

Determining Minimum Necessary Voltage and Current Specifications for an Individual Photovoltaic Cell

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ABSTRACT

The maximum voltage and current values needed to maintain a 200 Watt photovoltaic cell are calculated in this experiment by using a Microsoft Excel program. This program uses atmospheric data from NASA's meteorology and solar energy database to gauge the average insolation and temperature of a PV module at a given coordinate location. The voltage and current values calculated are an average of 0.569 Volts and 184 Amps, respectively. There is a lot of error in this experiment, mostly residing in the inputs and parameters into the Excel program. Future work on this project should start with the refining of the program itself and identification of the issue that resides inside of it.

INTRODUCTION

Photovoltaic cells, or solar cells, have been a large focus in the business of green energy. To be able to convert the power constantly bombarding the Earth into usable energy is the name of the game; however, the efficiency of solar panels, although increasing, is still too low for some people to consider viable to power large facilities or households. In an experimental setting, there are many alternatives to the commercial silicon PV cell. Some researchers have made cells that are constructed with organic material, of which achieve a higher efficiency.¹ There is also the issue of inconsistency with solar panels, being rendered less effective on cloudy days, at night, and in the heat. When the panel heats up, infrared light is trapped inside the module, causing the band gap energy to increase. This means more energy is required to generate a voltage.² To better increase this efficiency, one must understand the limitations of the PV module. In this experiment, these limitations are calculated.

THEORY

The main concept of this experiment is that of photovoltaic cell efficiency, or the percent of light converted into power. This efficiency percentage is one of the most important features of a PV cell, and is determined by the cell's construction, installment, and physical location. For most commercial PV modules, this value is at maximum around 18% efficiency. Although this value can be experimentally increased in a lab under controlled conditions, this is what a consumer will have if a high end module is installed for them. Two equations are used in this experiment to theoretically determine what this value is, both dependent on the sun's intensity, cell's ideality factor, and open-current voltage of the module. The equations are listed below:³

$$\text{Eq. 1: } V_{mp} = V_{oc} - \left(\frac{nKT}{q}\right) \ln \left(\frac{V_{mp} * q}{nKT} + 1\right)$$

$$\text{Eq. 2: } I_{mp} = I_{sun} \left(1 - \exp\left(\frac{q(V_{mp} - V_{oc})}{nKT}\right)\right)$$

These two equations are used to solve for the maximum power output of a module. V_{mp} is the maximum voltage, and I_{mp} is the maximum current—when they are both multiplied together, the maximum power output can be determined. By then comparing that to the solar flux, the efficiency percentage can be found. For this to be useable, however, Eq. 1 has to be altered. Because the max voltage is on both sides of the equation, some grouping has to be done for it to be used. When this is done, the equation can then be reduced to a simpler form:

$$\text{Eq. 3: } \frac{V}{V_{oc}} = \exp(\alpha(x)(1-x))$$

Where the following constants are used to reduce the equation:

$$\text{Eq. 4: } x = \frac{V_{mp}}{V_{oc}}$$

$$\text{Eq. 5: } \beta = \frac{P_{max}}{I_{sun} * V_{oc}}$$

$$\text{Eq. 6: } \alpha = \frac{q * V_{oc}}{nKT}$$

By using a root-finding technique in Microsoft Excel, the solutions to Eq. 3 can be determined. These values are used as 'x' in Eq. 4, allowing one to deduce the maximum voltage in the proposed PV system. By plugging this into Eq. 2 and comparing the result to the maximum power demand, the true maximum values are found. These can then be used to calculate the efficiency of the system as described above.

