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Interpreting I-V

By Paul Hernday

Courtesy Solmetric

Curve Deviations

When a measured I-V curve differs substantially from the predicted curve, commissioning agents or service technicians can use the nature of the deviation to screen for potential performance problems.

As PV arrays age, there are many potential causes of system underperformance. Some may be expected, such as soiling losses or long-term array degradation. Some may be unexpected, such as bypass diode failure, cracked modules and so forth.

Because I-V curve tracers capture all of the current and voltage operating points of a PV source, they are uniquely capable of identifying symptoms of underperformance in PV systems. As I describe in "Field Applications for I-V Curve Tracers" (*SolarPro,* August/September 2011), every module datasheet provides a model I-V curve that represents all the current and voltage combinations at which you can operate or load the module under Standard Test Conditions (STC). When a measured I-V curve differs significantly in height, width or shape from the predicted I-V curve—which is based on the model I-V curve, but adjusted for actual irradiance and temperature conditions—the nature of the deviation provides clues about potential performance problems.

Here I provide an overview of the process used to gather I-V curves and identify normal traces associated with healthy modules and source circuits. I then explain how to interpret differences between measured and predicted I-V curves. I discuss basic types of I-V curve deviations, all of which indicate that PV power is reduced, and consider possible causes. The discussion of I-V curve deviations is organized according to a troubleshooting flowchart process that is designed for optimal workflow efficiency (see pp. 22–23). I present strategies for identifying PV modules with performance problems. I also cover best practices for taking irradiance and temperature measurements, which can improve the accuracy of measured and predicted I-V curves.

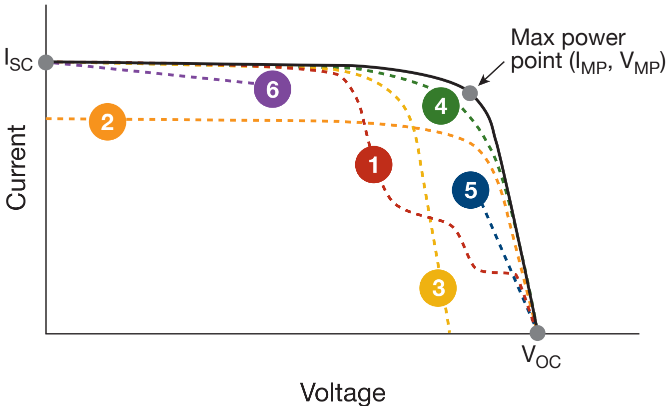
Getting Started

Safety is the first consideration when performing any type of electrical work. Before beginning to troubleshoot a PV system, make sure that you know how the system is constructed and how it operates. Verify that the test equipment is properly rated for the current and voltage you will expose it to. Use the necessary tools, procedures and personal protective equipment detailed in *NFPA 70E,* known as the *Standard for Electrical Safety in the Workplace.*

While PV systems present unique electrical hazards, using I-V curve tracers can improve safety relative to other testing methods. PV circuits do not need to be under inverter load for you to use an I-V tracer to look for a bad source circuit. Wade Webb, the vice president of quality assurance at Martifer Solar, explains: "To use a current clamp to test for bad strings, the technician has to work in a combiner box that is connected to an operating inverter, perhaps via a downstream recombiner. This is the main reason we prefer to look for bad strings using an I-V curve tracer. Besides the fact that an I-V curve tracer provides more detailed information than you can get using a clamp meter, it may also provide an additional level of safety by reducing the arc-flash hazard that the technician is exposed to."

Basic test procedure. In commercial and utility-scale PV systems, I-V curve traces are generally measured in combiner boxes that are electrically isolated from the rest of the PV system. For example, perhaps zone-level monitoring in the inverter indicates that a particular combiner box is underperforming. Unless immediate action is required, asset managers will likely flag that combiner box for inspection during a regularly scheduled site maintenance visit. Once on-site, you can electrically isolate the combiner box by locking out and tagging out an equipment disconnecting means. If a visual inspection of the PV modules does not point to a likely cause, you can use an I-V curve tracer to identify underperforming source circuits.

For calibrated performance measurements, install an irradiance sensor in the plane of the array and stick a temperature sensor to the backside of a thermally representative module. After ensuring that the PV source circuits are not under load, open each touch-safe fuseholder in the combiner box. Using an alligator clip or similar connector, connect one test lead to the positive busbar and another to the negative busbar. You can now test each of the PV source circuits one at a time by



Courtesy Solmetric

Figure 1 Each of the six types of I-V curve deviations discussed in this article is shown here. The deviations are numbered according to the order in which we consider them in the "PV Array Troubleshooting Flowchart" (pp. 22–23).

closing the appropriate fuseholder and initiating an I-V curve trace. The test process can take as little as 10 to 15 seconds per source circuit, and the data are saved electronically. (While the process described here represents a scenario commonly encountered in the field, test procedures and measurement times may vary somewhat in practice depending on the specifics of the PV system, the BOS equipment, the I-V curve tracer or the test goals.)

The Troubleshooting Flowchart

The "PV Array Troubleshooting Flowchart" (pp. 22–23) is based on extensive field experience, reviews of PV module reliability literature and input from subject matter experts at the National Renewable Energy Laboratory (NREL). I-V curve tracers provide an abundance of detail that is potentially useful for tracking down hardware performance issues. However, shading, soiling, irradiance, temperature or measurement technique can muddle any type of PV performance measurement. To reveal actual hardware performance issues—problems with PV modules or BOS components—you must peel away like layers of an onion any potential environmental or measurement impacts.

Here I describe the 2-step process of capturing a useful I-V curve and determining whether it indicates that the test circuit is performing normally. Since a normal curve is not always returned, I describe six types of I-V curve deviations, as shown in Figure 1, and elaborate on the process of identifying the most likely causes of each. I identify these according to descriptive terms that are useful for communicating how a curve deviates and for narrowing the range of possible physical causes. Each deviation has more than one possible cause, and multiple deviations may be present at the same time.

USEFUL I-V CURVE

First, verify that the test returns a useful I-V curve. If it does not, make sure the test lead connections are intact. If they are, then the source circuit may not be complete. Check to make sure a series fuse is installed; if it is, check the fuse for continuity. If the series fuse checks out, then the problem may be in the source-circuit wiring. Before testing for failed modules, you may want to check for open module interconnections and look for signs of damage, such as burn marks.

In rare cases, tests return an I-V curve that exhibits narrow vertical dropouts or downward spikes. The cause may be an intermittent electrical interconnection, such as a jostled test lead or an improperly crimped butt splice. If the intermittent connection is in the PV source circuit, isolate it and perform the necessary repairs.

NORMAL SHAPE & PERFORMANCE

To identify performance problems in the field, you must have a standard for comparison. In troubleshooting situations, you may use measurements taken on neighboring PV source

Figure 2 This I-V curve trace has a normal shape and a performance factor greater than 90%, which indicates that the test circuit is performing as expected. In this case, the technician will save the data and test the next circuit.

