SIMULATION AND VALIDATION OF THE PERFORMANCE OF A POLYCRYSTALLINE PHOTOVOLTAIC MODULE

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ABSTRACT
The performance of a solar module is described by its Current-Voltage (I-V) and Power-Voltage (P-V) curves, it is therefore necessary to generate these curves in order to validate the parameters of the module namely Short Circuit Current, Open Circuit Voltage, Maximum Power, Current and Voltage at Maximum Power Points, Fill Factor, and Efficiency. This study highlights two methods of generating I-V and P-V curves from a 30W sunshine (AP-PM-30) module. The methods include a computer simulation using MATLAB/Simulink software and an experimental procedure at different values of irradiance and cell temperature. Findings from this study show that an increase in irradiance at constant cell temperature of the solar module results to significant increase in the current produced but slight increase in voltage. Consequently, the power output of the solar module also increases, while increase in cell temperature at constant irradiance decreases the voltage but slightly increases the current produced by the module but power output decreases. Therefore, these explain the influence of irradiance and cell temperature on the performance of a photovoltaic module.

Keywords: Irradiance; Cell Temperature; I-V and P-V characteristic curves; Photovoltaic module; MATLAB/Simulink.

INTRODUCTION
Solar energy from the sun has always been a source of light and heat which the earth depends on. Similarly, terrestrial life need sunlight to survive and also to achieve their means of livelihood. In recent times the electromagnetic waves from the sun have been discovered not just to provide light and heat but also to generate electricity to meet the energy demands of the people (Maka & Alabid, 2022). The abundance of solar energy has made it the most sought after of all available renewable energy sources such as hydro, wind, geothermal and biomass available for electricity generation.

The transformation of the solar energy from the sun into electricity when its irradiance reaches the earth surface is done using photovoltaic modules (made up of silicon, germanium or other suitable materials) and heliostream which generates electricity through heating of a fluid and functions similarly as a conventional thermoelectric plant (Reis et al., 2017). Photovoltaic has become the mostly used amongst the two due to its convenience, therefore, photovoltaic modules have become very popular in both rural and urban settlements. As a result of this, the efficiency of the photovoltaic modules is crucial in order to meet the energy demands of the users; the efficiency of the module is the ratio of the useful electrical energy produced by the module to the solar energy incident on it at standard test condition, and this depends on the cell temperatures, energy conversion efficiency and Maximum Power Point Tracking (Dincer & Meral, 2010). A single photovoltaic cell is made of two or more thin layers of a semiconductor (absorber) such as silicon, germanium or any other suitable materials. When the cell is exposed to sunlight, the sunlight is absorbed in the absorber part of the cell. If the energy of the photon is equal to the energy band gap of the semiconductor, then electrons get enough energy to break loose from their atoms. This process causes electric potential difference across the cell. Therefore, direct current (DC) begins to flow in the material to terminate the potential difference. But if the energy of the photon is less than the energy band gap of the semiconductor, they do not generate voltage or electric current. Photons with energies greater or equal to the band gap generate electricity. However, only the photons with energies equal to the band gap are used. (Azzouzi & Stork, 2014).

Figure 1 shows the general current-voltage (I-V) and power-voltage (P-V) characteristic curves of a solar cell at a given solar irradiance G and a fixed cell temperature Tc (Pukhrem, 2013). The I-V and P-V characteristic curves describe the behaviour of a solar cell. This study presents an experimental method for generating the curves.

![Figure 1: I-V and P-V curves for a Solar Cell](image)

Figure 1: I-V and P-V curves for a Solar Cell

A photovoltaic cell can be characterized by the following basic parameters.

a. **Short Circuit Current** (Isc): This is the maximum amount of current produced by the solar cell due to the radiation from the sun. It is the current through the solar cell when the cell is short circuited (i.e when voltage is zero) or when the terminals of the cells are externally connected with zero resistance (Honsberg & Bowden, 1999).

\[ I(\text{at} \ V = 0) = I_{sc} \]  

(1)

The short circuit current and the photocurrent are the same parameters

\[ I_{sc} = I_{ph} \]  

(2)
b. **Open Circuit Voltage** ($V_{oc}$): This is the maximum amount of voltage produced by the solar cell when current is zero. The two terminals of the solar cell are externally disconnected and the resistance $R = \infty$ (Robbins, 2021).

\[
V(\text{at } I = 0) = V_{oc}
\]  

(3)

c. **Maximum Power Point** ($P_{mp}$): The power of a solar cell is produced from the product of the voltage and current in the circuit (Miller, 2010).

\[
P = IV
\]  

