MEASUREMENT TIPS
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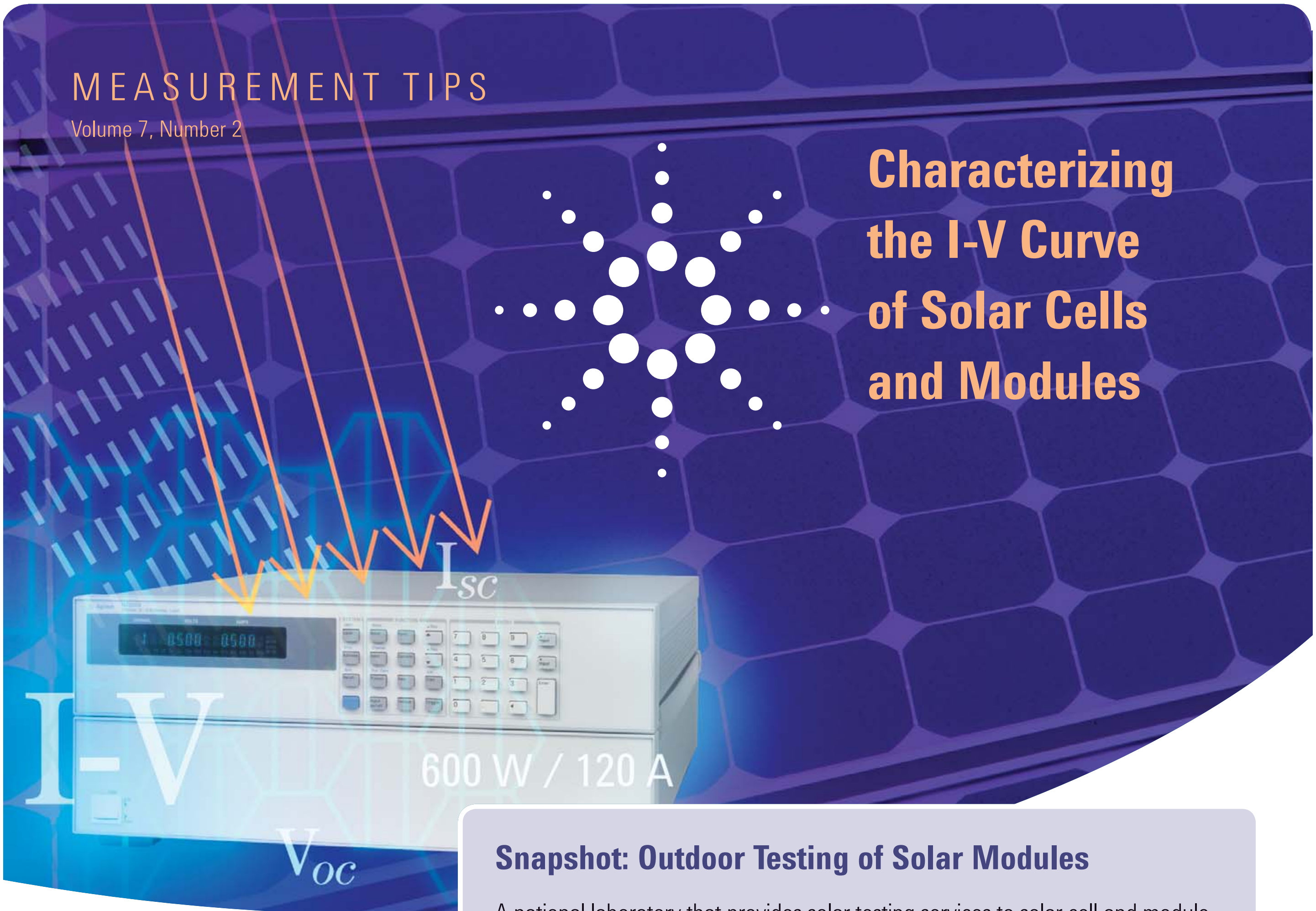
Characterizing the I-V Curve of Solar Cells and Modules