Courtesy Solmetric

circuits for comparison. However, module nameplate data are generally the basis of comparison, especially when you are benchmarking performance over time.

Prior to performing I-V curve testing, you specify which module you are testing and how many modules are connected in series or parallel. Based on these and other setup inputs, the software calculates expected performance characteristics—such as I_{SC}, I_{MP}, V_{OC}, V_{MP}, and P_{MP}—at standard test conditions. Since conditions in the field invariably differ from factory test conditions, I-V curve tracers use mathematical models to account for actual irradiance and temperature conditions in the field and generate a predicted I-V curve and maximum power value for the PV source circuit or module under test.

If a PV source circuit or module is performing normally, its I-V curve has a normal shape, like the one in Figure 2 (p. 18). Further, the maximum output power rating, which the curve tracer calculates from the I-V data, will closely approximate the predicted maximum power. We use the *performance factor* (PF) in this context to quantify how well a measured I-V curve agrees with a predicted curve. It is reported as a percentage and calculated using the measured and predicted maximum power (P_{MP}) as shown in Equation 1:

$$PF = (\text{measured } P_{MP} \div \text{predicted } P_{MP}) \times 100 \qquad (1)$$

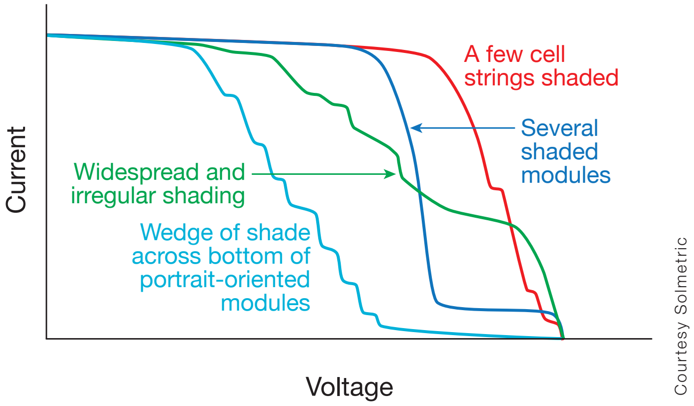
Generally speaking, a normal curve shape and a performance factor between 90% and 100% indicate that a PV source circuit or module is operating correctly and is not seriously shaded or soiled. If the measured I-V curve has a normal shape and the performance factor is greater than 90%, you can save the I-V data and proceed to test the next string.

STEPPED I-V CURVE

Notches or steps in the I-V curve, the first type of deviation, are associated with current mismatch in the test circuit. The steps in the curve occur when bypass diodes activate and pass current around cells that are weaker or are receiving less light. The number and width of the steps vary according to the density and extent of the shade. Many conditions cause current mismatch, including nonuniform soiling, partial shade, damaged cells or cell strings, or shorted bypass diodes.

Non-hardware issues. A shaded PV cell has a reduced current capacity, which in turn reduces the maximum current that the cell string can produce. If the PV source circuit's operating current exceeds the current that the shaded cell can supply, the bypass diode begins passing current around the shaded cell string to prevent hot-spot failures due to reverse bias in the shaded cell.

If the issue impacts more than one cell or cell string, an I-V curve may show multiple steps, as shown in Figure 3. For example, tree shade tends to impact cell strings in multiple modules, and the density of the shade may vary, causing bypass diodes to turn on at different current levels. This type of shade produces a broadly deviated I-V curve that rolls randomly on the descent, with or without discrete steps. Swirled patterns of accumulated dirt also produce this type of deviation. In contrast, localized shading produces very distinct steps. The narrowest step corresponds to an obstruction impacting a single cell string. If a single narrow step appears in an otherwise normal curve, localized soiling is a likely cause, but the step could also indicate localized shading, typically along the edge of a perimeter module.



Courtesy Solmetric

Figure 3 You need to screen for shade or soiling when an I-V curve is returned with steps or notches. The red I-V curve is typical of spot shading that impacts a few cell strings. The dark blue curve may indicate that several modules in the source circuit are shaded. The green curve is representative of a source circuit subject to widespread and irregular shading or soiling. The light blue curve is the result of a wedge-shaped band of shade sloping across the bottom of several portrait-oriented modules.

Leaf litter, bird droppings or spot shading can also cause mismatched deviations that tend to obscure other deviations. Since these issues make it difficult to assess performance, you want to remedy them—assuming it is possible and economically feasible to do so—prior to doing additional performance testing. For example, clear bird droppings from the PV modules or cut back tree branches. If shade is the issue, wait until the shade has cleared to conduct performance tests.

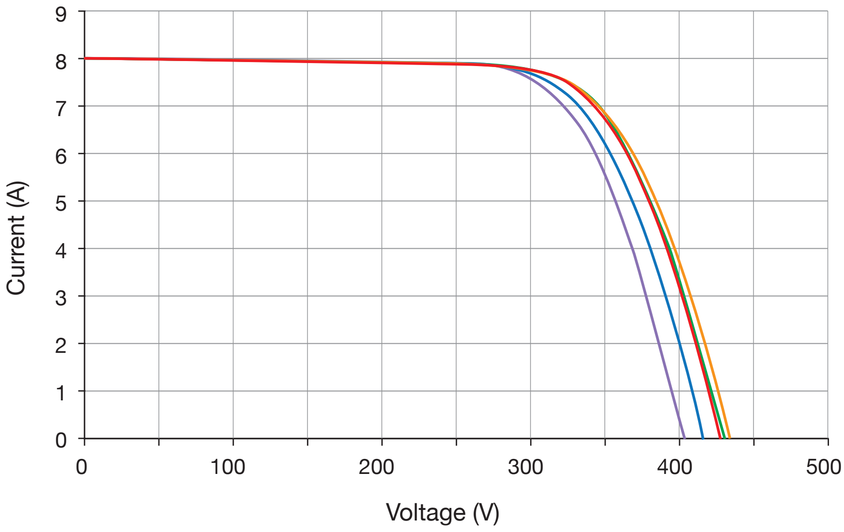
Hardware issues. Several hardware problems may return a stepped I-V curve. In a circuit that includes parallel-connected PV source circuits, a shorted bypass diode or shorted cell string shows up as a step in the I-V curve. Significant current mismatch between modules in the test circuit is another possible cause. Cracked cells are the most common cause, however.

Microcracks are present in PV cells even as the modules come off the production line. Since a typical crystalline-silicon (c-Si) PV cell is 400–800 times wider than it is thick, some degree of microcracking is probably inevitable. Shipping, handling and installation—especially torquing down or standing on modules—potentially create more microcracks. Though microcracks are nearly impossible to see, in some cases they are serious enough to stretch or separate the contact fingers, which increases series resistance and may lead to heat-induced discoloration or damage. Corrosion and discoloration effects known as *snail trails* often follow microcracks.

Although microcracks do not usually cause performance problems, they can become full-fledged cracks under stress. A crack that electrically isolates a portion of a cell creates a current bottleneck similar in effect to that from localized shading or soiling. Cell performance suffers most when a severe crack runs parallel to the cell's busbars and severs the contact fingers. In such cases, the bypass diode passes current around the cell string and produces a narrow step in the I-V curve.