(4)

The maximum power point is therefore obtained when the product of the voltage and current are at maximum values due to a wide range of voltages and currents produced from an increasing resistive load using a potentiometer.

\[
P_{mp} = I_{mp}V_{mp}
\]  

(5)

The current and voltages at maximum values are known as the Current and Voltage at Maximum Power Points ($I_{mp}$ & $V_{mp}$).

d. **Solar Cell Efficiency** ($\eta$): The most important parameter of the solar cell is its energy conversion efficiency which is the percentage at which solar energy is converted into usable electricity. It is basically used to compare the performance a solar cell with another. The efficiency of the solar is defined by ratio of the energy output of the solar cell to the input energy from the sun. It depends on the spectrum and irradiance of the sun $G$ and the solar cell temperature $T_c$. The solar cell efficiency is calculated by the formula in equation 6 (Zekry et al, 2018)

\[
\eta = \frac{P_{mp} \times 100}{P_{in} \times A} = \frac{V_{mp}I_{mp} \times 100}{AG}
\]  

(6)

Where $P_{in}$ is the incident solar power, $A$=Area of the solar module.

$G$=Solar Irradiance at Standard Test Condition (STC)

e. **Fill factor (FF):** Fill factor is a measure of the quality of the module. As FF increases, the efficiency of the module also increases. It can be increased by reducing $I_{sc}$ and $R_s$ and increasing $R_{sh}$. However FF decreases as the cell temperature increases. The fill factor can be obtained by the formula shown in equation 7 (Zekry et al, 2018)

\[
FF = \frac{P_{mp}}{P_{in}} = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}
\]  

(7)

Where $P_{in}$ is the theoretical power (product of $V_{oc}$ and $I_{sc}$).

The irradiance from the sun is an environmental factor that influences the performance of a PV module, its effect on the power output of the PV module is almost linear and can approximated by the function below as shown in equation 8 (Louwen et al, 2017).

\[
P_{mp} = G \frac{P}{1000W/m^2}
\]  

(8)

Where $P_{mp}$ and $P$ are measured and STC rated maximum power output respectively and $G$ is the in-plane irradiance.

The STC for irradiance is 1000W/m$^2$ at 25°C. Most information provided by manufacturers of PV modules is given at STC. However, PV module performance can be obtained under real operating conditions. The irradiance from the sun varies depending on the time and weather of the day. At varying irradiance and fixed temperature, the short circuit current produced by PV module increases significantly with slight increase in the open circuit voltage $V_{oc}$.

The cell temperature is another environmental factor that influences the performance of the of the PV module. The cell temperature varies due to the change in ambient temperature and also the change in solar radiation. The cell temperature can be estimated using the expression (equation 9) as defined by Masters (2004)

\[
T_{cell} = T_{amb} + \left(\frac{NOCT - 20}{800}\right) \times G
\]  

(9)

Where $T_{cell}$ is cell temperature (°C), $T_{amb}$ is ambient temperature, and $G$ is solar irradiance (W/m$^2$).

The NOCT in the equation above stands for nominal operating cell temperature which is an indicator provided by manufacturers to help system designers account for changes in cell performance with temperature. This is because only a small fraction of the irradiance on the module is converted to electricity while most of the incident solar energy is absorbed and converted to heat. The NOCT is cell temperature in a module when ambient is 20°C, solar irradiation is 800 W/m$^2$, and windspeed is 1 m/s. At fixed irradiance and varying temperature, the open circuit voltage $V_{oc}$ of the module drops significantly while short circuit current $I_{sc}$ increases slightly. The manufacturers of PV modules often provide some of the modules’ electrical characteristics namely the short circuit current $I_{sc}$, open circuit voltage $V_{oc}$, voltage and current at maximum power point ($V_{mp}$ & $I_{mp}$) and maximum power output ($P_{mp}$) of the module.

When exposed to sunlight, the photovoltaic cell which is a simple P-N junction semiconductor absorbs photons and thereby generates charge carriers which are separated by the P-N junction electric field and results to flow of electric current $I$ through the circuit. The current produced varies proportionally to the irradiance on module at the point in time (Ma et al, 2013). The PV cell model has been the basis for describing the behaviour of the PV cell, the most widely used is the single diode model shown in figure 2 (Jain & Kapoor, 2003).

