Modeling of Partial Shading on Solar Modules

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Abstract

There are many different factors that play into solar efficiency including solar tracking, partial shading, temperature, soiling, voltage/current miss match, and bypass diode configurations. Among these, one of the biggest contributors to energy loss is the effect of partial shading [1]. This research explores the effects of shading on solar modules under both uniform and partial shading conditions. Effects of temperature and serial/parallel connectivity are explored alongside the shading conditions to determine optimal performance. A design of experiments (DOE) is used to create inputs to the model. The solar cell model is built in Matlab while the results are analyzed using JMP.

Keywords: Partial Shading, Uniform Shading, Non-Uniform Shading, Solar Cell Model, Simulation

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1. Introduction

Background. Solar energy is becoming more main stream as costs drop and efficiency increases. From 2010 to 2017 levelized cost of energy (LCOE) for residential PV dropped from 0.52 to 0.15 ¢/kWh [2]. The U.S. Department of Energy's Solar Energy Technologies Office recently set a new LCOE target of 5¢/kWh for 2030 [2]. As solar costs continue to drop, more solar energy will be used to provide the world with power. The total world electricity generated in

[1] Since 1875.

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the the year 2016 was 24816.4 TWh [3]. This averages to 2.83 TW throughout the year. The sun's incident power on the earth is approximately 166 $X10^{15}W$ [4]. After accounting for an energy reflection of 30% and absorption of 15%, the potential energy on the earth at any given point in time is 85,000 TW [4]. This is just over 30,000 times the electrical energy produced in the year 2016. Since the sun produces a large amount of sustainable energy, solar should be considered as a viable resource for electricity generation.

Past work. Various solutions such as bypass diodes, and serial/parallel orientations have been studied as possible techniques to mitigate the effects of partial shading. Many of these studies use a discrete number of serial/parallel orientations to observe and understand optimal orientations for internal connectivity [5, 6]. Most of the recent studies use some form of Series, Series-Parallel, Total-Cross-Tied, Bridged-Linked, and Honey-Comb connection orientation [7, 8]. Researchers have also combined different bypass diode configurations with various serial/parallel connections to help understand how to increase the efficiency of solar cells [9, 10].

Research Overview. This work will focus on parallel, vs serial connected cells when applied to various shading schemes. It will utilize JMP to create a wide range of inputs to the model. Temperature will also be explored to understand effects of temperature on power output.

2. Model

Each solar cell was modeled with the single cell circuit shown in figure 1. The circuit provides an equation relating voltage to current as shown in equation 1. Constants used for the first three terms of equation 1 were found from a Sunpower data-sheet[12], and previous work[13, 11]. The third term I_{sh} was calculated using equation 2 (avalanch breakdown [14]) with constants pulled from Bishops study[14]. The equation was solved using Newtons Method and produces an IV curve shown in figure 2.

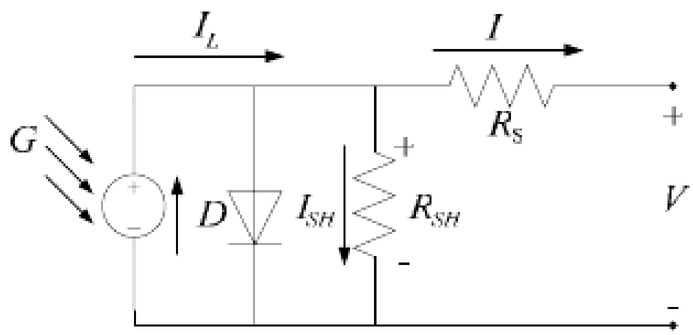

Figure 1: Single cell model[11]