The equation used to calculate the open-current voltage of the cell is shown below:

$$\text{Eq. 7: } V_{oc} = \frac{nKT}{q} * \ln \left(\frac{I_L}{I_o} + 1 \right)$$

Where I_L is the light generated current and I_o is the dark saturation current.²

MATERIALS AND METHODS

As this experiment is mostly theory, it is entirely done through Microsoft Excel and GNUplot. For mapping out the limits of the photovoltaic cell, multiple steps must be taken before the values can be calculated. First, the operating temperature of the cell must be found. This value is important because it is the temperature of the cell that determines overall efficiency. By using averaged insolation, air temperature, and NOCT values at Farmville's latitude and longitude provided in the NASA Atmospheric Science Data Center, the average operating cell temperature by month can be calculated.⁴

Next, values such as the cell's open circuit voltage must be determined. The open circuit voltage is calculated with equation seven and then used to find the maximum voltage value. The simpler equation derived from equations one and two is graphed in GNUplot to get a precise reading of the equation's roots. These root values are found with inspection, and used to calculate the maximum voltage with equation four. Once the maximum voltage value is determined, its corresponding current value is then deduced. This is done for every month out of the year to give the average optimized values of the PV module.

DATA

Shown below are the graphs generated in the Excel spreadsheet. Three of the twelve month calculations are shown to give an idea of what the program is doing.

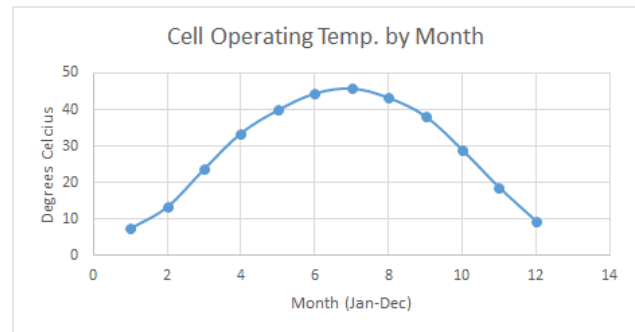


Figure 1: This graph was made when determining the average operating temperature of each individual photovoltaic cell. Notice the classic bell curve shape of the graph—this is the same shape as the sun's intensity curve over time.

Month	Insolation (mW/m^2)	Air Temp (Celcius)	NOCT (celcius)	Cell Temp av. (Celcius)
January	43	-7.64	48	7.41
February	52	-4.9	48	13.3
March	62	2	48	23.7
April	71	8.69	48	33.54
May	75	13.6	48	39.85
June	76	17.8	48	44.4
July	72	20.6	48	45.8
August	67	19.8	48	43.25
September	68	14.4	48	38.2
October	63	6.94	48	28.99
November	51	0.85	48	18.7
December	41	-4.83	48	9.52

Table 1: This table shows the calculation for the operating temperature of an individual PV cell by month. The values are specific for Farmville's latitude and longitude coordinates.

	March	June	November
insolation average (kWh/m^2/day)	4.63	6.69	3.33
sun intensity (W/m^2)	192.92	278.75	138.75
Ideality factor (n)	1	1	1
cell temperature avg. (Kelvin)	296.85	317.95	302.14
Dark Current (A)	1.00E-10	1.00E-10	1.00E-10
Generated Current (A)	0.5	0.5	0.5
V _{oc} (V)	0.571	0.614	0.599
Power _{max} (W)	200	200	200
alpha	23.629	25.277	24.05
beta	1.181	1.174	2.479

Table 2: This table shows the calculations for the alpha and beta values in Eq. 3 needed to satisfy the equations for March, June, and November. Notice that these values are dependent on the intensity of the sun and the power demand of the cell.

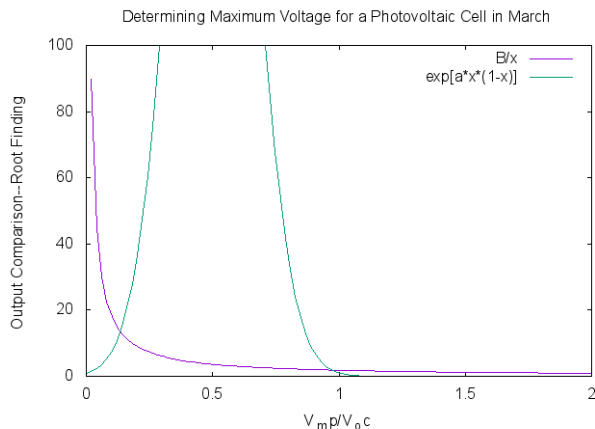


Figure 2: This graph showing the generated outputs for Eq. 3 for the month of March. The root values found are $x=0.136$ and $x=0.966$.

