## Laboratory 2: PV Module Current-Voltage Measurements

*Florida Solar Energy Center*

### Introduction and Background

The current-voltage (I-V) characteristic is the basic descriptor of photovoltaic device performance. A fundamental understanding of how solar irradiance, cell temperature and electrical load affect I-V curves is essential in designing, installing and evaluating PV system applications.

Figure 1 shows a typical I-V curve for a PV device. The I-V curve represents an infinite number of current-voltage (direct-current, DC) operating points, the specific operating point being determined by the electrical load connected to the PV device. For example, if a PV module is connected to a battery, the battery voltage establishes the operating voltage (and current) output of the PV device.

When maximum load is connected to a PV device (resistance = infinity), a PV device produces maximum voltage and zero current, referred to as its ***open-circuit voltage, Voc***. When zero load is connected to a PV device (resistance = zero), the device produces maximum current and zero voltage, referred to as its ***short-circuit current (Isc).*** The point at which a PV device delivers its maximum power output and operates at its highest efficiency is referred to as its ***maximum power point, Pmp***. The voltage and current values at the maximum power point are referred to as the ***maximum power voltage, Vmp*** and the ***maximum power current, Imp***, respectively.

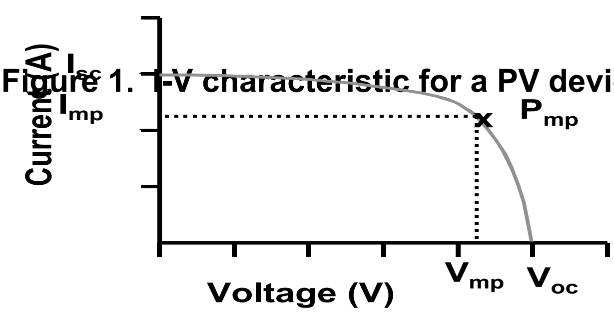



**Figure 1. I-V characteristic for a PV device.**

The I-V characteristic for a PV cell, module or array can be measured using several types of electrical loads as depicted in the circuit diagram in Figure 2. For larger PV modules and arrays, I-V curves are generally measured with capacitive loads, power transistors or sink/source power supplies. For small PV modules and arrays, a variable resistor can be used, as long as the current rating of the variable resistor is greater than the short-circuit current (Isc) of the PV under test. As a general rule, the minimum and maximum resistances required to operate over the full range of the I-V curve are:

Rmin = Voc/4Isc

Rmax = 4Voc/Isc

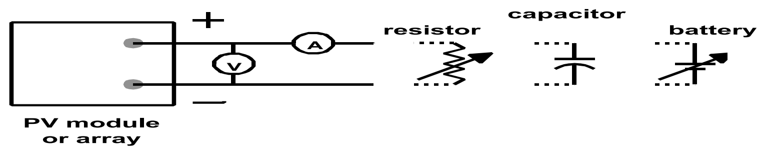



**Figure 2. I-V curve measurement methods.**

As the resistance connected to a PV device is increased from zero to infinity, the current and voltage output can be measured and recorded. The short circuit current (Isc) is measured when the resistance is set at zero (voltage = 0). The open circuit voltage (Voc) is measured when the resistance is set at infinity (current = 0). Figure 3 shows how resistance I-V load lines intersect the I-V curve for a PV device. Notice how the resistive load lines follow the linear relationship of Ohm's Law: R=V/I.