Generally speaking, a shorted bypass diode or cell string uniformly reduces the width of an I-V curve, as shown in Figure 4. (See "Low open-circuit voltage" on p. 21.) However, if you are measuring two or more strings in parallel, a step along the vertical leg of the I-V curve may indicate voltage mismatch caused by unequal numbers of modules in the source circuits or by one or more shorted bypass diodes. Consider taking an I-V curve trace on a prefabricated wire harness that connects a pair of 72-cell c-Si PV module source circuits in parallel. A single shorted bypass diode in the test circuit shows up as a step that is 10–12 volts wide halfway up the vertical leg of the I-V curve.

Figure 4 We took these I-V curves back-to-back on nominally identical PV source circuits under stable environmental conditions. They show the 10–12 V reductions in V_{OC} that are typical of shorted bypass diodes in 72-cell, 3-diode PV modules.



Courtesy Solmetric

LOW SHORT-CIRCUIT CURRENT

In an otherwise normal I-V curve, a lower-than-expected value of I_{SC} can result from operator error, poor irradiance measurement, shading or soiling, or module performance issues. Since you may be able to remedy some of these issues, the troubleshooting flowchart addresses this second type of deviation early.

Operator error. If you are not careful, it is easy to select the wrong module from the I-V curve tracer's database. When this happens, the nameplate specifications for the test circuit will not match those that the I-V curve tracer uses to model predicted performance. In some cases, EPCs install large PV arrays using modules from different batches, in which case the nameplate specifications for one source circuit could be slightly different from those for the next.

Irradiance measurement issues. Irradiance measurement error can also cause reduced I_{SC}. It is probably the most common source of error when making any type of PV system performance measurement. Failure to mount the irradiance sensor in the plane of the array, which can cause the model to over- or underpredict the value of the I_{SC}, is the most likely cause of measurement error. You can also introduce measurement error by using an irradiance sensor with a spectral and angular response that does not match that of the PV modules.

Non-hardware issues. Uniform soiling, dirt dams and strip shade are also likely causes. Uniform soiling is by far the most common cause of this I-V curve deviation.

If PV modules are coated with an even layer of dirt, the overall shape of the I-V curve will be correct, but the current at each measurement point will be reduced because the modules see a lower irradiance than the sensor does.

You typically encounter dirt dams on low-slope roofs where portrait-oriented modules are mounted at a slope of 5° or less. Water pools behind the module frame, at the lowest edge of the inclined plane, and a narrow band of sediment is left behind on the module when the water evaporates. When this band of dirt reaches the bottom row of cells, it begins to limit current. The wider the dirt band, the lower the current. If the dirt bands are similar enough from cell string to cell string and module to module, the effect resembles that of uniform soiling, which reduces each module's I_{SC} uniformly. You can eliminate the effects of soiling by cleaning the modules and retesting.

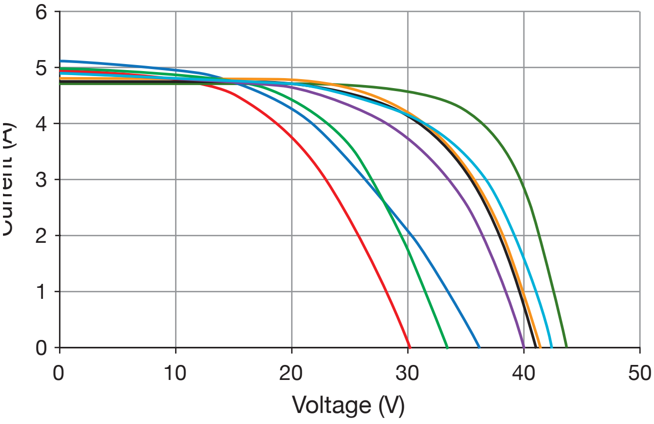
Strip shade is common in tilt-up arrays with closely spaced rows of modules mounted in portrait orientation. A parapet wall or the upper edge of a preceding row of modules casts a wide, thin strip of shade across the lower edge of the next row. If the shading is uniform in height, it reduces the current in all modules in proportion to the amount of the cell that is shaded, and none of the bypass diodes turn on. The remedy from the measurement standpoint is to test the array close to midday.

Hardware issues. Module degradation such as encapsulant browning or delamination can slightly reduce the height of the I-V curve. Since performance degradation of this type is a very slow process, you will need to monitor the system over time, look for trends in the data and compare these long-term trends to the manufacturer's power warranty terms. It is ideal to have established a performance baseline when you put the system into service.

Low I_{SC} may also be associated with an uncommon but potentially dangerous module failure mode. If a bypass diode has failed in the open-circuit mode and one of the cells it was intended to protect is shaded, soiled or severely cracked, the curve trace generally indicates reduced I_{SC}. It may also show an abnormally steep slope in the horizontal leg of the curve. This condition is hazardous, because the rest of the PV modules treat the current bottleneck as a load, which causes the temperature of the obstructed cell to rise rapidly. This process could destroy a module or even initiate a fire.

LOW OPEN-CIRCUIT VOLTAGE

The third type of deviation in the troubleshooting flowchart is low V_{OC}. An erroneous cell temperature measurement most likely causes low V_{OC}. In addition, shade can appear to reduce V_{OC} under certain test circumstances. Hardware problems are also possibilities. However, since open-circuit voltage has one of the lowest aging rates of all the PV module parameters, you should consider other causes before concluding that there is a causal relationship between cell degradation and low V_{OC}.



Courtesy Solmetric

Figure 5 This chart shows the effects of potential induced degradation on the I-V curves of modules. All the modules are from the same source circuit, and we captured all the traces within minutes of one another.

Measurement error. When performance tests return an I-V curve with low V_{OC}, check the quality of the thermal connection between the temperature measurement device and the back of the PV module. There is an inverse relationship between cell temperature and module voltage. If the thermal connection is not good, the reported temperature will be low, and the predicted I-V curve will have a higher V_{OC} than the measured curve.

Typically, c-Si PV cell temperature is several degrees Celsius higher than a thermocouple reading taken on the back of the PV module indicates. When you take curve traces on multiple PV source circuits, you also see some variation in the V_{OC} measurements, even if the modules themselves are perfectly matched. Wind, variable irradiance and nonuniform ventilation can all cause V_{OC} variation.

Non-hardware issues. Hard shade covering one or more cells causes the bypass diode associated with the cell string to begin conducting. This may show up on an I-V curve as a lower-than-expected V_{OC}, simply because the curve trace runs out of measurement points before it reaches the actual V_{OC} on the horizontal axis of the curve. Some curve tracers measure V_{OC} separately with a high-impedance voltmeter circuit before initiating an I-V curve trace; focus on this value if you suspect that a bypass diode is shorted.

Hardware issues. Shorted bypass diodes, missing modules, potential induced degradation (PID) and pinched PV source-circuit conductors are all possible issues. Pinched conductors typically show up during insulation resistance testing but can also develop over time. A hard ground fault in a grounded PV source circuit essentially shortens the length of the series string; therefore, a curve trace of the circuit returns a curve with low V_{OC}. (Note that I-V curve tracing is not a substitute for insulation resistance testing.)

