Application Note PVA-600-1

Guide To Interpreting
I-V Curve Measurements
of PV Arrays

March 1, 2011

Contents

Purpose

This *Guide to Interpreting I-V Curves Measurements of PV Arrays* is one of a series of application notes, videos and webinars designed to support users of the Solmetric PVA-600 PV Analyzer http://www.solmetric.com/pva600.html. An understanding of this material will be helpful for PVA users and others who troubleshoot problems in PV strings or modules. However, this level of knowledge is *not* required to operate or collect data with the PV Analyzer.

The Solmetric PVA-600 PV Analyzer

A large-scale PV array represents a major investment of capital and energy. As an installer, if your array has performance problems, you want to know about them during system construction, when fixing them is least costly. You also want test equipment that measures performance comprehensively and quickly, reduces the amount of manual record keeping, and makes troubleshooting more efficient. Data from these tests should allow prompt close-out of the contract and provide a solid performance baseline for ongoing maintenance.

The Solmetric PVA-600 PV Analyzer is designed to meet this need. It is a compact, rugged, powerful and easy-to-use portable electronic tool that's specifically designed for characterizing PV arrays, the *DC side* of PV systems. It measures a PV module or string in seconds, compares its I-V curve with the predictions of on-board PV models, identifies the maximum power point and other key parameters, and reveals performance issues that ordinary test instruments can't detect. Measurement results are saved for future reference and analysis, and manual data recording is eliminated. An optional Data Analysis Tool automatically imports and analyzes large amounts of data, drawing attention to problem strings and providing troubleshooting clues. The PV Analyzer is the ideal tool for commissioning, re-commissioning or troubleshooting PV arrays.

Introduction to I-V Curves

The I-V (current-voltage) curve of a PV string (or module) describes its energy conversion capability at the existing conditions of irradiance (light level) and temperature. Conceptually, the curve represents the combinations of current and voltage at which the string could be operated or 'loaded', if the irradiance and cell temperature could be held constant. Figure 1 shows a typical I-V curve, the power-voltage or P-V curve that is computed from it, and key points on these curves.

Referring to Figure 1, the span of the I-V curve ranges from the short circuit current (Isc) at zero volts, to zero current at the open circuit voltage (Voc). At the 'knee' of a normal I-V curve is the maximum power point (Imp, Vmp), the point at which the array generates maximum electrical power. In an operating PV system, one of the jobs of the inverter is to constantly adjust the load, seeking out the particular point on the I-V curve at which the array as a whole yields the greatest DC power.

At voltages well below Vmp, the flow of solar-generated electrical charge to the external load is relatively independent of output voltage. Near the knee of the curve, this behavior starts to change. As the voltage increases further, an increasing percentage of the charges recombine within the solar cells rather than flowing out through the load. At Voc, all of the charges recombine internally. The maximum power point, located at the knee of the curve, is the (I,V) point at which the product of current and voltage reaches its maximum value.
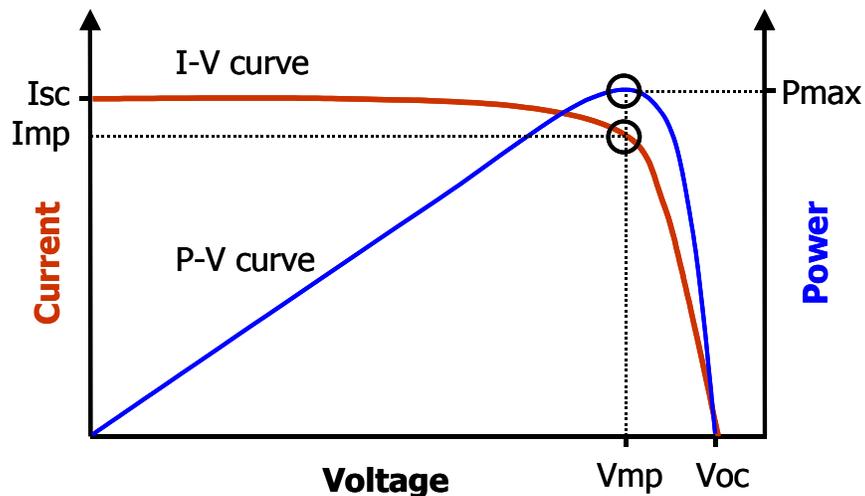
Figure 1. The I-V and P-V curves of a photovoltaic device. The P-V curve is calculated from the measured I-V curve.

Please note the abbreviations listed in Table 1, below. They will be used throughout this document.

Abbreviation	Definition
Isc	Short circuit current
Imp	Max power current
Vmp	Max power voltage
Voc	Open circuit voltage
Vx	Voc/2
Ix	Current at Vx
Vxx	Voltage midway between Vmp and Voc
Ixx	Current at Vxx
FF	Fill Factor = (Imp*Vmp)/(Isc*Voc)

Table 1. Abbreviations used in the discussion of I-V curves.