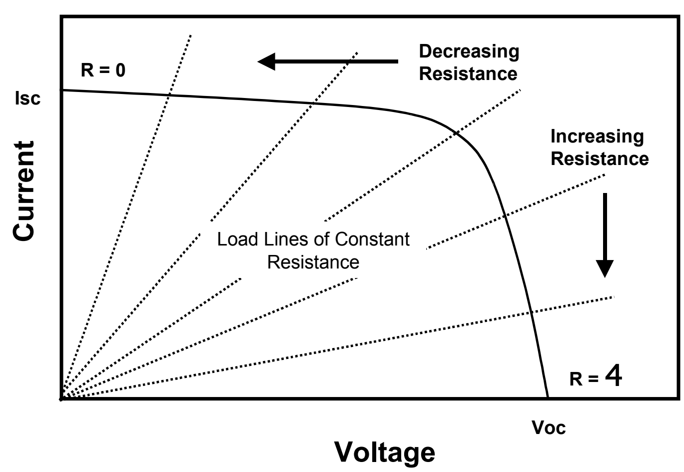



**Figure 3. I-V curve with load lines of constant resistance.**

An I-V curve only has meaning when the rating or measurement conditions are specified. These conditions include solar irradiance, spectral distribution and cell temperature. For this reason, solar irradiance and cell temperature are always measured and reported along with I-V curve data. The primary rating condition used for PV modules is Standard Test Conditions (STC). Under STC, the performance of a PV module is given for a solar irradiance of 1000 W/m$^2$ with a spectral distribution of AM1.5 and cell temperature of 25$^o$ C. Test and rating conditions other than STC are sometimes used to represent PV module performance under different conditions.

Changes in the incident solar irradiance and cell temperature affect the I-V characteristics of a PV device in different ways. Figure 4 shows how the I-V curve of a PV device is affected by changing solar irradiance. As the irradiance increases, the short-circuit current (Isc) and maximum power (Pmp) increase linearly. However, the voltage increases only slightly, primarily at lower irradiance levels. For example, the short-circuit current (Isc) and maximum power (Pmp) at 500 W/m$^2$ irradiance would be one-half of the Isc and Pmp at 1000 W/m$^2$.

***Example:*** *What would the maximum power output be at 600 W/m$^2$ irradiance for a PV module producing 50 watts maximum power at STC (1000 W/m$^2$)?*

***Solution:*** *The maximum power output of a PV device is generally proportional to solar irradiance. The maximum power at 600 W/m$^2$ irradiance is calculated by:*

*50 Watts * 600 W/m$^2$ / 1000 W/m$^2$ = 30 Watts*

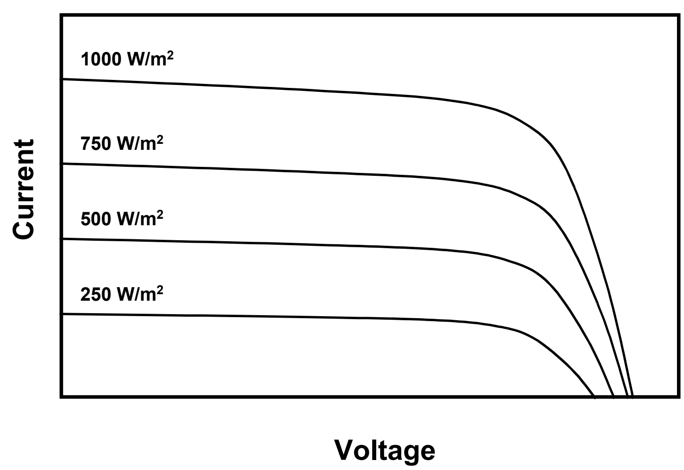



**Figure 4. IV curve response to irradiance, constant temperature.**

Cell temperature also affects the I-V characteristic of a PV device as shown in Figure 5. For most single and poly-crystalline silicon PV cells, increasing cell temperature reduces voltage and power output, and results in a slight increase in current output. For some thin-film PV materials, the effects of increasing operating temperature are significantly different than for single and polycrystalline cells, and in some cases there is no net power loss with increasing temperature. In general, however, PV module lifetime and performance are reduced with increasing operating temperature, suggesting installation practices that maximize the natural passive cooling of the array.