![Figure 2: Practical single diode model](image-url)

The current and voltage outputs of the module’s terminal are related by the implicit transcendental equation as follows

\[
I = I_{ph} - I_o \left( \exp \left( \frac{V + IR_s}{R_{sh}} \right) - 1 \right)
\]  

(10)

Where $V_e = \frac{kT}{q} = 25.7mV$ at 25°C.
This model has five parameters namely photocurrent \( I_{ph} \), reverse saturation current \( I_o \), ideality diode factor \( n \), shunt and series resistance \( R_{sh} \) and \( R_s \) respectively (Ibrahim & Anani, 2017; Nguyen & Nguyen, 2015).

MATERIALS AND METHODOLOGY
The materials used to carry out the study are as follows:
1. A 30 Watts sunshine polycrystalline solar module
2. A solar I-V Data capturing device
3. A data logging solar meter
4. A computer system with MATLAB/Simulink and PLX DAQ for Ms Excel

The experimental method was carried out using the materials mentioned above to obtain the I-V and P-V characteristic curves by making observations under the sun with the solar module. The parameters obtained from this method are Photocurrent \( I_{ph} \), Open Circuit Voltage \( V_{oc} \), Current and Voltage at maximum power points \((I_{mp} & V_{mp})\), Maximum power point \( P_{mp} \), Fill Factor \( FF \) and solar cell energy conversion efficiency \( \eta \).

The software used for the experiment is PLX DAQ in Microsoft Excel which enables data collection and analysis as the experiment is being carried out, while the MATLAB/Simulink was used for simulation.

The image below is the experimental setup carried out in the premises of Kaduna State University, Nigeria.

Figure 3: Experimental setup

Using the above experimental setup as shown in figure 1 the following steps were followed to carry out the experiment.
1. The solar module was connected to the Solar I-V Data Capture device which was connected to the computer using two USB cables (black and blue).
2. The black USB cable was connected to the computer, from the device manager of the computer the com port was taken note of e.g. COM 8 which was used to transmit logging values to excel spread sheet.
3. The blue USB was also connected to the computer to power the digital potentiometer.
4. The solar power was connected to the port on the device
5. The device made 4 beeps when the black cable was connected indicating that the device has booted up.
6. The I-V characteristics curve of the solar module was obtained by varying the potentiometer manually.
7. The excel spread sheet file “Solar-Panel logger” was opened and the "Click to log Data button" on the G1 cell was selected to display data from the solar module.
8. The appropriate com port obtained from device manager was inputted on the PLX DAQ dialog box and the “Connect button” was clicked to start the logging process.
9. The potentiometer of the I-V data capture device was used to vary the resistance each time the system made a beep indicating that a value has been logged or obtained.
10. The input logging delay was set to be 500 milliseconds.
11. The temperature of the solar module was measured using the temperature sensor which was placed behind the module.
12. The disconnect button was clicked to stop the logging process when finished
13. The values were logged automatically on the spread sheet workbook, and the graphs were plotted.

The I-V and P-V curves of the photovoltaic module can be generated using computer software such as MATLAB/Simulink from equation (1) above. The Simulink block representation of equation (1) is shown in the figure (2) below; it is done at STC which produces the parameters given by the manufacturer.

![Simulink block representation of the PV module.](image)

RESULTS AND DISCUSSION
The results of the experiments carried out under the sun at different conditions of irradiance and cell temperature are as follows.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Measured Irradiance (W/m²)</th>
<th>Measured Cell Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>153</td>
<td>303</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>548</td>
<td>309</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>638</td>
<td>313</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>712</td>
<td>315</td>
</tr>
</tbody>
</table>

Table 1: shows the amount of irradiance and cell temperature measured during the course of the experiments.
The figures below show the I-V and P-V characteristic curves of the module obtained from the experiments.

![Figure 5: (a) I-V characteristic curves](image-a)

![Figure 5: (b) P-V characteristic curves](image-b)

**Figure 5:** (a) I-V characteristic curves and voltages at maximum points \(I_{mp} & V_{mp}\).

(b) P-V characteristic curves and voltages at maximum points \(I_{mp} & V_{mp}\).

Figure 5 (a) shows the I-V curves of the four different experiments carried out at different irradiance and cell temperature. The I-V curves show significant increase in the short circuit current \(I_{sc}\) and a slight increase in open circuit voltage \(V_{oc}\) as irradiance and cell temperature increases. At the knees of the curves are the currents and voltages at maximum points \(I_{mp} & V_{mp}\).