The fill factor (FF) of a PV module or string is an important performance indicator. It represents the square-ness (or 'rectangularity') of the I-V curve, and is the ratio of two areas defined by the I-V curve, as illustrated in Figure 2. Although physically unrealizable, an ideal PV module technology would produce a perfectly rectangular I-V curve in which the maximum power point coincided with (Isc, Voc), for a fill factor of 1.

Why is the fill factor important? If the I-V curves of two individual PV modules have the same values of Isc and Voc, the array with the higher fill factor (squarer I-V curve) will produce more power. Also, any impairment that reduces the fill factor will reduce the output power.
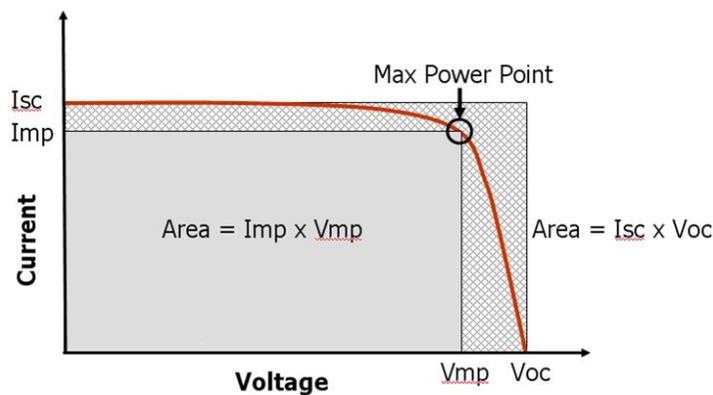
Figure 2. The Fill Factor, defined as the gray area divided by the cross-hatched area, or (Imp x Vmp)/(Isc x Voc), represents the square-ness of the I-V curve.

Under identical conditions, two healthy PV modules of a given model number should have similar fill factors. The actual magnitude of the fill factor depends strongly on module technology and design. For example, amorphous silicon modules generally have lower fill factors (softer knees) than crystalline silicon modules.

Any impairment that reduces the fill factor also reduces the output power by reducing Imp or Vmp or both. The I-V curve itself helps us identify the nature of these impairments. The effects of series losses, shunt losses and mismatch losses on the I-V curve are represented in Figure 3. Not represented in Figure 3 is the effect of uniform soiling, which simply reduces the height of the I-V curve by allowing less light to reach the PV cells. *Non-uniform* shading is a mismatch effect.
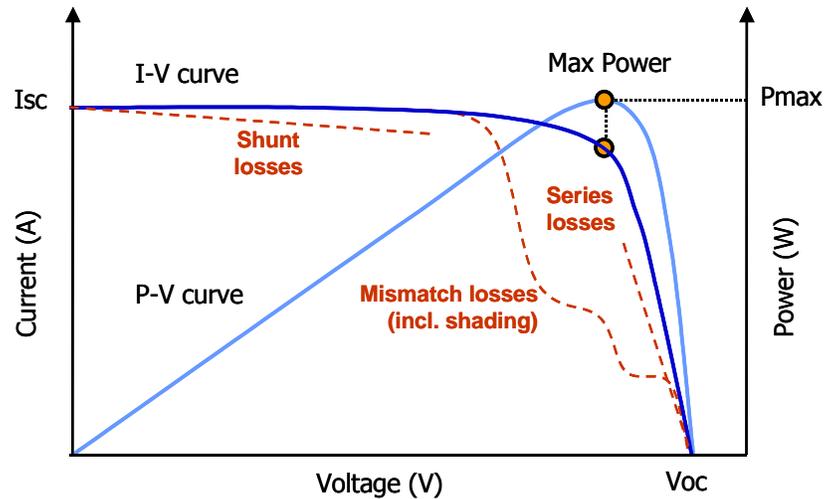
Figure 3. Several categories of losses that can reduce PV array output. The I-V curve provides important troubleshooting clues.

Scaling I-V Curves

Thinking of PV arrays as composites of smaller PV building blocks is key to interpreting electrical measurements in troubleshooting situations. The I-V curve of a PV array is a scale-up of the I-V curve of a single cell, as illustrated in Figure 4. For example, if a PV module has 72 series-connected cells and a PV string has 10 of these modules in series, the string's open circuit voltage is 720 times that of a single cell. Similar reasoning applies to the short circuit current, which scales with number of cells in parallel, and the maximum power point, which scales with the *product* of the number of cells in series and strings in parallel.