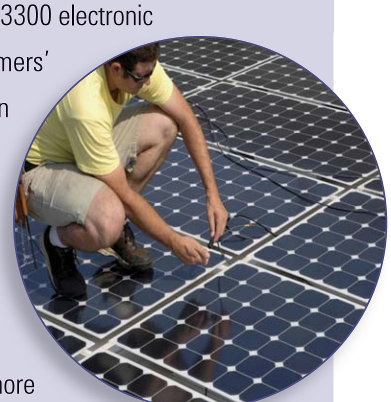


Explosive growth in the solar industry has intensified the need for test and measurement solutions that can quickly and accurately capture the I-V curve characteristics of solar cells and modules. Because solar technology is being used in residential, commercial and military applications, solar cells and modules are developed in a wide range of power levels and with various conversion efficiencies. Also, the different testing stages — research, quality assurance and production — have different needs for measurement speed, measurement accuracy and the range of device characteristics that must be captured. Because of these variables,, it is important to familiarize yourself with the test and measurement tools available for solar test and to understand their strengths and limitations.

This measurement brief explores the various test and measurement tools you can use for I-V curve characterization and provides tips to help you choose the instrument or instruments that best fit your solar cell or module measurement needs.

Snapshot: Outdoor Testing of Solar Modules

A national laboratory that provides solar testing services to solar cell and module manufacturing companies needed to test solar modules outdoors. Since the test was performed outdoors, the laboratory needed a rugged transportable measurement solution. The laboratory tested modules that varied widely in output power capability so the test solution had to have a large power range to avoid a "multiple-box" solution. The module's power could be as low as 30 W and as high as 500 W. The laboratory chose Agilent's N3300 electronic load family to characterize the power of its customers' solar modules. The N3300 Series electronic loads can handle up to 600 W and sink up to 120 A on a single channel, and its power handling capabilities are specified over a wide range of temperatures. These features allowed the lab to test outdoors under variable weather conditions. The lab used the N3300's built in list capability to step through more than a 100 voltage steps in less than a second.



Characterizing the I-V curve from I_{SC} to V_{OC}

Characterizing a solar cell from the short circuit current (I_{SC}) to the open circuit voltage (V_{OC}) requires a device with a voltage range that covers V_{OC} and can sink I_{SC}. Characterizing the I-V curve is typically accomplished by stepping the voltage from I_{SC} to V_{OC}. At each voltage step the current is measured. This can be achieved using an electronic load or a two-quadrant DC source.

- **Using an electronic load:**

  An electronic load used in a constant voltage mode allows you to step through a range of voltages and measure the current at each step. Electronic loads are a great solution for characterizing solar modules because they tend to have a much larger maximum power range compared to a two-quadrant DC source. For instance, Agilent's N3300 family of electronic loads provides up to 600 W on three channels or combines the channels for 1800 W. A limitation to using electronic loads for I-V curve characterization is that they cannot sink current down to 0 V. Typically, an electronic load's maximum current sink capability begins to drop somewhere around 3 V.

- **Using a two-quadrant DC source:**

  A two-quadrant DC source in this context is referring to a source that is capable of sourcing and sinking current, not a source that is capable of positive and negative voltage. Two-quadrant sources typically to do not have the large power range of an electronic load. But they can sink current at 0 V and often have more measurement accuracy than an electronic load. The Agilent 6611C-14C and 6631B-34B families of two-quadrant DC sources provide excellent solutions for characterizing the I-V curve of solar cells and modules. The half-rack-size 6611C-14C DC sources can sink up to 3 A of current and the full-rack-size 6631B-34B family can sink up to 10 A of current.

Performing full solar cell characterization

In research and quality assurance testing it is often necessary to characterize the I-V curve under illuminated conditions and also capture the reverse bias characteristics of the cell under dark conditions. The illuminated I-V curve of the cell allows you to calculate parameters such as the conversion efficiency of the cell and the maximum power point of the cell. Testing the solar cell in dark conditions in reverse bias allows you to calculate such parameters as the parallel resistance of the cell and the breakdown region of the cell.