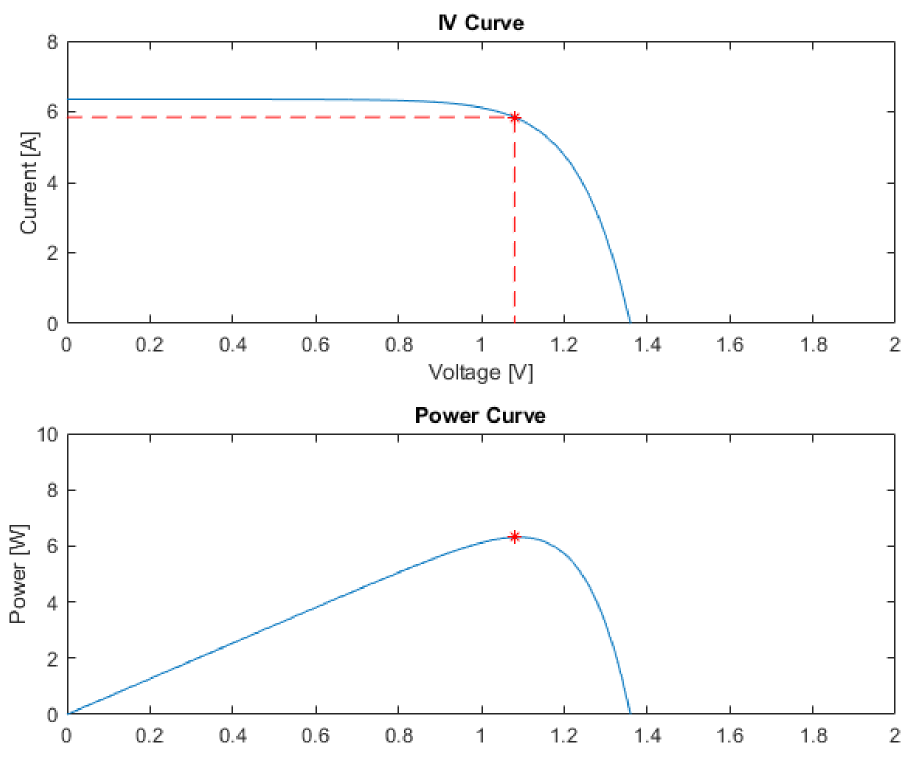

Figure 2: Single cell IV curve generated from the model at 0% shading

$$I = I_L - I_0(e^{\frac{q(V+IR_s)}{nkT}} - 1) - I_{sh} \tag{1}$$

$$I_{sh} = \frac{V + R_s I}{R_{sh}} \left[a \left(1 - \frac{V + R_s I}{V_b} \right)^{-\beta} \right] \tag{2}$$

3. Uniform Shading

A uniform shading scheme was analyzed to understand how power output is effected by temperature, serial/parallel connection, number of cells, and shading percentage. Uniform shading denotes one shading percentage applied to every cell in the solar module.

Creating the DOE. A DOE was generated to provide inputs to the circuit model described in equation 1. A Uniform Design with 5000 data points was created using a statistical package(JMP). Four different factors with various levels were used in the DOE. These factors consisted of:

- Number of Cells (36-72)
- Shading Percentage (0-100%)
- Parallel or Serial (1 = parallel, 0 = serial)
- Temperature (-62 - 52 °C)

Shading percentage applies an irradiance of $1000\frac{W}{m^2}$ at 0% shading and 300 $\frac{W}{m^2}$ at 100% shading[15]. Irradiance is denoted as G in figure 1.

Fitting the Model. The DOE generated 5000 inputs that were run using the circuit model shown in figure 1. The results were then fit to a regression model using JMP. All full factorial terms and squared terms were considered in the fit model. AIC and BIC were minimized to get an optimal, non bias fit. Both AIC and BIC suggested the same model with an R-Squared of .999995. The terms included in the fit model are shown in figure 3. All of the terms have a p-value $< .0001$.