Shorted bypass diode. If one or more diodes in the test circuit are shorted, the I-V curve also shows low V_{OC}. This is a relatively common module failure mode. Electrical transients can damage diodes; they can also fail from electrical and thermal stresses. Some module manufacturers have even had batch failures due to undersized bypass diodes.

It is relatively easy to identify a PV source circuit with one or more shorted bypass diodes by paying close attention to the distribution of V_{OC} values within the same combiner box, as shown in Figure 4 (p. 20). A typical 72-cell PV module has three bypass diodes, each one associated with one of three cell strings. If one bypass diode is shorted and one cell string is lost, that reduces the module's voltage by roughly 10–12 Vdc. You can easily detect this V_{OC} measurement difference with an I-V curve tracer or a digital multimeter. These test results are most accurate when average cell temperature remains constant, which requires stable irradiance, no wind, and short measurement intervals. If cell temperature varies from one

Interpreting I-V Curve Deviations

PV Array Troubleshooting Flowchart This workflow, proceeding from top to bottom, is designed to help you take advantage of the detailed information contained in I-V curve traces without allowing the effects of shading, soiling or measurement errors to sidetrack you. Those effects may cause deviant I-V curve traces that you may misread as hardware problems.

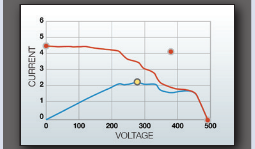
Save data and test next string

YES

Shading?

YES

Remove obstructions or retest when unshaded.

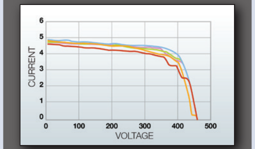


NO

Random soiling, debris or snow?

YES

Clear modules and retest.



NO

Mismatched modules?

YES

A string of modules with significantly mismatched currents will show slight steps along the I-V curve.

NO

Cracked cells?

YES

Cracked cells may not be visible to the eye. Find the bad module using the selective shading method. May be cause for module replacement if the cracked segment is electrically isolated. Cracked glass is always a cause for replacement.

NO

Burn marks?

YES

Replace module

NO

Check again for shade. Diffuse shade is hard to detect by eye. Look for more distinct shadows alongside the array. Light reflected from nearby objects can also cause steps. When you're testing strings in parallel, a shorted bypass diode can also cause a step in the curve.

1

YES

Smooth curve but low fill factor?

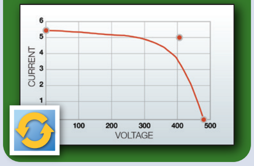
TROUBLESHOOTING TIPS

- For best performance measurement accuracy, measure with irradiance > 700W/m² in the plane of the array.
- You can often identify a bad PV module without disconnecting modules from one another, using the selective shading method. For a string of *N* modules, measure the I-V curve *N* times, applying hard shade to a different module each time. Cover at least two cells in each cell string. Shading the bad module bypasses it and returns a normal curve shape. In the case of a shorted bypass diode, shading the bad module causes a smaller drop in V_{oc}.

YES

4

Possible cell degradation. Retest in future to reveal trend.

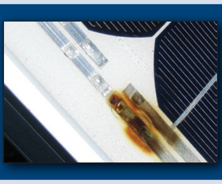


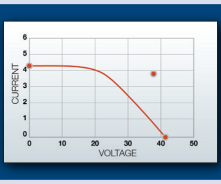
YES

5

✔ **Are the homerun wire length and gauge correctly accounted for in the PV model?**

Possible high series resistance. Check modules and string wiring for bad connections or overheating. Replace affected modules.





Courtesy Solmetric

START

Indicates possible need for PV module replacement

Does measurement return a useful I-V curve?

NO

✓ Are the test leads connected?
Are PV modules interconnected?

No I-V curve?

YES

Check for a missing or blown fuse, and for an open circuit in external string conductors. Check for burn marks on module ribbon conductors, overheated module J-boxes or bad PV connectors. Replace affected modules.

NO

Dropouts in I-V curve?

YES

Intermittent electrical connections in the PV source circuit may be causing narrow vertical dropouts (downward spikes) in the I-V curve. Troubleshoot to locations and repair.

YES

PF = performance factor

$$= \frac{P_{MP}\ \text{(measured)}}{P_{MP}\ \text{(predicted)}} \times 100$$

PF > 90% and normal shape?

NO

Steps in the I-V curve?

NO

Low I_{SC}?

YES

2

✓ Is the irradiance sensor oriented in the plane of the array?
Does it have the same view of the sky as the strings under test?
Is the sensor free of reflections?
Is the correct module selected for the PV model?

Uniform soiling?

YES

Clean modules and retest

NO

Dirt dams?

YES

A strip of shade or soiling that is consistent across the string can reduce current without causing steps in the curve. Retest after cleaning or removing shade.

NO

Strip shade?

YES

NO

Possible performance degradation. Retest in future to reveal trend.

NO

Low V_{OC}?

YES

3

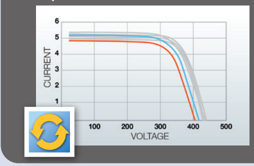
✓ Is the thermocouple attached at a typical temperature location, and is it contacting the module backside?
Is the irradiance high enough for a reliable V_{oc} test?

Tip: V_{oc} normally ages very slowly *(adjusted for temperature)*. Check for other causes before concluding that V_{OC} has degraded.

Low by multiple of cell string V_{OC}?

YES

Possibly shorted bypass diode(s). Locate the module using selective shading method. Replace affected modules.

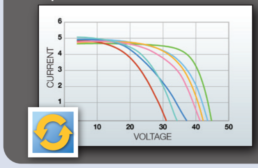


NO

Combined with other deviations?

YES

Possibly potential induced degradation (PID), especially if combined with reduced fill factor. Replace affected modules.



NO

Replace module or retest in future to reveal trend.

NO

Rounder knee?

NO

Low voltage ratio? ($V_{MP} \div V_{OC}$)

NO

Low current ratio? ($I_{MP} \div I_{SC}$)

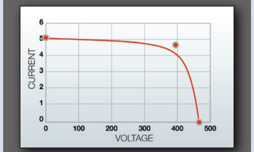
YES

6

Tapered shade or soiling across modules?

YES

Retest clean and unshaded.



NO

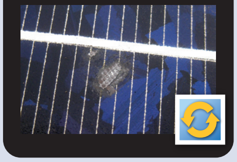
Slightly current-mismatched modules?

YES

I-V curve may show increased slope in the horizontal leg, with or without slight steps. Document mixed module types.

NO

Possible degradation of cell shunt resistance. Serious shunts may be visible to an IR imager or to the eye. May also be a symptom of PID. May require module replacement.



test circuit to the next, then V_{OC} will vary, making it difficult to identify a discrete 10–12-volt shift in V_{OC} for one source circuit relative to the others.