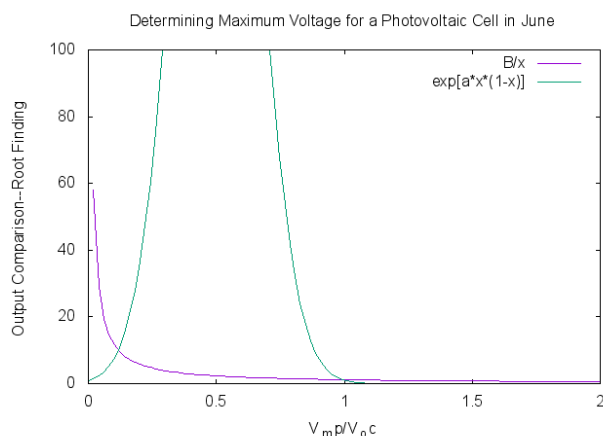


Figure 3: This graph showing the generated outputs for Eq. 3 for the month of June. The root values found are $x=0.117$ and $x=0.990$.

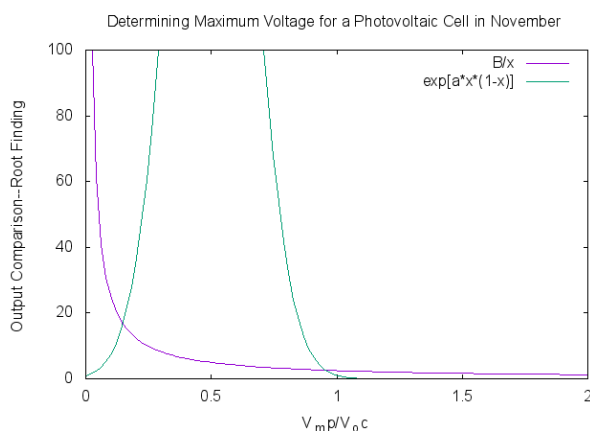


Figure 4: This graph showing the generated outputs for Eq. 3 for the month of November. The root values found are $x=0.149$ and $x=0.951$.

DATA

The first calculations done are those for cell temperature by month. This calculation is dependent on the sun's average insolation for the month, and also on the air temperature around the cell. These atmospheric values were taken from Farmville, Virginia's latitude and longitude lines. With the following equation, the cell temperature values were calculated.²

$$T_{cell} = T_{air} + \left(\left(\frac{NOCT - 20}{80} \right) * I_{sun} \right)$$

These values were calculated and placed into Table 1. The maximum voltage values for each month were found with equation three with the root finding technique, and each value was then used with equation two to find each's corresponding maximum current. Although there were two roots found in each graph, the larger x -value was used because that would give a maximum voltage value on the same order of magnitude of the open-circuit voltage. These two values are the proposed voltage and current values that satisfy the power maximum set. In the program, the photovoltaic cell was set to 200 Watts of power. The maximum voltage and current values are 0.607 Volts and 213 Amps in July, respectively. Conversely, the minimum values were set at 0.508 Volts and 117 Amps in January. More power is generated in July, but the input-output return is higher in January. In short, the cells are more efficient in the colder months.

CONCLUSION

The goal of this experiment was to better understand how photovoltaic cells operate, and the limiting factors to their overall efficiency. In this lab, an excel spreadsheet was made to compute the voltage and current values that would yield an average 200 Watt power draw. With the coordinates 37.3 degrees north and 78.4 degrees west used for temperature and insolation, an average voltage of 0.569 Volts and current of 184 Amps was calculated. Now, these values are not correct. There error probably occurred in the parameters set in the program, such as the proposed generated current value in the max voltage equation, as this value does not match up with the outcome of equation 2. The answers do, however, follow the bell curve relationship that is given in the intensity graph, which shows that, although some of the parameters are wrong, the math is correct. Looking forward, at least now the nature of a photovoltaic cell is known, and the limitations are

understood. Future lab work attempting to increase the actual efficiency of a cell can be carried out now with an understanding of what affects this value.

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