Term	Estimate
Intercept	66.835067
Temperature	-0.369951
Number of Cells	2.1992847
Shading Percentage	-1.385233
(Temperature+5.2)*(NumCells-54.0)	-0.006851
(Temperature+5.2)*(ShadingPercentage-49.8)	0.0045763
(NumCells-54.0)*(ShadingPercentage-49.8)	-0.025639
(Temperature+5.2)*(NumCells-54.0)*(ShadingPercentage-49.8)	0.0000847
(Temperature+5.2)*(Temperature+5.2)	-0.000136
(ShadingPercentage-49.8)*(ShadingPercentage-49.8)	0.0004299

Figure 3: Parameter estimates from the fit model

Results. As can be seen from figure 3, number of cells and shading percentage factors have the biggest coefficients and thus the biggest effect on power output. It should be noted that serial/parallel connection isn't in the model because it isn't statistically significant in a uniform shading situation. This is shown in the the graph in figure 4. The two cells hooked together have the same maximum power point, but act at different voltages. In reality, each cell is never acting identical to every other cell in a solar module. Non-uniform shading, degradation and other factors can effect each individual cell. Since important terms were left out of the model, an unreasonably high R-squared value was achieved.

The next section explores non-uniform shading and the effects of serial/parallel connectivity. Temperature will be neglected due to its small effect on power output.

4. Non-Uniform Shading

Process. Non-uniform shading required a more complex method for hooking cells in parallel and serial. Cells hooked in parallel must operate at a common