In some cases, you can use infrared (IR) imaging to identify a shorted bypass diode while the system is on line. A bypassed cell string is slightly warmer than its neighbors because more of its incident solar energy converts to heat. The module's junction box may also be slightly warmer than that of other modules due to power dissipation in the conducting bypass diode. While this approach works well on a small scale, scanning a large array is quite time consuming.

The selective shading troubleshooting method discussed on p. 26 is also useful for identifying a module with a shorted bypass diode.

Potential induced degradation. PID is another possible cause of an I-V curve with low V_{OC}. The irreversible form of PID is the result of electrochemical reactions driven by voltage stress and facilitated by an electrolyte comprised of water and metal ions. Decreased shunt resistance characterizes initial stages of PID; as the degradation continues, V_{OC} decreases, as shown in Figure 5 (p. 21). Therefore, the likelihood that PID is the root cause of the problem increases if both of these conditions are present.

Mani Tamizhmani, the director of the PV test laboratory at TÜV Rheinland, elaborates: "Although PID can occur in any array, it occurs with greater frequency in arrays with high system voltages that are located in regions with high and variable temperature and humidity. In ungrounded arrays, it is more likely to occur in modules toward the negative end of the string."

ROUNDER KNEE

A rounder-than-expected knee characterizes the fourth type of I-V curve deviation. It is often difficult to tell whether a rounder knee region is a distinct I-V curve impairment or whether it is an illusion caused by changes in the slope of the curve. Knee rounding by itself is likely a manifestation of the aging process. You will have to retest and monitor the circuit over time to identify and track trends.

LOW VOLTAGE RATIO

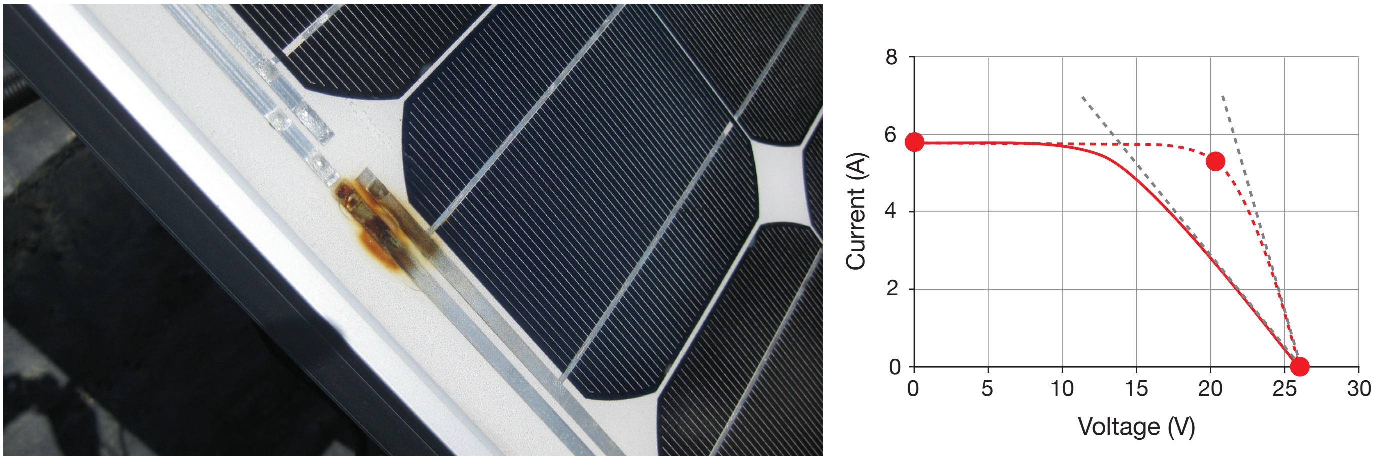
A lower-than-expected slope in the vertical leg of the I-V curve distinguishes the fifth I-V curve deviation. You can detect this condition by visually comparing the measured and predicted curves, or by comparing voltage ratio values across the population of string measurements, with the prerequisite that the curves be free of steps from mismatch effects. The *voltage ratio* is calculated according to Equation 2:

$$\text{Voltage ratio} = V_{MP} \div V_{OC} \qquad (2)$$

As shown in Figure 6, voltage ratio is an excellent metric for identifying a string with an atypical slope in the vertical leg of the I-V curve.

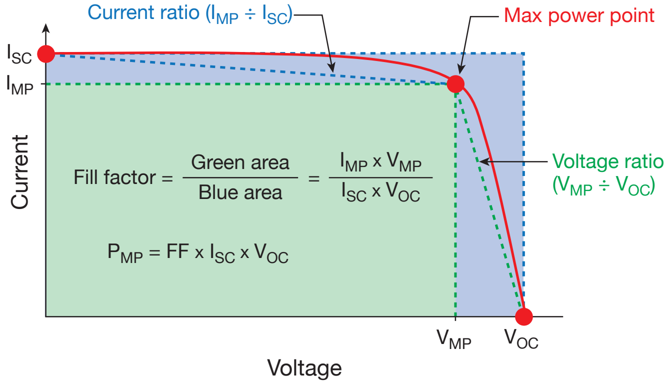
Inaccurate data. The homerun conductors add external resistance in series with the PV modules themselves. The smaller the cross-sectional area of the wire or the longer the wire run, the higher the excess series resistance is. To avoid attributing the excess resistance to the modules themselves, some curve tracers compensate for it—or back it out of the calculation—when generating the predicted I-V curve shape. For best test results, enter reasonable estimates of the homerun wire length and gauge. Assuming the system is properly designed with respect to voltage drop, there is no need to calculate the exact wire length per source circuit.

Hardware issues. If the model reasonably accounts for homerun conductor resistance, several potential causes of excessive series resistance can result in an I-V curve with a



Courtesy Solmetric (2)

Low voltage ratio The brown spot shown in the photo on the left is the result of a failing solder bond between the module's busbar ribbon and output conductor. This bad connection results in excess series resistance, which reduces the module's output voltage linearly in proportion to current and causes the vertical leg of the curve to pivot counterclockwise around V_{OC}.



Courtesy Solmetric

Figure 6 This figure provides equations and graphical representations for the following figures of merit: *current ratio* (dashed blue line), *voltage ratio* (dashed green line) and *fill factor* (green area ÷ blue area).

low voltage ratio. These include undersized PV source-circuit conductors, resistive interconnections or module degradation. PV interconnections, terminal blocks and modules are the most likely places to find increased resistance. For example, leaks in moisture seals in connectors, junction boxes and combiner boxes can lead to corrosion and increased series resistance.

The modules themselves may also be the source of the problem. Paul Jette, the vice president of operations at True South Renewables, explains: "Increased series resistance is the most common I-V curve deviation we have come across in the field. While the problem is occasionally associated with poorly made module-to-module interconnections, bad module solder joints are the most common cause. When this is the case, we use IR imaging to find the hot spots that are the source of the loss."

Series resistance increases gradually as modules age. However, certain module failure modes also cause excessive series resistance. For example, in salty environments, connections may corrode inside module junction boxes. Manufacturing defects may result in a cracked tab or ribbon bus inside a PV module. In some cases, you can see burn marks within a PV module. Using an IR camera can help you identify problems and provide documentation for warranty claims.

