the specified convergence criteria.

The second condition to be evaluated for solar cells is when the cells are operating in reverse bias mode. In this case, a general equation for determining the output current given by equation (3.2) is used. The currents for the reverse biased cell in every row is added, and compared with the initial $i_{\text{total}}$. The difference is calculated. If this difference lies out of the range of the convergence condition defined, then the voltage at that row is adjusted (increased or decreased) in steps and the new set of current values are calculated.

When all the cells in every row for a particular value of $i_{\text{total}}$ are in the specified range, then the voltages in $V_{\text{OCNS}}$ column vector are summed up. It is important to note that the whole procedure is carried out for every guess of $i_{\text{total}}$ in the specified range. Thus
the corresponding value of output voltages is determined for an entire range. The technique is useful since maximum or peak power is tracked over an entire range of operation for the illumination levels across all the cells.

Figure 4-2: Flow Chart to Model a Solar Cell Module Without Bypass Diodes
4.2 With Bypass Diodes

The bypass diodes allow current to pass around shaded cells and thereby reduce the voltage loss across the module. However using bypass diodes causes different voltage levels to develop in a solar array.

In the absence of bypass diodes, large reverse voltage can develop across a shaded parallel string in the module. When a bypass diode is present, it becomes “forward biased” and provides a path for the module current to bypass the solar cell(s) diode. This limits the negative voltage developed across the bypassed cells to approximately 0.4 V to 0.7 V. This smaller negative voltage improves the overall output voltage of the solar module. In addition, the reduced voltage drop across the shaded cells also reduces the power consumption in the shaded cells. This reduction in power consumption results in reduced local heating at the shaded area and extends the life time of the solar cell.

A non-overlap bypass diode configuration has been used in the modeling as shown in Figure 4-3. A bypass diode has been incorporated across each of the 10 series rows within the 10X20 module structure. Each bypass diode will provide an alternative path for module current based on the operating conditions.
A configuration of solar module with overlapping bypass diodes is shown in Figure 4-4. Depending on the sub-section of solar cells that are shaded either Diode1 or Diode 2 will conduct [34]. If cells in sub-section 1 and/or sub-section 2 are shaded, then diode 1 would conduct. Bypass diode 2 will conduct if Subsection 3 and/or 3 are shaded and thus...
would restrict the maximum reverse voltage to the reverse voltage of the diodes. Similarly if cells within sub-section 2 are shaded then both Diode 1 and Diode 2 would conduct but carry different currents. If all the sub-sections are shaded, then both the diodes may conduct. Under no shading, the diodes will not conduct and will be off.

Progressive shading pattern on a solar cell module comprising of 72 series cell distributed in 6 rows with 12 cells in each have been carried out in [35]. \( I-V \) and \( P-V \) curves are plotted with overlapping and non-overlapping diode configuration and it has been observed that the power losses in PV modules with overlapped diodes can be one third of its peak power. In the PV modules with no-overlapped bypass diodes, the power losses are only produced by the power consumption of the diodes [35].

Non-overlapping bypass diode architecture has been used in the modules across each parallel row. The current and voltage specifications for the bypass diode as calculated in Appendix A results in the reverse saturation current of (4.1)

\[
i_{BP} = 9.485e - 8 \text{ A}
\]

This value is used for the bypass diode’s reverse saturation current in simulating the module (10X20) incorporating them across every row.

All the cells within the module are illuminated randomly but lie within a predefined range of values. This is achieved by assigning a row vector of illumination values (values taken by cell photonic current) randomly distributed across the cells.
4.2.1 Modeling a $N_S \times N_P$ module with Bypass Diodes

The basic algorithm for the analysis of the modules still remains the same as discussed before with a small difference of additional section for bypass diode. After the forward bias and reverse bias conditions are evaluated depending on whether the cells are illuminated or partially shaded, respectively; equation (4.1) is solved and the current through the bypass diode is evaluated. This is added to the currents in the cells at forward bias and reverses bias conditions. Similar to the previous case, the difference in the calculated output current for every value in the range of $i_{\text{total}}$ is evaluated and depending on this difference the voltage at the particular row is modified in steps to calculate new set of output current values. The whole algorithm is run over the range of $i_{\text{total}}$ values to generate $P-V$ and $I-V$ curves for the maximum power point for random shading patterns in the module.
4.3 Results and Discussion

Several cases are discussed below showcasing the effectiveness of using bypass diodes and results have been compared when no bypass diode is used in the modules.