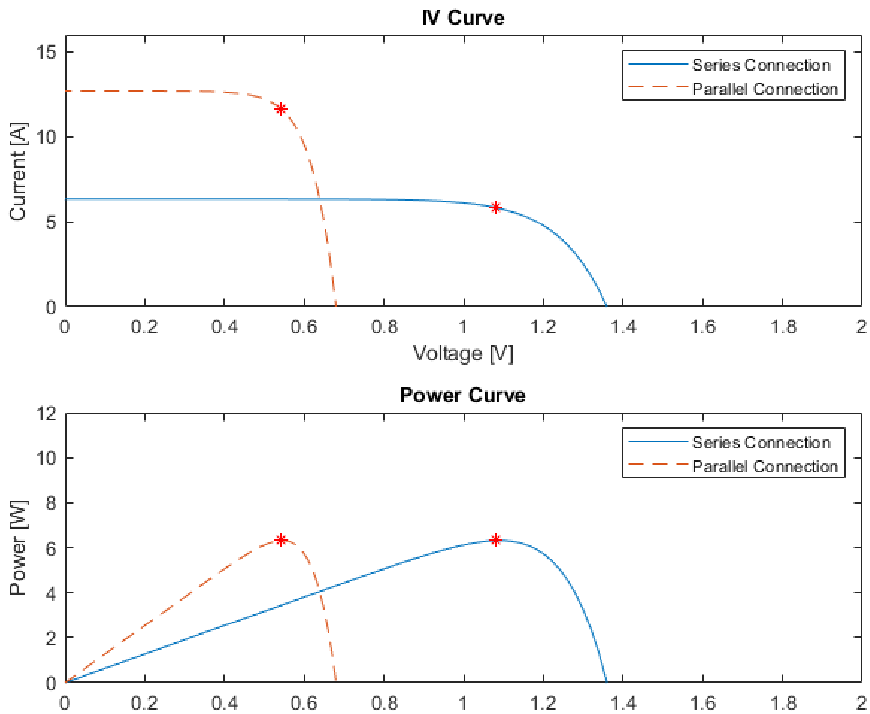

Figure 4: Two cells hooked in parallel vs serial under uniform shading

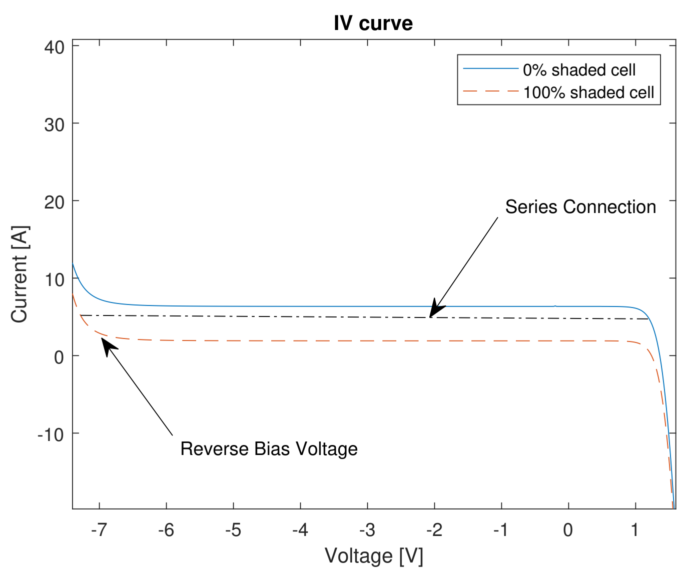

Figure 5: Negative voltages can emerge in reverse bias when hooking cells in series.

voltage, while cells in series must operate at a common amperage. As can be seen from figure 6, when hooking up cells in series, a horizontal line is drawn and each intersection point corresponds to a voltage that is summed up for the total voltage. In parallel, a vertical line is drawn and each intersection corresponds to a current value that is summed up for the total current. When the current is a value that extends to the reverse bias region, as shown in figure 5, the cell will consume power. A two cell connection example is shown in figure 7. This process was done for 36, 60, and 72 cells in a module corresponding to commercially available solar panels[15]. The partial shading inputs were provided from three uniform DOEs, each with 36, 60, and 72 values ranging from 0 -100%.

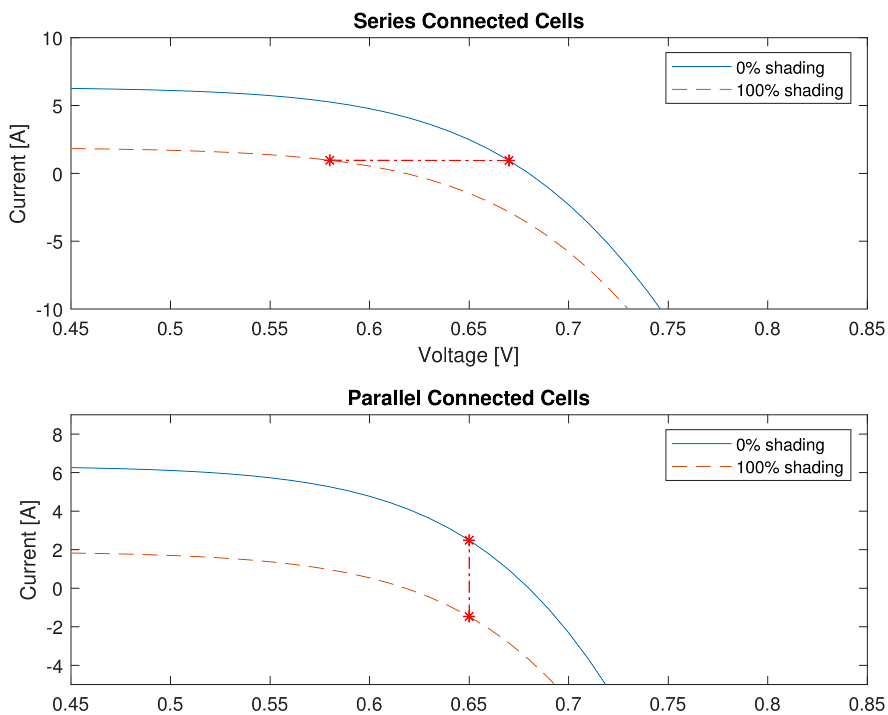

Figure 6: Showing how to hook up cells in parallel vs serial when under non-uniform shading