As illustrated in Figure 4, we can think of the maximum power point of an array in terms of building blocks, where each cell, or each module, or each cell string within a module, is a building block whose upper right corner represents its maximum power point. When these building blocks are stacked in a rectangle, the upper right corner is the max power point of the array.
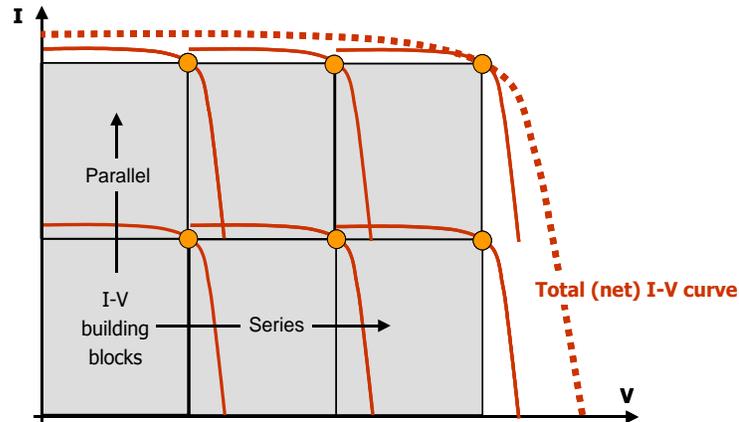
Figure 4. Scaling the I-V curve from a PV cell to a PV array. Thinking of an array in terms of building blocks makes troubleshooting much easier.

PV Performance Models

The value of a measured I-V curve is greatly increased when it can be compared with the curve predicted by a comprehensive PV model. Models take into account the specifications of the PV modules, the number of modules in series and strings in parallel, and the losses in system wiring. Other data used by the models include the irradiance in the plane of the array, the module temperature, and array orientation.

The PVA-600's mathematical models predict the ideal shape for this curve for approximately two thousand different PV modules and configurations. Occasionally the shape of the measured I-V curve will deviate substantially from the shape predicted by the model. These changes from the ideal shape contain information about the performance of the PV System. This Application Note describes the most common deviations and identifies possible causes for these deviations.

For the prediction to be accurate, inputs to the model must be valid. The model inputs are:

- PV module characteristics
- Number of PV modules wired in series
- Number of PV modules or strings wired in parallel
- Length and gauge of wire between the module or string and the PV Analyzer
- Irradiance in the plane of the array
- Cell temperature
- For some instrument modes it is also necessary to provide: latitude, longitude, time zone, and array orientation.

The PV Analyzer can indicate the maximum power tracking (MPT) range of your PV system's inverter by shading the corresponding span of the I-V curve graph. This feature does not affect the PV modeling and prediction, but it brings to the user's attention the amount of tracking margin for existing conditions. If the knee of the measured I-V curve is close to either edge of the inverter's MPT range, it could go out of range at extreme temperatures or as the system ages.

Measured and Predicted PV Curves

A normal I-V curve has a smooth shape with three distinct voltage regions:

1. A slightly sloped region above 0 V
2. A steeply sloped region below Voc
3. A bend or 'knee' in the curve in the region of the maximum power point

In a normal curve, as shown in Figure 5, the three regions are smooth and continuous. The shape and location of the knee depends on cell technology and manufacturer. Crystalline silicon cells have sharper knees; thin film modules have more gradual knees.

The pattern of five dots displayed along the I-V curve in Figure 5 represent the prediction of the PV Analyzer's on-board PV model. The P-V (power-voltage) curve is also shown. (blue line). Power is calculated as the product of measured current and voltage at each I-V point. The yellow point at the peak of the P-V curve locates Pmax, which is calculated from a polynomial curve fitted to the peak of the P-V curve.
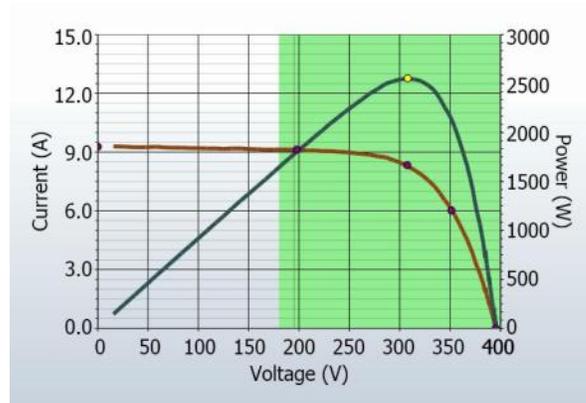
Figure 5. A normal I-V curve for the parallel combination of two strings of eight 175-watt modules, showing conformance with five points predicted by the PV model.

The five PV model (I,V) points are defined as follows:

- Isc, 0   Short circuit condition (first point, at left)
- Ix, Vx   At one-half of the open circuit voltage (second point)
- Imp, Vmp   The maximum power point (third point)
- Ixx, Vxx   Midway between Vmp and Voc (fourth point)
- 0, Voc   Open circuit condition (fifth point, at right)

These five prediction points are adopted from the Sandia PV Array Model, which is the most comprehensive and detailed of the PV models built into the PV Analyzer.