Case 1: Array Design incorporating Modules with and without Bypass Diodes

An array of 12 solar modules arranged in the parallel in series configuration with 3 parallel modules in each of the 4 series rows has been used. Each module has 20 parallel cells in each of the 10 series rows. In the first six modules in the array: the last three rows are maintained at 100% shading (zero illumination) while the remaining cells have 0% shading (full illumination). The remaining six modules have random distribution of illumination levels. This is shown in Figure 4-5(a) and Figure 4-5(b). All the modules are protected internally with bypass diodes across each row in Figure 4-5(b) whereas the bypass diodes are absent in Figure 4-5(a). Both arrays are incorporated with modules having the same illumination and shading level as described above and $P-V$ and $I-V$ curves are plotted in Figure 4-6 and Figure 4-7 respectively.
Figure 4-5: (a) Array comprising of Modules Without Bypass Diodes (b) Array comprising of Modules With Bypass Diodes
Figure 4-6: $P-V$ Curves With and Without Bypass Diode

Figure 4-7: $I-V$ Curves With and Without Bypass Diodes
With bypass diodes across each rows in the modules used, the performance of the array to produce output power is increased considerably as compared to that without the use of bypass diodes. This is indicated in the Table 4-2.

Table 4.1: Variation of Individual Row Voltage with Load Current Without Bypass Diode

<table>
<thead>
<tr>
<th>Row I (Volts)</th>
<th>Row II (Volts)</th>
<th>Row III (Volts)</th>
<th>Row IV (Volts)</th>
<th>Total Output Current (Amps)</th>
<th>Total Output Voltage (Volts)</th>
<th>Total Output Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.66</td>
<td>5.66</td>
<td>6.8</td>
<td>6.8</td>
<td>0.5</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>4.01</td>
<td>4.01</td>
<td>7.02</td>
<td>7.02</td>
<td>2.5</td>
<td>22</td>
<td>55</td>
</tr>
<tr>
<td>3.2</td>
<td>3.2</td>
<td>6.7</td>
<td>6.7</td>
<td>8</td>
<td>20</td>
<td>160</td>
</tr>
<tr>
<td>2.75</td>
<td>2.75</td>
<td>6.2</td>
<td>6.2</td>
<td>8.5</td>
<td>18</td>
<td>153</td>
</tr>
<tr>
<td>-5.17</td>
<td>-5.17</td>
<td>5.88</td>
<td>5.88</td>
<td>9.0</td>
<td>1.42</td>
<td>12.78</td>
</tr>
</tbody>
</table>

Table 4.2: Variation of Individual Row Voltage with Load Current With Bypass Diode

<table>
<thead>
<tr>
<th>Row I (Volts)</th>
<th>Row II (Volts)</th>
<th>Row III (Volts)</th>
<th>Row IV (Volts)</th>
<th>Total Output Current (Amps)</th>
<th>Total Output Voltage (Volts)</th>
<th>Total Output Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.96</td>
<td>2.96</td>
<td>5.74</td>
<td>5.74</td>
<td>15</td>
<td>17.4</td>
<td>261</td>
</tr>
<tr>
<td>2.4</td>
<td>2.4</td>
<td>5.04</td>
<td>5.04</td>
<td>47.5</td>
<td>14.88</td>
<td>706.8</td>
</tr>
<tr>
<td>1.92</td>
<td>1.92</td>
<td>3.83</td>
<td>3.83</td>
<td>80.5</td>
<td>11.52</td>
<td>927.5</td>
</tr>
<tr>
<td>1.65</td>
<td>1.65</td>
<td>0.67</td>
<td>0.67</td>
<td>100</td>
<td>4.64</td>
<td>464</td>
</tr>
</tbody>
</table>

For the modules with last three rows at 100% shading, the shaded cells cannot produce enough current output for the fixed voltage across that row (parallel cells in the respective series row has the same voltage). In this case, the value of total current flowing through the module becomes greater than the summation of photonic currents in the individual last three rows. As a result of which the rows start pulling current from the
remaining illuminated rows. This causes the shaded cell to operate in reverse bias mode and produces an effectively high negative voltage for modules if bypass diodes are not used. This can be seen in Table 4.1 where Row I and Row II generate negative voltages and operate under reverse bias condition for an output current of 9A. Power across the load reduces drastically to very low values. The shaded cells start consuming power instead of generating. For modules having bypass diodes with random shading patterns limit the voltage drop to match the current requirements. The bypass diodes across these modules do not turn on and the modules themselves continue to operate in the forward biased mode.