Table 2: shows the result of the experiments carried out

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Measured Irradiance (W/m²)</th>
<th>Measured Temperature (K)</th>
<th>Cell</th>
<th>(V_{oc}) (V)</th>
<th>(I_{sc}) (A)</th>
<th>(P_{mp}) (W)</th>
<th>Fill Factor</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>153</td>
<td>303</td>
<td>19.60</td>
<td>0.31</td>
<td>4.61</td>
<td>0.76</td>
<td>15.45</td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>549</td>
<td>309</td>
<td>21.40</td>
<td>1.25</td>
<td>18.76</td>
<td>0.70</td>
<td>17.51</td>
<td></td>
</tr>
<tr>
<td>Experiment 3</td>
<td>638</td>
<td>313</td>
<td>21.60</td>
<td>1.46</td>
<td>22.77</td>
<td>0.72</td>
<td>18.30</td>
<td></td>
</tr>
<tr>
<td>Experiment 4</td>
<td>712</td>
<td>315</td>
<td>21.80</td>
<td>1.67</td>
<td>25.91</td>
<td>0.71</td>
<td>19.54</td>
<td></td>
</tr>
</tbody>
</table>

The figures below are the I-V and P-V characteristic curves of the module from the Simulink block representation at STC.

![Figure 6: (a) I-V characteristic curve](image-a)

![Figure 6: (b) P-V characteristic curve](image-b)
Table 3: shows the results from the curves

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Circuit Current I_{sc}</td>
<td>1.92A</td>
</tr>
<tr>
<td>Open Circuit Voltage V_{oc}</td>
<td>22.05V</td>
</tr>
<tr>
<td>Current at Maximum Power Point I_{mp}</td>
<td>1.71A</td>
</tr>
<tr>
<td>Voltage at Maximum Power Point V_{mp}</td>
<td>17.5V</td>
</tr>
<tr>
<td>Maximum Power Output</td>
<td>30W</td>
</tr>
</tbody>
</table>

The values of the parameters above have good agreements with the information provided by the manufacturer as shown in Table 4.

<table>
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<th>Value</th>
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<tr>
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<td>17.5V</td>
</tr>
<tr>
<td>Maximum Power Output</td>
<td>30W</td>
</tr>
</tbody>
</table>

At different irradiance the I-V and P-V characteristic curves exhibit the behaviours below.

Figure 7: (a) I-V Characteristic Curves (b) P-V Characteristic Curves

The irradiance is been varied from 200W/m² to 1000W/m² at constant temperature of 25°C.

At different values of cell temperature, the module exhibits the following behaviours.

Figure 8: (a) I-V characteristic curves (b) P-V characteristic curves

The best comparison of the model is done by comparing with the experiment observed. This was done by plotting the difference of the maximum power output (P_{s} - P_{e}) of the simulation and experimental results against their Voltages V and also calculating their Root Mean Square Error (RMSE) as shown in figure 9.
Simulation and Validation of the Performance of a Polycrystalline Photovoltaic Module

Figure 9: (a)-(d) Comparison between the simulation and experimental results

Conclusion
The graphs shown above depict excellent agreement between the model and the experimental observations. The average Root Mean Square Error (RMSE) of all experiments is 0.13 which is known as the measure of uncertainty.

Solar energy has a great potential across the globe and Nigeria in particular, harnessing this potential will contribute to solving the energy problems. Abundant sunlight and the non-pollutant nature of the solar module is what makes it a better choice of alternative source of energy worldwide.

The short current circuit $I_{sc}$ produced by the different experiments are 0.31A, 1.25A, 1.46A and 1.67A respectively, while the open circuit voltage $V_{oc}$ are 19.60V, 21.40V, 21.60V and 21.80V the fourth experiment has the maximum current and voltage and consequently has the maximum power output as a result of the product between the current and voltage outputs of the module.

The power outputs for the experiment are 4.61W, 18.76W, 22.77W and 25.91W respectively. The fill factor for the module is approximately 0.7 and the solar cell energy conversion efficiencies for each experiment carried out are 15.45%, 17.51%, 18.30% and 19.54%. The fourth experiment has the maximum solar cell efficiency.

Results from the experiments is due to the irradiance and cell temperature of the module which are the two main factors influencing the behaviour of a solar module, it was found that an increase in irradiance and cell temperature increases the current produced by the module significantly and the voltage slightly. The experiment 1 with the lowest irradiance and cell temperature has the lowest short circuit current $I_{sc}$, the lowest open circuit voltage $V_{oc}$ and consequently has the lowest power output $P_{mp}$ while experiment 4 with the highest irradiance and cell temperature has the highest short circuit current $I_{sc}$, open circuit voltage $V_{oc}$ and...
consequently with the highest power output $P_{mp}$. Therefore, current generated from this module can be used to solve some energy problems. The amount of sunlight in Nigeria can be used to generate electricity that will meet the needs of the populace for their work, businesses and leisure etc.

REFERENCES


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