To fully characterize a solar cell, a four-quadrant DC source is ideal. A four-quadrant source can sink and source current and output positive and negative current, which allows you to fully characterize the cell with a single instrument. For example, the Agilent U2722A source measure unit is a three-channel (parallel operation) four-quadrant DC source that has built-in high-accuracy measurement capability. The U2722A's voltage range is +/–20 and its maximum sink/source current is 120 mA.

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Four-quadrant sources on the market today have two limitations when it comes to the solar cell test market: high cost and insufficient maximum current. To overcome these drawbacks, you could simulate a four-quadrant source by using a two-quadrant DC source with some simple switching, or you could use a pair of two-quadrant DC sources in anti-series. Both of these methods can mimic a four-quadrant DC source, but both involve making trade-offs.

Using a two-quadrant source with a simple matrix switch

Two-quadrant sources cannot produce negative voltages like four-quadrant sources, but with simple switching they can be used like four-quadrant sources. **Figures 1a** and **1b** show test setups using a two-quadrant DC source and a simple matrix switch to characterize a solar cell.

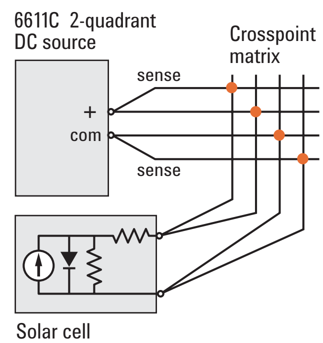

Figure 1A. ***Solar cell electrical characterization test setup configured to capture I-V curve of a solar cell***

In Figure 1a, a simple matrix switch was used to connect the DC source's output leads and external sense leads to the solar cell. Each matrix crosspoint represents a connection between a row and a column of the matrix. Figure 1a shows the DC source and matrix switch configured to capture the I-V curve of a solar cell. In this setup the DC source has the ability to deliver positive voltage along with negative (sink) and positive (source) current to the solar cell.

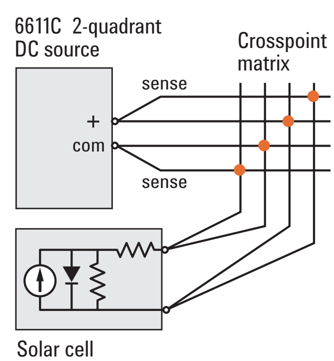

Figure 1B. ***Solar cell electrical characterization test setup configured to capture the reverse bias electrical characterization of a solar cell***

In Figure 1b, the DC source and matrix switch is configured to deliver negative voltage along with negative and positive current to capture the reverse bias electrical characterization of a solar cell.

With the simple setup in Figures 1a and 1b you can use a two-quadrant DC source with simple switching as a substitute for a four-quadrant supply. The trade off here is there will be an instant during switching where a discontinuity will exist between the DC source and the solar cell under test. Your test plan must be able tolerate the switching discontinuity. Most Agilent DC sources offer this switching built-in as an option.

Using two two-quadrant DC sources in anti-series

Obtaining an uninterrupted voltage ranging from a cell or module's open circuit voltage, or higher, to full reverse polarity can be achieved with a pair of two-quadrant power supplies connected in anti-series. The negative terminals of the supplies are connected together and the positive terminals of both are connected to the solar device under test. **Figure 2** depicts two Agilent 6631B power supplies in anti-series to fully characterize a solar cell. The positive terminal of power supply 1 is connected to the positive terminal of the solar cell. The positive terminal of power supply 2 is connected to the negative terminal of the solar cell. When you connect the supplies and solar devices in an anti-series configuration, the combination offers operation in four quadrants. When power supply 1 sources current, power supply 2 will sink current. Conversely, when power supply 2 sources current, power supply 1 will sink current. With the solar cell illuminated, power supply 1 is programmed from zero volts to V_{OC} and will sink current generated by the solar cell. Power supply 2 is programmed to zero volts and is held there. When the device is dark and the total voltage on the cell is greater than zero, power supply 1 will source current and power supply 2 will sink current. When the device is dark and the total voltage on the cell is less than zero, power supply 2 will source current and power supply 1 will sink current.