With the use of bypass diodes, the negative voltage effects in the shaded row are mitigated as the bypass diode starts to conduct. The excess of module current over the photonic current passes through the bypass diode. It restricts the maximum reverse voltage across that row to be equal to the forward-bias voltage of the diode. As a result, the shaded cells do not produce very high reverse negative voltages resulting in a larger output voltage and increased output power. This is clearly indicated in Table 4.2 where the use of bypass diodes across the shaded cells effectively generates positive voltage across the output. However the use of bypass diodes, introduces multiple peaks in the $I-V$ and $P-V$ curves. Therefore the system may not be able to track maximum peak power and may settle in a local peak power point. Moreover the curves seem to be distorted in shape from the convention making it difficult to characterize the modules/arrays. This effect becomes more prominent for cases where shading is relatively high [36]. More complex algorithms are needed by the MPPT control circuitry to resolve this issue.
Case 2: Random illumination across Modules with and without Bypass Diodes

a) In this case, both the modules (with and without bypass diodes) have a triangular pattern at 100% shading and the remaining cells are assigned random illumination. Figure 4-8(a) and Figure 4-8(b) below depicts the architecture. This is a case of intermediate level of shading across a module. P-V and I-V curves for modules with and without bypass diodes are plotted in Figure 4-9 and Figure 4-10 respectively. Though relatively high power levels are observed for modules with bypass diodes (54.36 W) as compared to modules without bypass diodes (4.4W), the problem of shape distortion due to multiple peaks cannot be avoided.

![Diagram showing modules with and without bypass diodes](image)

**Figure 4-8:** (a) Modules Without Bypass Diodes  (b) With Bypass Diodes- 100% Shading in a Triangular Pattern and Random Illumination across remaining Cells
Figure 4-9: $P-V$ Curves With and Without Bypass Diodes

Figure 4-10: $I-V$ Curves With and Without Bypass Diodes
Table 4.3: Variation of Individual Row Voltage with Load Current Without Bypass Diode

<table>
<thead>
<tr>
<th>Total Current (Amps)</th>
<th>0.5</th>
<th>0.68</th>
<th>1.07</th>
<th>1.805</th>
<th>1.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row 1 (Volts)</td>
<td>0.604</td>
<td>0.603</td>
<td>0.601</td>
<td>0.596</td>
<td>0.595</td>
</tr>
<tr>
<td>Row 2 (Volts)</td>
<td>0.617</td>
<td>0.616</td>
<td>0.613</td>
<td>0.609</td>
<td>0.608</td>
</tr>
<tr>
<td>Row 3 (Volts)</td>
<td>0.605</td>
<td>0.603</td>
<td>0.601</td>
<td>0.597</td>
<td>0.595</td>
</tr>
<tr>
<td>Row 4 (Volts)</td>
<td>0.603</td>
<td>0.602</td>
<td>0.6</td>
<td>0.596</td>
<td>0.594</td>
</tr>
<tr>
<td>Row 5 (Volts)</td>
<td>0.603</td>
<td>0.601</td>
<td>0.599</td>
<td>0.595</td>
<td>0.593</td>
</tr>
<tr>
<td>Row 6 (Volts)</td>
<td>0.597</td>
<td>0.596</td>
<td>0.594</td>
<td>0.589</td>
<td>0.588</td>
</tr>
<tr>
<td>Row 7 (Volts)</td>
<td>0.595</td>
<td>0.594</td>
<td>0.592</td>
<td>0.587</td>
<td>0.586</td>
</tr>
<tr>
<td>Row 8 (Volts)</td>
<td>0.586</td>
<td>0.584</td>
<td>0.582</td>
<td>0.576</td>
<td>0.575</td>
</tr>
<tr>
<td>Row 9 (Volts)</td>
<td>0.298</td>
<td>0.262</td>
<td>-0.311</td>
<td>-1.825</td>
<td>-2.206</td>
</tr>
<tr>
<td>Row 10 (Volts)</td>
<td>0.298</td>
<td>0.262</td>
<td>-0.311</td>
<td>-1.825</td>
<td>-2.206</td>
</tr>
<tr>
<td>Total Voltage (Volts)</td>
<td>5.906</td>
<td>5.323</td>
<td>4.16</td>
<td>1.095</td>
<td>0.322</td>
</tr>
<tr>
<td>Total Power (Watts)</td>
<td>2.953</td>
<td>3.61964</td>
<td>4.4512</td>
<td>1.976475</td>
<td>0.6279</td>
</tr>
</tbody>
</table>

Table 4.4: Variation of Individual Row Voltage with Load Current With Bypass Diode