The measured and predicted curve shapes may disagree to some extent even when the PV string (or module) under test is performing perfectly. This can be caused by errors in irradiance or temperature measurement, or by soiling of the array.

Interpreting I-V Curves

Deviations between measured and predicted I-V curves typically fall into one of these categories:

1. The measured I-V curve shows higher or lower current than predicted
2. The slope of the I-V curve near Isc does not match the prediction
3. The slope of the I-V curve near Voc does not match the prediction
4. The I-V curve has notches or steps
5. The I-V curve has a higher or lower Voc value than predicted

A single I-V curve may show one or more of these deviations, all of which indicate a reduction in maximum power produced by the module or string under test.

The remaining sections of this application note explore the possible root causes for each of these deviations.

NOTE   A measured I-V curve may deviate from the ideal IV curve due to physical problems with the PV array under test, or may be the result of incorrect model values, test instrument settings or measurement connections. Always select the correct PV module from the on-board PV module list, double check the measurement connection, and ensure the proper temperature and irradiance values are used.

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1. The measured I-V Curve Shows Higher or Lower Current than Predicted

An example of this type of deviation is shown in Figure 6.
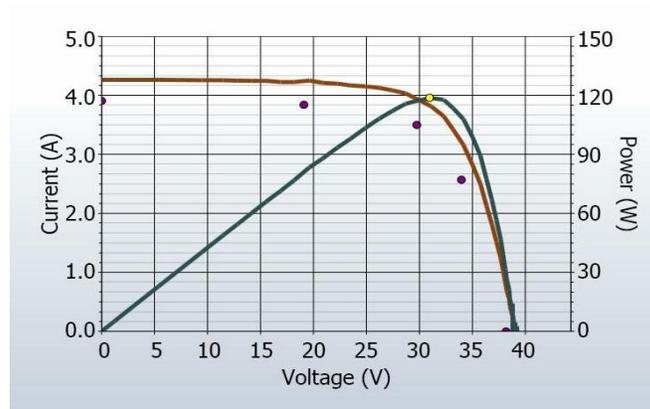
Figure 6. Example of a measured I-V curve that shows higher current than predicted.

Potential causes of this deviation are summarized below, and then discussed in more detail.

Potential causes located in the array include:

- PV array is soiled (especially uniformly)
- PV modules are degraded

Potential causes associated with the model settings include:

- Number of PV strings in parallel is not entered correctly in the model

Potential causes associated with irradiance or temperature measurements include:

- Irradiance changed during the short time between irradiance and I-V measurements
- Irradiance sensor is oriented incorrectly
- Irradiance sensor calibration factor is entered incorrectly
- Reflections contribute additional irradiance
- Irradiance is too low, or the sun is too close to the horizon
- Manual irradiance sensor is not well calibrated

PV Array Is Soiled

The effect of uniform soiling is like pulling a window screen over the entire array, or reducing the actual irradiance; the overall shape of the I-V curve is correct, but the current at each voltage is reduced. Non-uniform soiling can also have this effect. The most common example is a low-tilt array with modules in portrait mode. Over time, a band of dirt extends upward from the lower edge of each module. When the band of dirt reaches the bottom row of cells, the height of the I-V curve is reduced.

PV Modules Are Degraded

Degradation of PV module performance with time and environmental stress is normally a very slow process. Given the number of factors – for instance, soiling or irradiance measurement accuracy – that can affect the height of the I-V curve, the operator should estimate the impact of these other factors before concluding that the modules have degraded.

Incorrect PV Module Is Selected for the Model

PV modules with similar model numbers may have different Isc specifications. Check that the module you selected from the on-board module list matches the nameplate on the back of the PV modules. If the array is known to have a mix of PV modules of different types, this can also contribute to changes in Isc.

Number of PV Strings in Parallel Is Not Entered Correctly in the Model

The measured value of Isc scales directly with the number of strings in parallel. Check that the correct value is entered into the model.

Irradiance Changed Between Irradiance and I-V Measurements

When measuring irradiance with an external irradiance sensor, the time delay between the irradiance measurement and the I-V measurement can translate into measurement error.

Irradiance Sensor Is Oriented Incorrectly

The accuracy of the irradiance measurement is very sensitive to the orientation of the sensor. The PV Analyzer's model assumes that the irradiance sensor is oriented in the plane of the array. It is difficult to reliably hold hand-held sensors in the plane of the array. To see how much error this can introduce, orient the sensor to match the plane of the array and note the reading. Then tilt the sensor slightly and notice how much the reading changes.