Jenya Meydbray, the CEO of PV Evolution Labs, notes: "Solder-joint failures are the number one cause of module quality assurance and quality control failures in the factory, and weak solder joints in the factory invariably lead to solder joint issues in the field." These joint failures can cause catastrophic module failures. For example, repeated temperature cycling can cause a poor-quality ribbon bond to degrade, which might eventually lead to a series arc fault that could potentially start a fire.

LOW CURRENT RATIO

A higher-than-expected slope in the horizontal leg of the I-V curve distinguishes the sixth and final I-V curve deviation. You can detect this condition by visually comparing the measured and predicted curves, or by comparing the current ratio values across the population of string measurements, so long as the curves are free of steps from mismatch effects. You calculate the *current ratio* according to Equation 3:

$$\text{Current ratio} = I_{MP} \div I_{SC} \qquad (3)$$

As shown in Figure 6, current ratio is an excellent metric for identifying a string with atypical slopes in the horizontal leg of its I-V curve. Before looking for hardware issues, rule out shade, soiling and irradiance measurement error.

Non-hardware issues. If irradiance changes significantly during the I-V curve measurement cycle, that may affect the horizontal leg of the curve. The longer the data acquisition time and the more rapid the change in irradiance, the greater the slope error. For best results, use a curve tracer capable of acquiring I-V data in less than 1 second. (Note that high-efficiency modules may require longer trace times.) Repeat the test and note any change in the I-V curve to determine whether changes in irradiance are causing a horizontal slope deviation.

Unique shade or soiling conditions can also cause an I-V curve to have a low current ratio. The typical situation is a thin wedge of shade or dirt along the bottom edge of a portrait-oriented PV source circuit. If the magnitude of the change in obstruction is slight from one cell string to the next, the I-V curve will not show the visible steps associated with nonuniform shading or the low I_{SC} associated with strip shade.

Hardware issues. I-V curves always show a slight slope in their horizontal leg, caused by current leakage across the semiconductor junction at defects in the crystal lattice in the cell body or edges of the cell. The lower the leakage, the higher the shunt resistance.

Shunt resistance decreases as modules age. If the decrease is relatively uniform across all the cells in a string, the net effect is that the slope in the horizontal leg of the I-V curve pivots downward around the point labeled I_{SC}. However, if the degradation is present in only some of the modules in the source circuit, the increase in the horizontal slope of the curve starts closer to the knee. Because the industry is relatively new, we do not yet know how uniformly shunt resistance will age.

More severe, localized shunts sometimes develop in the field. These can concentrate relatively high currents, damage the cell and even destroy the module. An IR camera can detect serious localized shunts.

Using Fill Factor to Jump the Curve

For manufacturers and researchers, *fill factor* is a critical metric for characterizing the efficiency of a PV power source relative to I_{SC} and V_{OC}, as shown in Figure 6 (p. 25). Since P_{MP} is itself a function of I_{MP} and V_{MP}, you calculate fill factor according to Equation 4:

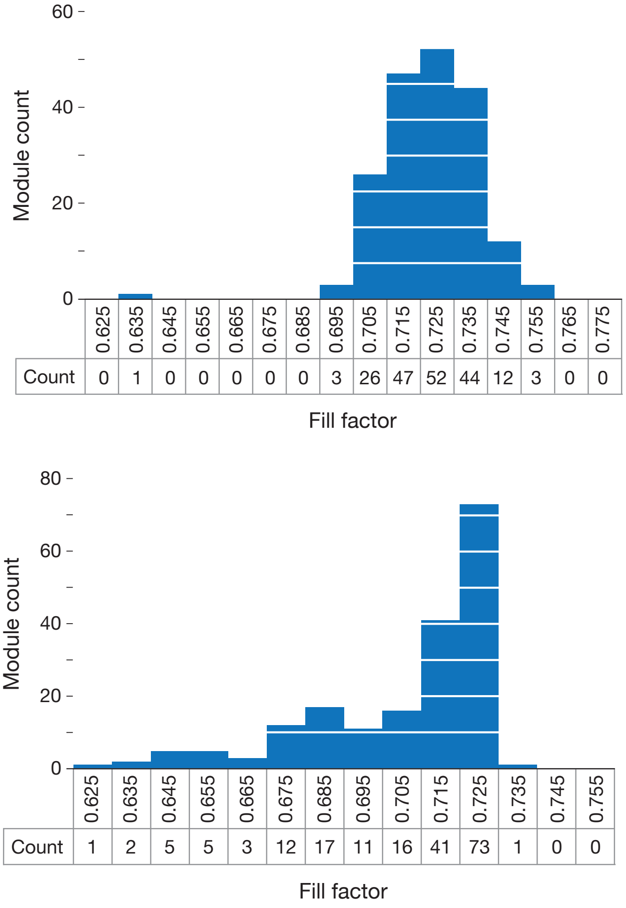
$$FF = (I_{MP} \times V_{MP}) \div (I_{SC} \times V_{OC}) \qquad (4)$$

Fill factor varies according to cell type and efficiency. For example, new c-Si PV modules should have fill factors in the 70%–80% range. Typical fill factors for thin-film technologies are lower, ranging from the upper 60% range for cadmium telluride to the lower 60% range for amorphous silicon, with copper indium selenide and copper indium gallium (di)selenide falling somewhere in the middle.

As shown in Figures 7a and 7b, fill factor is a quick way to identify and flag test circuits with potential performance problems. This screen is an especially effective way to identify underperforming test circuits that otherwise return a smooth-shaped I-V curve, such as circuits with a rounder knee or a lower voltage or current ratio. Once underperforming circuits are identified, study the shape of the I-V curve for clues about the likely or possible cause of the impairment. Note that series resistance in homerun conductors slightly reduces fill factor in PV source circuits.

Assuming irradiance levels are high, fill factor is relatively insensitive to irradiance. Therefore, it is an excellent means of comparing curves measured at dissimilar irradiance levels, without the need to translate results to STC.

Fill factor degrades over time, mainly due to increased series resistance and reduced shunt resistance. Given its intimate relationship to module efficiency, fill factor is an important parameter to monitor over time, and can be a vital piece of evidence to a module warranty claim. ●



Data courtesy Miller Bros. Solar and groSolar

Figures 7a and 7b These histograms show the distribution of fill factor—an indicator of the fullness and consistency of I-V curve shapes—as measured in the field on nominally identical source circuits. On one hand, the outlier in Figure 7a (top) points to an isolated performance problem; on the other, the cluster of low fill factors in Figure 7b (bottom) is typical of the effects of potential induced degradation.

Identifying the Source of a Problem

Identifying a PV source circuit with a specific I-V curve deviation is often the start of a more detailed investigation. While module-by-module testing is sometimes necessary, you may be able to zero in on a bad module by using less invasive methods such as half splitting or selective shading. These labor-saving strategies are especially useful when you are dealing with multiple PV source circuits connected in parallel using wiring harnesses.