<table>
<thead>
<tr>
<th>Total Current (Amps)</th>
<th>5</th>
<th>12</th>
<th>25.5</th>
<th>34</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row 1 (Volts)</td>
<td>0.576</td>
<td>0.534</td>
<td>0.42</td>
<td>0.257</td>
</tr>
<tr>
<td>Row 2 (Volts)</td>
<td>0.59</td>
<td>0.552</td>
<td>0.469</td>
<td>0.41</td>
</tr>
<tr>
<td>Row 3 (Volts)</td>
<td>0.576</td>
<td>0.532</td>
<td>0.418</td>
<td>0.322</td>
</tr>
<tr>
<td>Row 4 (Volts)</td>
<td>0.575</td>
<td>0.53</td>
<td>0.413</td>
<td>0.304</td>
</tr>
<tr>
<td>Row 5 (Volts)</td>
<td>0.573</td>
<td>0.528</td>
<td>0.411</td>
<td>0.299</td>
</tr>
<tr>
<td>Row 6 (Volts)</td>
<td>0.566</td>
<td>0.516</td>
<td>0.37</td>
<td>0.217</td>
</tr>
<tr>
<td>Row 7 (Volts)</td>
<td>0.564</td>
<td>0.512</td>
<td>0.355</td>
<td>0.211</td>
</tr>
<tr>
<td>Row 8 (Volts)</td>
<td>0.55</td>
<td>0.484</td>
<td>0.231</td>
<td>-0.469</td>
</tr>
<tr>
<td>Row 9 (Volts)</td>
<td>-0.447</td>
<td>-0.476</td>
<td>-0.499</td>
<td>-0.506</td>
</tr>
<tr>
<td>Row 10 (Volts)</td>
<td>-0.447</td>
<td>-0.476</td>
<td>-0.499</td>
<td>-0.506</td>
</tr>
<tr>
<td>Total Voltage (Volts)</td>
<td>3.994</td>
<td>3.271</td>
<td>2.132</td>
<td>0.595</td>
</tr>
<tr>
<td>Total Power (Watts)</td>
<td>18.47</td>
<td>39.252</td>
<td>54.366</td>
<td>20.23</td>
</tr>
</tbody>
</table>

Table 4.3 shows the individual row voltages in the module at corresponding output current across the load. Higher negative voltages are developed across the lower shaded rows with increasing currents. The modules become ineffective and consume power reducing the total output power to as low as 4.4W.
The Table 4.4 shows that with the use of bypass diodes the maximum negative voltages developed across the shaded rows of the module can be restricted to values equal to or lower than the reverse bias voltage of the diode itself. Thus, the output power is improved than in the case where no bypass diodes are used. Peak power occurs at 54W.

b) 100% shading across the triangular pattern with full illumination (0% shading) across the remaining cells for modules with and without bypass diodes is evaluated. The architectural design is depicted in Figure 4-11(a) and Figure 4-11(b). This is an extreme case of shading that might deteriorate a PV system even more drastically than the previous case. The maximum power for modules with bypass diodes is approximately 46 W as compared to 3.7 W that is generated by the module not protected with bypass diode. The inclusion of secondary peaks in the PV curve for modules with bypass diodes is prevalent. The IV curve for module without bypass diode is severely distorted. The $P-V$ and $I-V$ curves are plotted in Figure 4-12 and Figure 4-13.

![Figure 4-11](image)

Figure 4-11: (a) Modules without Bypass Diodes (b) With Bypass Diodes: 100% Shading in a Triangular Pattern and Random Illumination across remaining Cells
Figure 4-12: $P-V$ Curves With and Without Bypass Diodes

Figure 4-13: $I-V$ Curves With and Without Bypass Diodes
The cells with 100% shading do not have the capability to generate positive voltage to match the current requirement at the load. These cells may pull current from other cells or operate in reverse bias. For the last three rows with 100% shading, the capability of the row plummets drastically producing very high reverse negative voltages. But in case of modules with bypass diodes, the maximum reverse voltage across these rows is limited to greater than -0.7V thus helping provide acceptable levels of maximum output power.

Case 3: Row wise shading

a) With 100% shading for first row of the 10X20 modules (with and without bypass diodes) has been analyzed. The illumination levels for the remaining cells are maintained at 0% shading. The architecture is shown in the Figure 4-14(a) and Figure 4-14(b). The $P-V$ and $I-V$ curves are plotted in Figure 4-15 and Figure 4-16 respectively.
Figure 4-14: (a) Modules With Bypass Diodes and (b) Without Bypass Diodes: 100\% Shading in the First Row and remaining Cells at Full Illumination

Figure 4-15: $I$-$V$ Curves With and Without Bypass Diodes
b) 80% shading for first row of the 10X20 modules (with and without bypass diodes) have been analyzed. The illumination levels for the remaining cells are maintained at 0% shading or full illumination. The architecture is shown in the Figure 4-17 (a) and Figure 4-17(b). The $P-V$ and $I-V$ curves are plotted in Figure 4-18 and Figure 4-19.
Figure 4-17: (a) Modules Without Bypass Diodes and (b) With Bypass Diodes: 80% Shading in the First Row and remaining Cells at Full Illumination