Results. As can be seen from figure 8, there is a correlation between number of cells and power difference. The power difference is calculated as $ParallelPower - SeriesPower$. More series connected cells cause a greater power difference un-

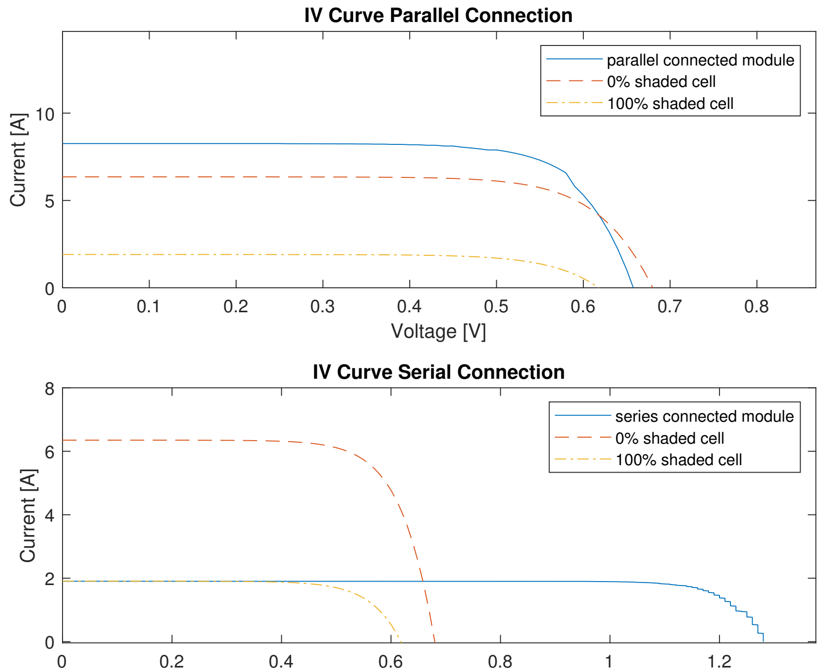

Figure 7: Two cell module hooked up in parallel vs serial when under non-uniform shading

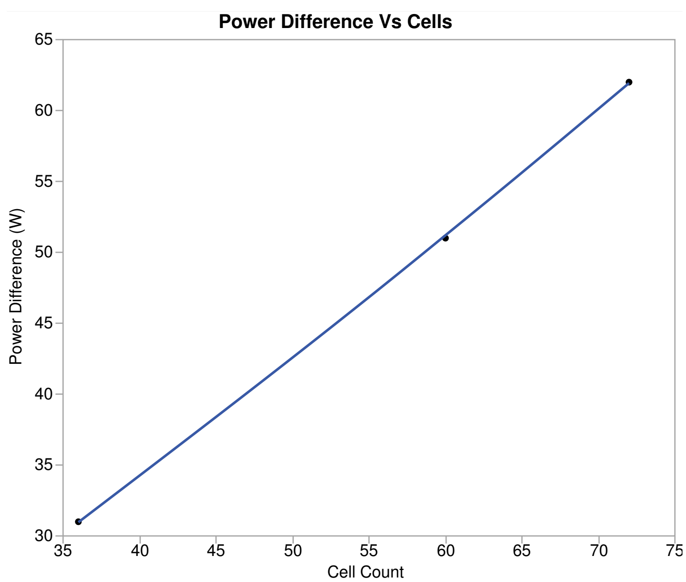

Figure 8: Power difference (Parallel - Serial) in Watts for a 36, 60, and 72 cell module

der non-uniform shading. Parallel connection is a more efficient configuration when solar modules are under partial shading conditions.

5. Conclusion

Serial vs parallel connectivity doesn't influence power when under uniform-shading situations. Temperature was also found to have a negligible effect on power output from the uniform-shading tests. When a solar panel is partially shaded, serial vs parallel connectivity matters a lot more. It is recommended that partially shaded modules be hooked in parallel as much as possible.

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