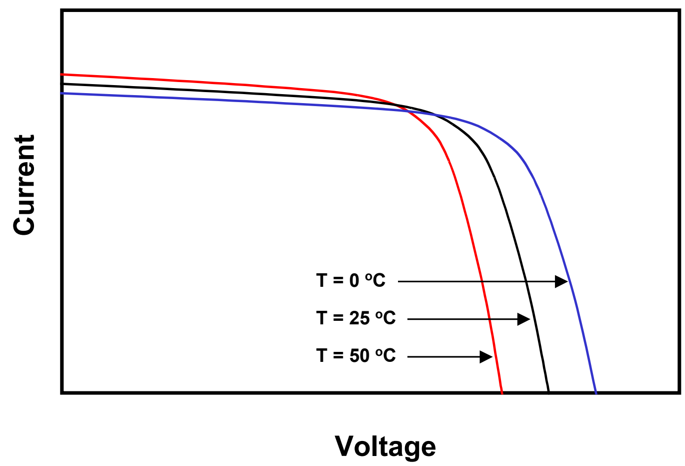



**Figure 5. I-V curve response to cell temperature.**

Approximate temperature coefficients for voltage, current and power for silicon PV cells are:

**Voltage: -0.45% per °C    Current: +0.1% per °C    Power: -0.4% per °C**

***Example:*** *What would the maximum power voltage be at 50 °C for a crystalline silicon PV module producing 17.1 volts maximum power at STC (25 °C)?*

***Solution:*** *The voltage temperature coefficient for crystalline silicon is –0.45%/°C. The maximum power voltage at 50 °C is calculated by:*

*17.1 Volts – [ 17.1 Volts * (0.0045/°C * (50-25))°C ] = 15.2 Volts*

## Objectives

- Measure the current-voltage (I-V) characteristics of a PV module using a variable resistance load.

- Understand how solar irradiance and cell temperature affect the electrical output of a PV module.
- Determine how the electrical load connected to a PV device establishes its operating point.
- Estimate the electrical output of PV cells, modules and arrays based on rated conditions and given values of solar radiation and cell temperature.

## Equipment

- PV Module
- Resistor
- Voltmeter/Ammeter
- Solar Irradiance Meter (pyranometer or reference cell)
- Temperature Sensor

## Procedure

For best results, I-V curves should be measured under clear skies, within two hour of solar noon, and with the plane of array perpendicular to the sun's rays. Cell temperature should be allowed to stabilize before being measured. During the test, the I-V curve data points should be taken as quickly as practical to minimize the effect of a change in irradiance level or a change in cell temperature during the test period.

1. Using a PV module, test kit and banana jacks, assemble the test circuit as shown in Figure 2, leaving the positive lead to the PV module disconnected. Be sure to observe the correct polarity to prevent damage to the meters. Ask an instructor to check your circuit before continuing.

2. Face the PV module toward the sun to maximize irradiance on the module surface. On the data sheet, record the irradiance reading for the orientation of the module. Record the cell temperature.

3. Adjust the resistance to zero ohms or short-circuit the PV module (voltage reading should be zero). Record the short-circuit current, Isc.

4. Increase the resistance until the voltage reading is approximately one-fourth of the estimated Voc. For example, if the estimated Voc is 24 volts, adjust Rvar until the voltmeter reads 6 volts. Record the current and voltage readings.

5. Increase the resistance until the voltage is increases by approximately 2 volts. Record the current and voltage readings. Repeat this step until the maximum resistance setting is reached or the current is zero.

6. Disconnect the resistor from the test circuit (current becomes zero). Record the open-circuit voltage, Voc.

7. The test is complete. Record the irradiance reading and the cell temperature again. Average the initial and final irradiance and cell temperature measurements.