Figure 4-18: $P-V$ Curves With and Without Bypass Diodes
When percentage of shading is increased between 80% and 100% of the photonic current, the entire row almost becomes ineffective resulting in reduced output power. In fact the complete module can be assumed to be devoid of the first row across the first parallel string in terms of generating current but the string consumes power due to developed reverse voltage. When the cells get shaded more, the photonic current is reduced resulting in less current at the output. Accordingly, the series connected parallel string develops more reverse voltage which accounts for reduced power at the output.
**Case 4: Column Wise shading:**

A scenario with first cell of each row for both the modules with and without bypass diodes is shaded with 0% illumination (100% shading) while the remaining cells are maintained at full illumination. The shading patterns for the two cases are shown in the Figures 4-20(a) and Figure 4-20(b). Both the modules are evaluated and $P-V$ and $I-V$ curves are plotted in Figures 4-21 and Figure 4-22.

![Shading Patterns (a) Modules Without Bypass Diodes (b) With Bypass Diodes: 100% Shading in the First Column and remaining Cells at Full Illumination](image)

*Figure 4-20: (a) Modules Without Bypass Diodes (b) With Bypass Diodes: 100% Shading in the First Column and remaining Cells at Full Illumination*
Figure 4-21: $P-V$ Curves With and Without Bypass Diodes

Figure 4-22: $I-V$ Curves With and Without Bypass Diodes
Since the first cell in each row is the one that is affected by shading, the remaining cells in that row have capability to maintain the voltage for same current flowing into the load. A portion of the current from the remaining parallel illuminated cells in that row flows through the diode of the shaded cell and voltage is still maintained constant which is instrumental in keeping the current values very close to that obtained in fully illuminated conditions. This explains why the bypass diode does not turn on and the $P-V$ and $I-V$ curves for both the modules (with and without bypass diodes) match exactly the same overlapping each other.

### 4.4 Discussion

The shading across a column of the modules does not cause any drastic shift in the maximum power generated irrespective of the use of bypass diodes. For row wise shading across several cells in the respective parallel rows the maximum power is affected severely and the modules with bypass diodes can maintain power at higher levels. For the cases discussed above the percentage decrease in the maximum power derived from the modules with and without bypass diodes is 94.15% for case 3a and 68.5% for case 3b. Unless more than 70% cells within the same parallel row are shaded, the bypass diode does not turn on and the remaining illuminated cells in that row continue to provide current though the diodes in the solar cell model. This is applicable to the architecture under study (parallel in series architecture) [37]. But for conventional architecture of arrays having series strings of modules connected in parallel; this does not hold true. In the absence of a bypass diode, shading of a single solar cell in a series string in a module will almost render the entire column to be ineffective and drastically reduces
the power output. For shading in case 2a and case 2b, the reduction of maximum output power for modules without bypass diode is 91.28% to one with bypass diodes. For an array incorporating modules, power is reduced by 85.78% for modules without the use of bypass diodes.

In summary, a bypass diode has the following important functions:

a) Protection of solar cells within the modules/arrays against hot-spot formation.

b) Reduces the reverse voltage across the shaded cells in the modules/arrays; thus limiting the drop to the reverse voltage across the diode.

But all the above advantages introduce multiple peaks, making the MPP control circuitry very tedious to implement as the system may settle down at one of the local minima in the $P-V$ characteristics [37].
Chapter 5

Modeling Solar Array Behavior with the Use of Reconfigurable Switching Architecture

In the previous chapter the impact of bypass diodes on the power generation of solar modules operating under shading conditions is discussed. It was noted that the shaded cells causes some modules to dissipate power even in the presence of bypass diodes. In this chapter modeling work on a scheme to isolate power consuming modules is presented.

An innovative design that incorporates switches at the array level across the modules is shown in Figure 5-1. This scheme can dynamically isolate or switch off the power dissipating modules from the main array architecture under shaded conditions to obtain the maximum output power. Traditionally arrays have hard wired connections between solar cells in the modules making it very difficult to exercise enough control over them.
Figure 5-1: Array incorporated with Modules in Parallel in Series Architecture and Reconfigurable Switching Mechanism
The switch implementation can be achieved by employing controllable switching elements like transistors. In MATLAB modeling, the switch is implemented as an ideal element. It is necessary to use switches which have zero or very low on-resistance and very high off-resistance. An ideal switch has the following characteristics:

a) It should block arbitrarily large forward and reverse voltages with zero current flow when off.

b) It should conduct arbitrarily large currents with zero voltage drops when on.

c) Whenever the switch is triggered it should switch from on to off or vice versa instantaneously.

d) The controlling mechanism to trigger the switch must consume small amount of power.