Irradiance Sensor Calibration Factor Is Entered Incorrectly

The irradiance sensor in the optional wireless sensor kit has a calibration sticker. For accurate measurements, the calibration factor value on the sticker must be entered into the PV Analyzer software.

Reflections Contribute Additional Irradiance

The energy production of PV modules can be increased by reflections from nearby buildings, automobiles, and other reflecting surfaces. The error is most pronounced if the reflections are not uniform across the array and/or are not captured by the irradiance sensor.

Irradiance Is Too Low, or the Sun Is Too Close to the Horizon

Crystalline silicon PV modules behave somewhat differently in low light conditions. Also, early and late in the day, sunlight hits the surface of the PV module at glancing angles, and differences in the reflectivity of the surfaces become more important. Finally, the spectrum of sunlight changes in the course of a day. For best results, measure PV arrays during the central part of the day.

Manual Irradiance Sensor Is Not Well Calibrated

Irradiance sensors vary widely in their basic calibration accuracy, response to diffuse light, and spectral match to the array being measured. Choose a well-calibrated sensor of a technology similar to that of the array under test. The irradiance sensor provided in the PV Analyzer sensor kit is of high quality and is well calibrated, with a spectral response similar to crystalline solar cells.

2. The Slope of the Curve near Isc Does Not Match the Prediction

An example of this deviation is shown in Figure 7.
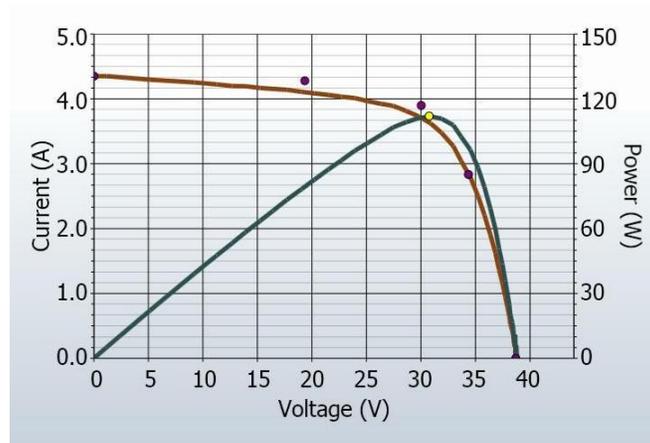
Figure 7. An I-V curve showing more slope than expected in the region above Isc.

The slope of the I-V curve in this region is affected by the amount of shunt resistance (or shunt conductance - the inverse of shunt resistance) in the electrical circuit. Reduced shunt resistance (increased shunt conductance) results in a steeper slope in the I-V curve near Isc and a reduced fill factor. A decrease in shunt resistance may be due to changes within the PV cells or modules.

Potential causes of this deviation are summarized below, and then discussed in more detail.

Potential causes located in the array include:

- Shunt paths exist in PV cells
- Shunt paths exist in the PV cell interconnects
- Module Isc mismatch

Shunt Paths Exist In PV Cells or Modules

Shunt current is current that bypasses the solar cell junction without producing power, short circuiting a part of a cell or module. Some amount of shunt current within a solar cell is normal, although higher quality cells will have a higher shunt resistance and hence lower shunt current. Shunt current can lead to cell heating and hotspots appearing in the module's encapsulant material. Shunt current is typically associated with highly localized defects within the solar cell, or at cell interconnections. Infrared imaging of the PV module can usually identify minor shunt current hot spots since a temperature rise of 20° C or more is common.

A reduced shunt resistance will appear in I-V curves as a steeper (less flat) slope near Isc. As the cell voltage increases from the short circuit condition, the current flowing in these shunts increases proportionally, causing the slope of the I-V curve near Isc to become steeper. The shunt current in a series of modules or within a single module can be dominated by a single hotspot on a single cell, or may arise from several smaller shunt paths in several series cells.

Shunts within a module can improve over time, or can degrade until the module is damaged irreparably. Smaller shunts can self-heal if the high current through the shunt path causes the small amount of material shorting the cell to self-immolate. Larger shunts can result in localized temperature rises in the module that can reach the melting point of encapsulant material or the module backsheet. Modules that have failed in this manner will tend to show burn spots or other obvious evidence of failure. Bypass diodes in the PV module are designed to prevent damage due to hotspots, and so failure of the bypass diode may accompany hotspot damage.

If the I-V measurement of a PV string shows a substantial slope, you can localize the problem by successively breaking the string into smaller segments and measuring the segments individually. Be sure to update the model with the reduced number of modules in series.

Module Isc Mismatch

A reduction in slope of an I-V curve for a series string may have less to do with shunt resistance, and more to do with small mismatches between the Isc values of each module. Isc values in a real PV system will have some mismatch, due to slight manufacturing variations, different installation angles, or partial soiling. The impact on the I-V curve from Isc mismatch will not be as obvious as a partial shading condition (refer to 4. The I-V Curve Has Notches or Steps) and may only be visible as a slight change in I-V slope and the fill factor.