Module by module. One widely used troubleshooting method is to disconnect and test individual modules, starting at one end of a PV source circuit and moving to the other end. One benefit of module-by-module testing is that you can compare I-V curves and pick out any abnormal modules. While this method is comprehensive and straightforward, it is also potentially time consuming. It is best used selectively, such as when screening for PID, which may appear in multiple modules in a source circuit.

Module-by-module testing is especially problematic when PV wire whips are not readily accessible and you have to lift modules to test them. In some cases, it may be necessary to remove and reinstall 15 good modules to identify and replace one bad module. This process can compromise the installation's quality and safety.

Half splitting. This electrical troubleshooting method involves splitting the PV source circuit into two parts and testing each half. You repeat this process as many times as

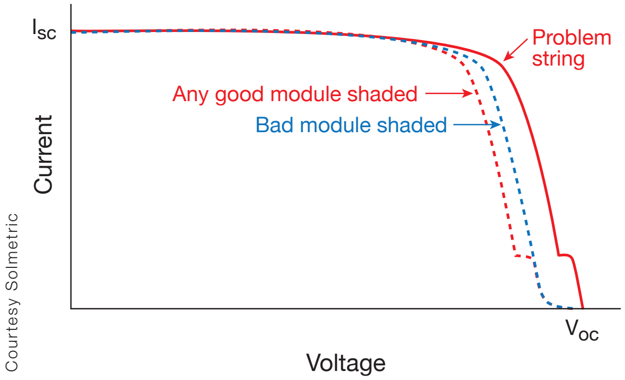


Figure 8 Technicians can use the selective shading method to identify a bad PV module without opening any interconnections. In this example, when properly performing modules are shaded, the deviation in the I-V curve remains unaffected (dashed red curve). However, when the bad module is shaded, the source circuit returns an I-V curve with a normal shape (dashed blue curve).

necessary to home in on a bad module. On average, identifying a single bad module should require about one-third the time compared to a module-by-module approach. The drawback is that you may overlook small problems in the "good half" of the test circuit because stronger modules may mask performance problems.

Selective shading. This method takes advantage of bypass diode behavior to identify a problem module. The process involves shading one module at a time in the test circuit and measuring the effect this has on the performance of the PV source circuit. In effect, this allows you to remove one module from the test circuit without unplugging any of the source-circuit interconnections. Selective shading is most effective when there is a distinct difference between the I-V curve of the problem module and those of the other modules.

For example, selective shading is the simplest way to identify a module with a shorted bypass diode. Without disconnecting the modules, you apply hard shade to a PV module, shading at least two cells in each of the module's cell strings, and capture an I-V curve. You then repeat this process for every module in the test circuit, and compare the resulting I-V curves for each shaded module. If a shaded module is working properly, the V_{OC} for the source circuit drops by an amount approximately equal to the expected V_{OC} for one PV module. However, when you shade a module with a shorted bypass diode, the V_{OC} for the source circuit drops by an amount less than predicted, as shown in Figure 8.

If the selective shading test method returns inconclusive performance measurements, you can justify module-by-module testing.

Harnessed PV circuits. Large-scale PV systems sometimes use prefabricated dc wire harnesses to connect two or more PV source circuits in parallel. When dc wire harnesses are used in a c-Si PV array, they typically connect two or three source circuits in parallel. In a thin-film array, wire harnesses may connect as many as eight source circuits in parallel. Series fuses located in molded inline fuseholders provide the required source-circuit protection, and you only route two conductors per wire harness back to a dc combiner box.

While the use of dc wire harnesses cuts down up-front costs in large, uniform PV arrays—reducing the required number of dc combiners and standardizing the array wiring—it can impede troubleshooting. It is more complicated to isolate and test a single PV source circuit when systems are deployed using dc wire harnesses. For example, if a measurement at the combiner identifies an underperforming wire harness, you must take clamp meter readings on the individual source circuits in the array and compare the results. If you identify an underperforming source circuit, you can unplug and troubleshoot that string.

With a bit of practice, you can identify certain types of performance problems in harnessed PV circuits by studying the width or depth of a step or notch in a deviant I-V curve. However, when troubleshooting PV systems with prefabricated dc wire harnesses, you must make sure that the test equipment is rated for the combined short-circuit current under the maximum expected irradiance conditions. While a 20 A–rated I-V curve tracer is typically sufficient, Solmetric recently released a 30 A–rated model that accommodates the higher currents occasionally encountered in harnessed PV circuits.

Best Practices for Performance Measurements

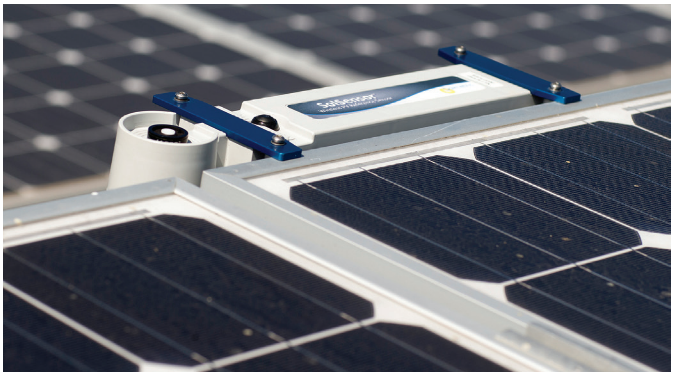
You must know the plane of array irradiance and cell temperature to evaluate PV circuit performance, regardless of test method. To assure that you can interpret your I-V curves with accuracy, pay attention to environmental conditions, as rapid changes in plane of array irradiance or cell temperature can introduce errors. Also take care to use proper sensor types and test methods.

Environmental conditions. Ideally, carry out performance tests under relatively stable weather conditions when the irradiance is above 700 W/m^2. This is most critical when establishing a performance baseline at commissioning or recommissioning, but is also relevant to troubleshooting scenarios. The module data used to predict the I-V curve shape are based on standard test conditions. The closer the field test conditions are to standard test conditions, the less error is introduced when the software translates data to or from STC. Good test conditions are most likely to occur during the 4-hour window around solar noon.

Irradiance measurements. Irradiance measurement is typically the greatest source of error in PV performance measurements. For example, a 1% or 2% irradiance error can dwarf the current and voltage measurement inaccuracy inherent in a quality I-V curve tracer, and significantly reduce the accuracy of the performance test results. Fast-moving clouds near the sun and high-elevation cirrus clouds are particularly problematic. One of the benefits of using I-V curve tracers for performance test measurements is that you may be able to save critical environmental data along with the I-V data. This eliminates manual data entry errors that can cause trouble later, and minimizes the opportunity for errors associated with rapid changes in test conditions.

True pyranometers are not a good choice for I-V curve testing, as they have a wide, flat spectral response that differs from that of crystalline and thin-film technologies. Hand-held irradiance sensors are also not a good choice, as it can be difficult to orient them reliably and repeatedly in the plane of the array. Hand-held irradiance sensors may also have an angular response that differs substantially from that of fielded PV modules. Angular response is especially important early and late in the day, and on days when cloud cover scatters a significant amount of the sunlight. Under these test conditions, the array and sensor must have an equally wide view of the sky.