However, an ideal switch does not exist in practice in the real world. As a result the switches dissipate power when they are closed. With excessive dissipation, it can result in device failure thereby affecting the entire system in which it has been employed. Therefore, it is necessary to use switching elements with characteristics closest to ideal ones. For solar panels comprising of modules of solar arrays, the switch architecture can be used to reconfigure to add or subtract the modules depending on its capability to generate power and contribute to the total output power. An algorithm to implement a reconfigurable switching mechanism to turn on/off modules within the array design has been carried out using MATLAB platform. The flow chart of the algorithm shown in Figure 5-2 followed by its description.
Figure 5-2: Flow-Chart to implement Switching Mechanism between Modules in an Array
The user has the choice of deciding the number of modules that will be incorporated within the array. In short, the size and the capacity of the array that will be modeled to predict the performance under random shading patterns are left to the discretion of the user.

Each module used in the array acts as a sub-routine. So, for a system comprising of 12 modules, 12 function calls are made (4 series rows each containing 3 parallel modules). Each function call will store the entire operating range of that module with its corresponding currents and voltages in its specific table. This means that the voltage and corresponding current calculations for every module in the array is only done once when the function call is made. The maximum voltages of each of the module are then stored in a two dimensional matrix at the corresponding module location. The program selects appropriate voltage and current combinations for the modules using its specific table to achieve convergence for the array currents and voltages.

A row vector $I_{array}$ defining the complete range of total current across the array and a column vector $V_{row}$ defining initial voltage in each row has been initialized. The purpose is to adjust the voltages across each row of the array for every current in the range passed in $I_{array}$. At the same time, the modules that are incapable of generating enough voltage for the required current are switched off. If the particular row (each containing the 3 parallel modules) has a reverse voltage value greater than this maximum value then the current and voltage is kept at zero. This is done to make that module ineffective. Since this module will be switched off (removed from the existing array architecture), the current contributed by it is kept at minimum i.e. zero. If this is not true, then the value of calculated voltage across that module that is closest to the initial guess is passed and the
current for the module at the corresponding state is noted. The current across all the modules in a row is summed up to be compared with the initial guess in the range of $I_{\text{array}}$. If the error does not fall within a tolerance value of the initial guess, then the voltage at the particular row is readjusted and next iteration for analysis is initiated. If the voltage across the entire row falls below zero or goes negative, then all the parallel modules in it are rendered ineffective. As a result of which, the entire row has to be switched off. The power contributed by the modules in the respective row will then be zero. Several cases have been discussed to show how switching can be implemented across these modules.

5.1 Case-1: With no bypass diodes across all the rows of each module

For each of the modules at position 1, 5, 7, 10, and 11, the solar cells in the last three rows are maintained at 100% shading (no illumination); while the remaining cells have full illumination pattern. The modules at the remaining position (2, 3, 4, 6, 8, 9, and 12) have random illumination pattern across the solar cells within. No bypass diodes are used across the modules in this case. The architecture is shown in Figure 5-3.
Figure 5-3: Modules at no. 1, 5, 7, 10 and 11 have All the Cells at Full Illumination while the Last Three Rows are maintained at 100% Shading (Zero Illumination). The remaining Modules have Random Illumination Pattern.
Figure 5-4: $P-V$ Curves With and Without Switches

Figure 5-5: $I-V$ Curves With and Without Switches
In this case, the maximum power derived from array with reconfigurable switching mechanism is around 630 W. No multiple peaks are observed in the $P-V$ and $I-V$ characteristics as indicated in Figure 5-4 and Figure 5-5 respectively. The modules that are affected by shading in the defined architecture will be inoperative for higher current rating outputs and will produce negative voltages to match up with the current requirement. These can be switched or turned off and the array architecture will be re-modified to continue to provide positive power. Not significant difference is observed in the peak power of the array architecture with one without switching mechanism. The latter case produces around less than 600 W. The fill factor of the array with switching is 0.12 and without switching is 0.115. The percentage decrease in fill factor is 4.76%. This indicates a slight improvement in fill factor with the use of switching.