3. The Slope of the Curve near Voc Does Not Match the Prediction

An example of this type of deviation is shown in Figure 8.
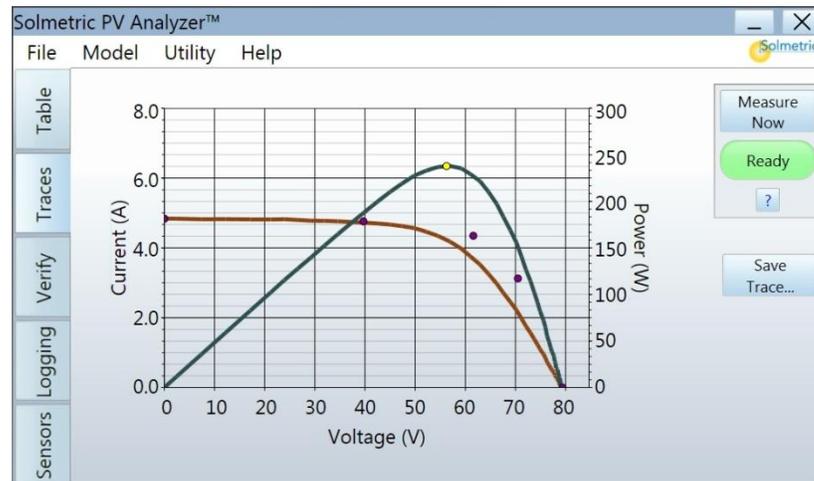
Figure 8. An I-V curve in which the slope of the measured I-V curve near Voc does not match the predicted slope.

The slope of the I-V curve between Vmp and Voc is affected by the amount of series resistance internal to the PV modules and in the array wiring. Increased resistance reduces the steepness of the slope and decreases the fill factor.

Potential causes are summarized below, and then discussed in more detail.

Potential causes located in the array include:

- PV wiring has excess resistance or is insufficiently sized
- Electrical interconnections in the array are resistive
- Series resistance of PV modules has increased

PV Wiring Has Excess Resistance or Is Insufficiently Sized

The electrical resistance of the PV modules and their connecting cords are accounted for in the models stored in the PV Analyzer module database. The resistance of additional wire between the PV modules and the PV Analyzer should be accounted for by entering the wire gauge and length in the Wiring section of the model.

To see the effect of wire resistance on the predicted I-V curve, enter 500 feet (1-way) of #10 wire. This will add approximately 1 ohm of series resistance. Notice the change of slope in the I-V curve near Voc.

The resistance of the primary test leads of the PV Analyzer is extremely low and can be neglected. If additional test leads are attached to the primary leads, be sure that these test leads are of a heavy gauge wire in order to add minimal resistance. Small-gauge test leads can add significant resistance and corresponding measurement error.

Note that wire sizing guidelines for safety considerations (NEC tables, etc.) may not be sufficient to minimize DC power losses from series resistance in cabling. Some sizing guidelines call for a maximum 1% voltage drop due to cabling, which could result in larger sized cabling than would be required to meet code safety considerations.

### Electrical Interconnections in the Array Are Resistive

Electrical connections anywhere along the current path can add resistance to the circuit. Assure that connectors between modules are fully inserted, and if using test leads with alligator clips, be sure the clips have a good grip on a clean metal surface.

### Series Resistance of PV Modules Has Increased

Certain degradation mechanisms can increase the amount of series resistance of a particular module. Corrosion of metal terminals in the module connectors, in the module junction box, or on the interconnects between cells may increase series resistance. Corrosion damage is more common in aged modules in humid or coastal environments. Manufacturing defects within the module can also result in poorly interconnected solar cells. Before deciding that excess resistance comes from these sources, be sure to properly account for PV wiring resistance in the model, and check the electrical connections external to the PV modules for signs of damage or heating.
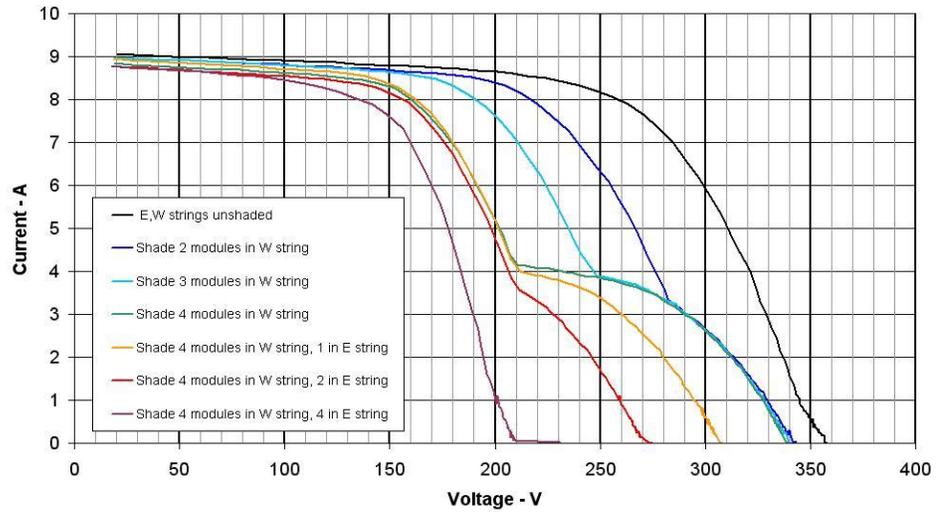
4. The I-V Curve Has Notches or Steps