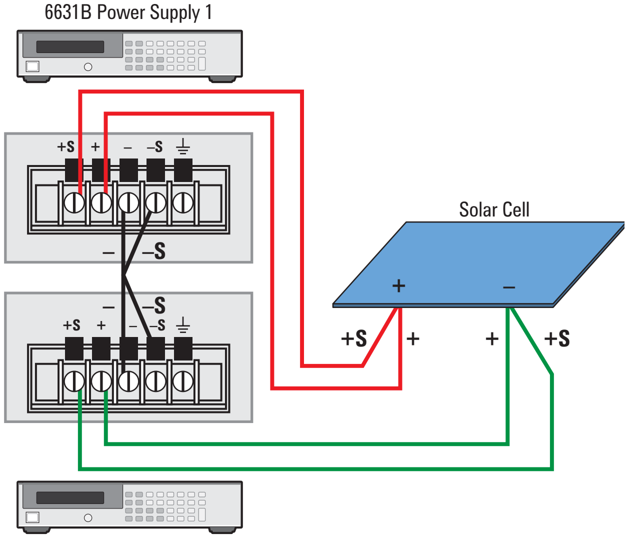

Figure 2. ***A pair of two-quadrant DC sources connected in anti-series***

For more information on using a pair of two-quadrant DC sources in anti-series to fully characterize a solar cell please refer to: *Agilent 663XB Power Supplies Connected in Anti-Series to Achieve Four Quadrant Operation for Solar Cell and Module Testing*

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To characterize solar cell performance over various temperature, wind speed and solar raditation conditions, use LAN data acquistion equipment such as the Agilent 34972A for flexible, remote measurement capabilities.

Increasing measurement accuracy

If the measurement accuracies of the electronic loads and DC sources you are employing to test your solar cells and modules are insufficient, you can add a digital multimeter(s) (DMM) to the setup to increase measurement accuracy. In a typical setup three key measurements are made with the DMM: supply voltage, solar cell/module current and current of the reference cell(s). Current measurements can be made with the DMM in series with the output current. Another way to make the current measurements is by placing a precision shunt in series with the output current. The DMM is then used across the shunt in parallel to measure the voltage drop across the shunt. Knowing the resistance of the shunt and using the measured voltage yields the output current of the DUT. Because you choose the shunt value, this method has the advantage of giving you control over which measurement range of the DMM is used. Using a shunt also means you do not have to worry about having the DMM close to the DUT; you can now take advantage of the voltage sense capability of the DMM.

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The DMM measurements can be performed using a single DMM with some simple switching versus the higher-cost method of using multiple DMMs. A problem with the single DMM method arises if your light source flickers. The flicker means the light intensity on your reference cell and your DUT will differ if the current measurements are not done simultaneously, which adds measurement uncertainty to your test. To overcome uncertainty caused by light flicker, you will need a DMM for each measurement. To ensure simultaneous measurements with multiple DMMs, use the external trigger on each DMM to trigger the measurement.

Agilent digital multimeters

Agilent offers a family of DMMs that vary in accuracy, measurement speed, and price to fit your solar test requirements.

	34401A	34410A	34411A	3458A
Resolution	6½ digits	6½ digits dual display	6½ digits dual display	8½ digits
Basic DC Accuracy	35 ppm	30 ppm	30 ppm	8 ppm
Max readings/s	1,000	10,000	50,000	100,000

Summary

With the numerous solar cell applications and technologies on the market today, solar cells and modules come in various forms of power and current ranges. The speeds, accuracies, and measurements you require for solar tests differ depending on the phase of product development and the application. With varying parameters and test requirements, selecting the right test equipment for your exact solar test needs can be challenging. This measurement brief gave you information on the various solutions available and provided helpful tips to help you set up your solar test solution for measurement success

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