5.2 Case2: Random Illumination 1

In this case, array incorporating modules at no: 1, 2, 3, 4, 5, 7 and 9 are maintained under full shading i.e. zero illumination levels. The remaining modules have a non uniform random shading pattern. The architecture is shown in Figure 5-6. All the modules with bypass diodes are used. In order to maintain uniformity in comparison, the random pattern in the modules is maintained the same for modules with and without switches. Comparison is made for the entire array architecture with and without switches and the $P-V$ and $I-V$ characteristics are as shown in Figure 5-7 and Figure 5-8 respectively.
Figure 5-6: Modules at position: 1, 2, 3, 4, 5, 7 and 9 are maintained under Full Shading i.e. Zero Illumination Levels. The remaining Modules have a Non Uniform Random Shading Pattern.
Figure 5-7: $P-V$ Curves With and Without Switches

Figure 5-8: $I-V$ Curves With and Without Switches
The algorithm is designed to calculate the output current corresponding to the voltage over an entire range of total output current across the load. Thus the maximum output power can be tracked over the entire operating range of the array.

In this case, the first row of the array is completely ineffective due to shading with zero illumination. This might be a very common occurrence in real life situations such as shading formed by a structure such as building. The maximum output power is tracked by choosing a load that can extract this maximum power by adjusting the duty cycle of the converters following the array architecture. The maximum power extracted in this case is around 360 W.

Since all the modules are connected in Parallel in Series architecture, current in each series row is to be constant. As can be seen in Figure 5-8 at approximately 36 A, the second and third rows that are incapable of supporting that much current start to develop reverse voltage when the switching occurs. The second peak at 3 V occurs as the last row alone can support higher currents. Without switching, the peak output power falls to a very low value around 150 W. This happens as the entire first row is incapable of generating enough voltage for the particular output array current and starts to develop negative voltages. Instead of generating power, it starts to consume power dropping it low values. Power reduces by 58% in this case if modules were not switched. Fill factor decreases from 0.06 to 0.02 without using switching mechanism. This indicates a direct decrease of 58.33% in the fill factor. This is one of the worst cases where majority of the modules are affected by shading. Hence, the fill factor sees a steep decrease in the value for no switching. Thus, switching can improve the fill factor of PV systems affected by shading.
5.3 Case 3: Random Illumination 2

A triangular pattern of shading is assumed across modules in the array design. The pattern of shading across the architecture is as shown in Figure 5-9. So, modules 4, 7, 8, 10, 11 and 12 are fully shaded at zero illumination and the remaining modules have a random illumination pattern. Bypass diodes are incorporated across each row in every module. Both the switching and non switching cases are evaluated and $P-V$ and $I-V$ curves are plotted to make the comparison. These are indicated in Figure 5-10 and Figure 5-11 respectively.
Figure 5-9: Modules at no. 4, 7, 8, 10, 11, and 12 are Fully Shaded at Zero Illumination and the remaining Modules have a Random Illumination Pattern
Figure 5-10: $P-V$ Curves With and Without Switches

Figure 5-11: $I-V$ Curves With and Without Switches
With shading pattern being triangular, only one row at a time is switched. The last row that has all the modules non-illuminated will be switched first due to its inability to generate any current. With two completely shaded modules, the third row is switched and the first peak occurs at approximately 13 V. The second row has only one fully shaded module and so the respective row can operate at even higher currents introducing a second peak at around 7 V. The first row has the maximum ability to generate higher currents and the voltage range between 0-4 V denotes the normal mode of operation supported solely by the first row. The peak power obtained in the case of switching is approximately 500 W. The modules that are shaded tend to reduce the output power as they are not able to produce enough voltage required to support the output array current. But with switching, these modules are reconfigured and rearranged in a manner where these are removed and the whole array is treated devoid of these modules. The reduction in the output power due to the negative voltage of these modules is thus eliminated. This results in higher peak power than one would have been achieved without switching off the bad modules. For array architecture that does not employ switching the bad modules deteriorates the peak power. The $P-V$ and $I-V$ characteristics are adversely affected since the bad modules pull the peak power to very low values of around 60 W as shown in Figure 5-10 and Figure 5-11 respectively. No peaks are recognized and the whole system falls below the minimum requirement of operation. Also drastic decrease of 88% in the fill factor is observed with no switching mechanism is used. With switching the fill factor decreases from 0.09 to 0.011 when no switching is used.
The cases discussed above, clearly show the advantage of switching of the photovoltaic modules in an array design. The redesigning of the array architecture by turning the modules on and off based on their capacity to deliver power (and not consume power) to the load is an effective way to extract maximum output power.

5.4 Discussion

An attempt has been made to present switching at the module level in an array structure as an alternative and innovative mechanism to deal with shading. This way it is possible to bypass the modules that are worst affected by shading and are incapable of maintaining enough voltage to produce the output current and increase output power.