Examples of this type of deviation are shown in Figures 9, 10 and 11.
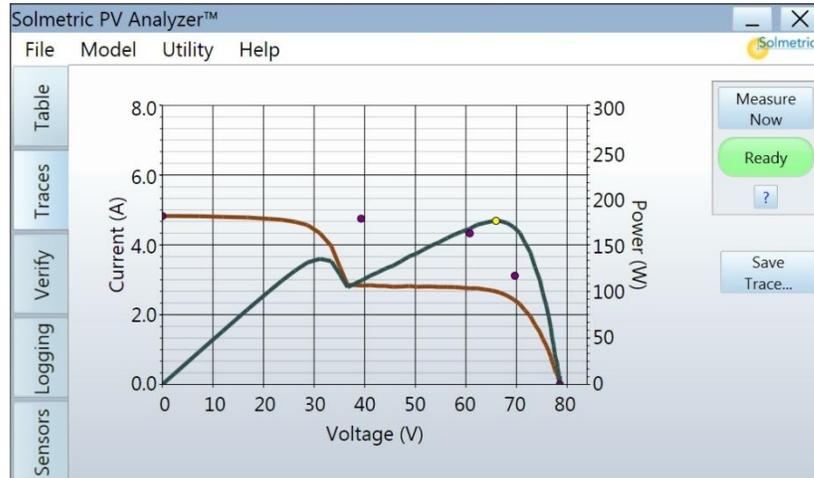
Figure 9. The effect of partial shading on two paralleled strings of eight 175-watt modules.
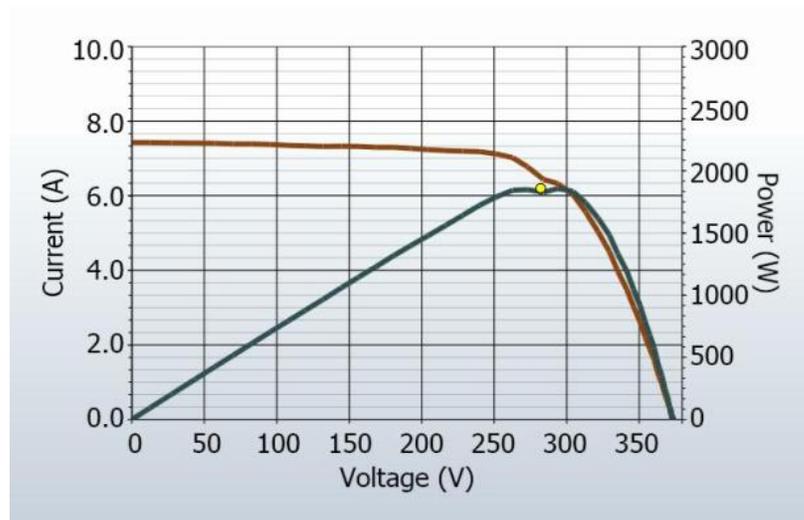
Figure 10. The shading impact of placing a business card on a single cell in a string of fifteen 180-watt modules.

Figure 11. The effect of intentionally shading entire modules in different combinations, in two parallel-connected strings.

In general, these types of patterns in the I-V curve are indications of mismatch between different areas of the array or module under test. Although all three of the preceding figures involve shading, mismatch can have other causes. The notches in the I-V curve are indications that bypass diodes in series connected modules are activating and passing current around the affected module(s).

Potential causes are summarized below, and then discussed in more detail.