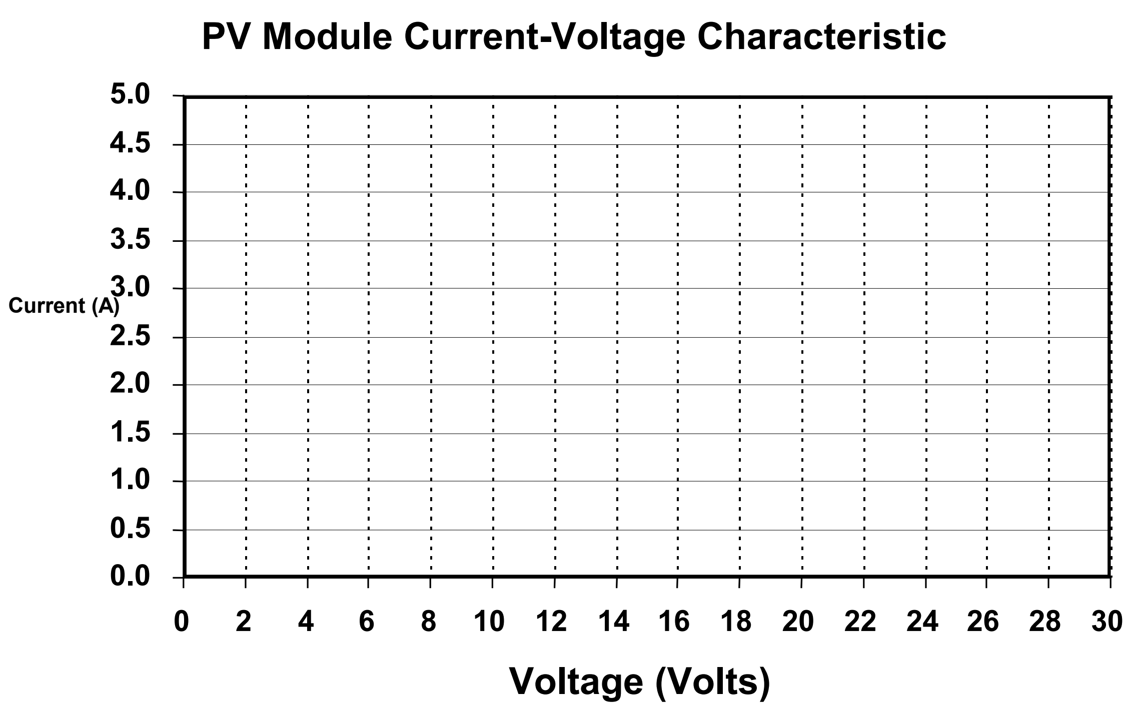
8. Calculate the power in watts (P=VI) for each current-voltage measurement. Plot the data on the graph paper provided.

9. Determine the power, voltage, and current at the maximum power point (Pmp, Vmp, Imp).

## Results

| Voltage (Volts) | Current (Amps) | Power (Watts) = Volts x Amps |
|---|---|---|
| 0 | Isc = | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| Voc = | 0 | |

| | Irradiance ($W/m^2$) | Cell Temperature ($^oC$) |
|---|---|---|
| Initial | | |
| Final | | |
| Average | | |



## Review Questions

1. Ignoring corrections for cell temperature, what would be the approximate maximum power of your module for an irradiance of (a) 1000 $W/m^2$ and (b) 500 $W/m^2$? Remember maximum power is directly proportional to irradiance level.

2. Suppose your module is connected directly to a battery without a voltage regulator. Use your I-V curve to determine current, voltage and power the module produces for the following battery voltages: (a) 6 volts, (b) 12 volts and (c) 24 volts.

3. A 25-ohm resistive load is connected directly to your module.

(a) On the graph paper, draw the I-V curve for the 25-ohm resistive load. (Hint: The I-V curve for a resistor is a straight line and $V = IR$.)

(b) For the irradiance level and cell temperature at which you measured your I-V curve, at what current, voltage and power will your module operate when connected to the 25-ohm load?

(c) If the irradiance level is half that at which you measured your I-V curve, at what current, voltage and power will your module operate?

## Conclusions

- The variable resistance method is one way to determine a module's I-V characteristic or curve.

- Each PV module has a specific I-V curve for a given cell temperature and irradiance level.

- The electrical load connected to a PV device determines its operating point on its I-V curve. A higher resistance load operates closer to the open-circuit voltage (Voc), and lower resistance load operates closer to the short-circuit-current (Isc)

- Increases in irradiance level result in proportional increases in the current and power output of a PV device.  Voltage increases slightly with increasing irradiance.

- Increases in cell temperature result in significant voltage and power reductions, and slight increases in current.