Advantages:

a) A modeling scheme that can dynamically reconfigure solar cells in series and parallel connections for adaptive configurations has been implemented. This will enable the photovoltaic system to operate at its maximum potential and generate output power even under worst shading scenarios i.e. with varying insolation (shading) consequent changes in temperature, loads etc.

b) The modeling techniques can predict the performance of the arrays and modules can prove beneficial to foretell about its characterization prior to their installation. Also a better understanding can improve reliability of the solar panel.
c) The algorithm is flexible and allows the user to specify the number of modules that can be integrated in the array. Since faster iterative techniques have been used; the modeling approach is instrumental to characterize the array design under consideration quickly. With slight modifications it is possible to study different architectures for performance prediction, under random shading patterns.

d) Since switching takes place between the modules that exist within the array, no additional bank of solar cells need to be added as in [38]. Thus the overhead of extra hardware is reducing making the system less costly and more efficient.

e) Considerable improvement is observed in the fill factor for systems employed with switching over the ones with no switching.

Modeling of the solar modules with bypass has been integrated with switching the modules in a bigger array system. The cumulative effect of both has been compared with systems devoid of bypass diodes and switching mechanism. Several cases with characterized $I-V$ and $P-V$ curves have been documented and the advantage of using the proposed modeling architecture has been presented.
Chapter 6

Conclusion and Future Work

6.1 Conclusion

Though gaining wide scale popularity from small scale stand-alone to larger grid-tied applications, the PV industry faces a big challenge of maximizing the efficiency and minimizing the cost of energy generation.

This thesis studies the effects of shading patterns on random cells within a module of solar cells. The main contributions of this work are:

a) Simple and accurate models of solar cells under different shading patterns have been modeled in MATLAB and the results have been compared in PSPICE.

b) Faster iterative techniques have been implemented to improve the simulation time and the estimate of the peak power under the specified shading patterns.

c) The use of bypass diodes as a preventive measure to counter the reverse bias operation of solar cells due to effects of shading has been modeled.
d) An innovative algorithm to reconfigure the array through the use of switch modules that consume power has been modeled. Only the existing modules within the array are switched; thus reducing the burden of additional hardware and thus the cost.

Several cases of extreme to moderate level shading has been discussed within the array and $I-V$ and $P-V$ plots are discussed in terms of maximum power that can be extracted. Results are compared with alternate implementations. A considerable increase in the Fill Factor has been observed with the use of switches and bypass diodes. The proposed modeling schemes are effective to predict the performance characteristics of PV systems prior to their installation.
6.2 Future Work

Switches across the modules in an array/panel can be implemented using control elements like transistors. But care has to be taken to use switching elements that have low conduction and switching losses so that these losses are not additive on the power loss that the shaded cells would generate. Simulations using PSpice with a practical implementation of switches must be made to see the impact of switch resistances in the overall improvement of the reconfigurable scheme.

There is a significant advantage of using reconfigurable switches and bypass diodes within the solar modules; however, this would require a significant change to fabrication process and can be expensive. The use of reconfigurable switches provides a number of scenarios where there is significant increase in power delivered to the load as compared to the architecture without the switches. But they introduce multiple peaks in P-V characteristics. New control algorithms to track the peak power need to be developed. The use of neural network based MPPT algorithms to control the switches will be very well suited for the reconfigurable switch array PV architecture.
References


[38] N. D. Duc, "Modeling and re-configuration of solar photovoltaic arrays under non uniform shadow conditions," in Electrical Engineering Disertation, IRIs North Eastern University, July 2008.
Appendix-A

**Specification of the bypass diode used in the model**

The specifications for the bypass diode employed in the solar cell model are given below:

For each cell at full illumination,

Maximum value of output voltage and current is: \( V_m = 0.356 \text{V}, I_m = 2.53 \text{V} \).

Typically, a bypass diode that is integrated in the module/array should have current and voltage specifications as given below:

\[
I_{BP(max)} = 2 \times \text{total output current across the module/array}; \\
V_{BP(max)} = 1.5 \times \text{total voltage across the module/array};
\]

For a module of size: 10X20

Total current that can be managed by the bypass diode without getting destroyed \( I_{BP} \) =

\[
20 \times 2.53 \times 2 \approx 100 \text{Amps (with a safety margin of +10%)}
\]

Since, the proposed model has a bypass diode across each row of the module; the maximum voltage that can be developed across that row has been used to find the voltage specification [34].

A bypass diode across each parallel row or several rows is the most effective configuration to side track the current through them. It is a very promising design concept
and has been widely suggested against several shading scenarios; thereby reducing powloss to a great extent [36].

Total voltage that can be managed by the bypass diode without getting destroyed ($V_{BP}$) = 0.356X 1.5 ≈ 0.534V (with a safety margin of +10%)