Potential causes located in the array include:

- Array is partially shaded
- PV cells are damaged
- Bypass diode is short-circuited

Array Is Partially Shaded

Partial shading of a PV cell reduces the current that can be generated by that cell, which in turn reduces the maximum current that can be produced by other series connected cells. For example, slightly shading one cell in a 72-cell module that has 3 bypass diodes will slightly reduce the current in 24 cells. Bypass diodes are present to prevent that section of cells from going into reverse bias. If the PV module is supplying a load and the current demanded by the load is above the (reduced) current provided by the partially shaded cells, the bypass diode will begin conducting and short them out. Without the bypass diode present, the cells would be reverse biased, which can generate potentially damaging reverse breakdown voltage and hotspot failure (refer to section <u>2. The Slope of the Curve Near Isc Does Not Match Prediction</u>)**.** The impact of partial shading on the I-V curve is to create a distortion or notch, as shown in Figures 9, 10 and 11. In a single PV string, the vertical height or current at which the notch appears is equal to the reduced short-circuit current of the partially shaded cells. The horizontal or voltage distance from Voc to the notch is related to the number of cell strings within modules that have been bypassed.

PV Cells Are Damaged

In a cracked cell, a portion of the cell may be electrically isolated. This has the same effect on the I-V curve as shading of an equivalent area of a normal cell. A notched I-V curve can result depending on the severity of the PV cell damage.

Cell String Conductor Is Short Circuited

As described in 2. The Slope of the Curve near Isc Does Not Match the Prediction, a localized hot-spot can also effectively short out a particular cell. When this happens, the bypass diode spanning that cell string can turn on, causing a notched I-V profile. This I-V profile would be similar to a completely shaded PV module, but with a lesser voltage reduction corresponding to the loss of a single cell string.

5. The I-V Curve Has a Higher or Lower Voc Value than Predicted

An example of this type of deviation is shown in Figure 12.
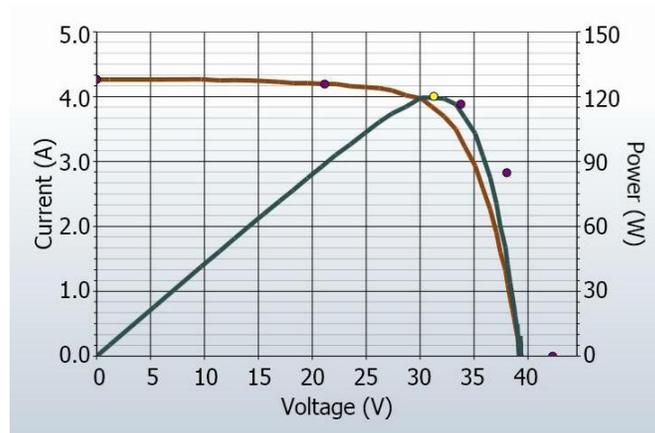
Figure 12. Example of an I-V curve with lower Voc value than predicted.

Potential causes are summarized below, and then discussed in more detail.

Potential causes located in the array include:

- PV cell temperature is different than the modeled temperature
- One or more cells or modules are completely shaded
- One or more bypass diodes is conducting or shorted
- One or more PV modules were not included in the circuit as-built

PV Cell Temperature Is Different than the Modeled Temperature

The module Voc is dependent on the temperature of the solar cells, with higher temperatures resulting in a lower Voc. It is possible that a poor thermal connection exists between the temperature measurement device and the back of the module. Also, if the temperature measurement is taken on the front side of the module, direct sunlight on the temperature sensor itself could result in erroneous temperature readings. It is also possible that the PV module under test has a poor thermal connection between the back of the module and the actual PV junction. In this case, it may be necessary to take a shaded front-side measurement.

One or More Cells or Modules Are Completely Shaded

Shading a cell or module with very high opacity (hard shade) causes its bypass diode to begin conducting when any current passes through it. In this case, the notch in the I-V curve can be similar to that discussed in: 4. The I-V Curve Has Notches or Steps, but the notch occurs at such a low value of current that it may be difficult to differentiate this case from that of a normal curve with a reduced Voc.

One or More Bypass Diodes Are Conducting or Shorted

Failure modes within individual PV modules may cause a bypass diode(s) to conduct even in the absence of shade or severe module-to-module mismatch. The I-V curve shape may look normal except that the Voc value is lower than predicted. If the reduction in Voc is approximately equal to a multiple of the Voc of a module cell string (in 72 cell modules, typically Voc/3) look for a module(s) with conducting or shorted bypass diodes. Start by inspecting module front and backsides for burn marks. You can also use selective shading to locate the module(s). When good modules are completely shaded their Voc values will drop by similar amounts. In contrast, shading a module that has conducting or shorted bypass diodes will reduce the string Voc by a smaller amount, due to the fact that one or more of its cell strings are not contributing voltage.

One or More PV Modules Were Omitted When The String Was Wired

If a string is short by one or more modules, its I-V curve will fall short of the model prediction along the voltage axis. Otherwise, the shape of the curve will be normal. A clue to this situation is that Voc of the string is lower than expected by some multiple of the open circuit voltage of an individual module. This situation is very much like the case of a shorted cell string, but since the missing voltage is larger in magnitude, it is easier to identify.

Acknowledgements