Strong optical reflections must not influence irradiance sensor measurements. If the irradiance sensor picks up significantly more reflected light than the PV modules under test, the model will overpredict I_{SC} and the module will appear to be underperforming. Under certain circumstances, sunlight reflected from metal surfaces can greatly exaggerate the irradiance reading. You can usually remedy this by changing the sensor mounting location.



Courtesy Solmetric

Irradiance sensor For accurate array performance measurements, mount the irradiance sensor in the plane of the array and make sure that the sensor's spectral response matches that of the PV modules. The wireless unit shown here contains a spectrally corrected silicon photodiode irradiance sensor, and also measures backside temperature and module tilt.

Temperature measurements. PV module performance is inherently less sensitive to temperature changes than to irradiance variations. However, temperature impacts are still very significant, and weather conditions and measurement technique deserve attention. Wind and rapidly changing irradiance complicate the picture by making cell temperature a rapidly moving target.

The best way to obtain cell temperature, especially under variable environmental conditions, is to use a light-gauge thermocouple—such as 24- or 30-gauge wire—that will track cell temperature more closely than a larger sensor. If you have access only to a more massive sensor, allow time for thermocouple temperature to stabilize as heat transfers from the PV cell to the thermocouple through the encapsulant and backsheet material, which have low thermal conductivity.

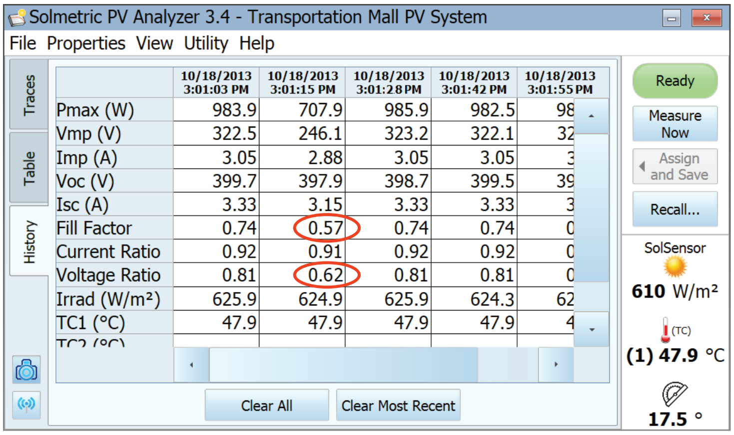
Since array and module edges tend to run cool, position the thermocouple between the corner and the center of a module located away from the cooler array perimeter. The aim of this practice is to select a sensor attachment point that approximates the average backside temperature. Stick the thermocouple in place using high-temperature tape, such as the specialty products manufactured by Kapton or those used in the HVAC industry. The tip of the thermocouple must make good contact with the back of the PV module, as air gaps interrupt heat transfer, resulting in low temperature readings. When moving the thermocouple between identical array sections, place it at the same relative location each time to avoid introducing artificial temperature shifts.

While testers sometimes use digital IR thermometers to characterize cell temperature, their accuracy depends on surface emissivity. IR thermometers measure glass temperature rather than cell temperature. Calibrate an IR thermometer reading by taking a side-by-side measurement of the same PV cell using the IR device and a thermocouple, and then adjusting the emissivity control on the IR device until the two temperature readings match.

Some I-V curve testers can also calculate module temperature from the measured I-V curve. This method achieves its best accuracy at high irradiance values where the relationship between V_{OC} and cell temperature is well known. When irradiance is low, the temperature differential between the PV cells and the module backsheet is much smaller, and backside temperature sensing is more accurate.

Warranty Returns and Remedies

I-V curve tracers can ease the warranty claim process by making it possible to identify system performance problems



	10/18/2013 3:01:03 PM	10/18/2013 3:01:15 PM	10/18/2013 3:01:28 PM	10/18/2013 3:01:42 PM	10/18/2013 3:01:55 PM
Pmax (W)	983.9	707.9	985.9	982.5	98
Vmp (V)	322.5	246.1	323.2	322.1	32
Imp (A)	3.05	2.88	3.05	3.05	3
Voc (V)	399.7	397.9	398.7	399.5	39
Isc (A)	3.33	3.15	3.33	3.33	3
Fill Factor	0.74	0.57	0.74	0.74	0
Current Ratio	0.92	0.91	0.92	0.92	0
Voltage Ratio	0.81	0.62	0.81	0.81	0
Irrad (W/m²)	625.9	624.9	625.9	624.3	62
TC1 (°C)	47.9	47.9	47.9	47.9	4
TC2 (°C)					

Courtesy Solmetric

Data outlier This screen capture shows how easy it is to spot a single poorly performing PV source circuit. After troubleshooting reveals the source of the problem, these data may prove helpful in expediting a warranty claim.

caused by isolated failures, systemic degradation or poor installation practices. Jeff Gilbert, the director of O&M services at Vigilant Energy Management, notes: "We are currently pursuing a warranty claim for modules that show numerous hot cells, and the most useful field diagnostic tool has been our I-V curve tracer."

You do not have to be an expert in PV module failure mechanisms to use an I-V curve tracer to identify an underperforming module. However, you may need to document a problem expertly to get a manufacturer to process a warranty claim. I-V curve tracers are unique in their ability to detail and monitor the rate of change in key performance metrics over a period of years.

According to Meydbray of PV Evolution Labs: "PV module manufacturers rarely accept field measurements as the sole evidence required for PV module replacement. But even if they want the suspect modules sent to the factory or an independent laboratory for additional testing, I-V curve data gathered in the field is a good way to get the process started."

We are all still learning about module aging characteristics and failure modes. However, our knowledge base will grow as fielded systems age, especially when actual performance diverges from expected. As this knowledge base grows, our troubleshooting techniques will advance. The process outlined in the troubleshooting flowchart is dynamic, one that we will update over time with the help of industry stakeholders. Please contact me if you have feedback, suggestions, curve traces or case studies that we can learn from. ⏚

» CONTACT

Paul Hernday / Solmetric / Sebastopol, CA / paul@solmetric.com / solmetric.com /

RESOURCES

"PV Array Troubleshooting Flowchart," free solar poster (24 by 36 inches) from Solmetric: freesolarposters.com

» ADDITIONAL RESOURCES

Solmetric
www.Solmetric.com

Free Solar Wall Posters (Shade and I-V measurement)
http://www.freesolarposters.com/

Solmetric Application Notes & Articles
http://www.solmetric.com/newsletters.html
- Field Applications of I-V Curve Tracing (SolarPro Aug/Sep 2011)
- Measuring I-V Curves in Harnessed PV Arrays
- I-V Curve Tracing Exercises for the PV Training Lab
- Guide to Interpreting I-V Curves

Solmetric Webinars
http://www.solmetric.com/webinar.html

Solar Noon Calculator
http://www.esrl.noaa.gov/gmd/grad/solcalc/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