Keysight Technologies

I-V Curve Characterization in High-Power Solar Cells and Modules

Application Note

KEYSIGHT TECHNOLOGIES

Introduction

Characterizing both the illuminated and reverse bias regions of a solar cell or module typically requires a four-quadrant power supply, which can be expensive. Four-quadrant power supplies also provide a limited power range so they often cannot handle high power solar cells and modules. This application note explains how to configure and implement an I-V characterization solution for high-powered solar cells, modules and cell concentrator systems. The solution is based on a DC electronic load (eload) and a single-quadrant power supply. This solution is unique in that it lets you capture the I-V curve of a cell or module under illuminated conditions and also offers the ability to characterize the dark or reverse bias region of the cell or module under test as well.

This application note covers the following topics:

- DC electronic load basics
- Configuring an eload-based test system for capturing illuminated I-V curves and reverse bias I-V curves
- How to optimize Keysight’s N3300 electronic load family for speed or accuracy
- Test setup configuration options for increasing accuracy and performance
- Choosing a boost supply

DC Electronic Load Basics

A DC electronic load (eload) is a device with an adjustable load resistance that can dissipate and measure the output DC power of a device under test (DUT). Eloads can typically measure both the output current of the DUT and the voltage that the DUT is dropping across the eload. Eloads typically have three operation modes: constant current (CC), constant voltage (CV), and constant resistance (CR). In each operation mode the set variable remains constant while the other inputs vary depending on the source and the eload settings. These modes are represented in Figure 1.

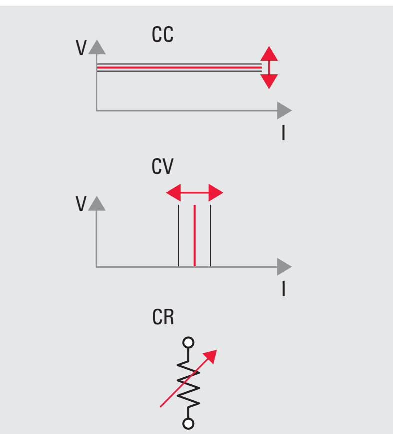

Figure 1. CC, CV, and CR modes

Typically, for solar cell and module testing the eload is used in CV mode to capture the I-V curve. The curve is captured by sweeping or stepping the voltage and measuring the current at each step. In this application note, when we discuss eload-based solar I-V curve testing, we will be referring to stepping the voltage and measuring the current, but the same measurement could be carried out by stepping the current and measuring the voltage.

One downside to using an eload for solar cell and module test is that at somewhere less than 3 V, depending on the eload you are using, the performance specifications and the current handling ability of the eload begin to de-rate. For solar cell and module testing, you need to achieve a zero voltage potential across the cell in any illuminated I-V curve test, since that is where the short circuit current is measured. To overcome this characteristic of eloads, you can configure a power supply to boost the voltage potential of the cell or module at or above the threshold voltage of the eload. For example, if you are working with an electronic load whose performance characteristics begin to reduce at a CV level of < 3 V, you need a boost supply to lift the solar DUT ≥ to 3 V. The configuration for this example is shown in Figure 2.

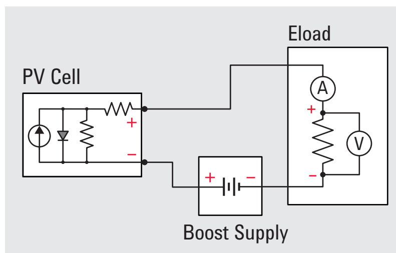

Figure 2. Configuring a boost supply

Keep the boost supply as close to the threshold voltage as possible to avoid taking too much of the eload's available voltage range. The voltage setting you are using on the boost supply is now your 0-V point where you would measure the cell's short circuit current. For instance, in Figure 2 we are using a boost value of 3 V. That means the eload must be set for a CV value of 3 V to achieve a 0-V potential across the cell, which means the cell is now in a short circuit current (I_{SC}) condition.

Adding a boost supply to an eload-based solution designed to capture I-V characteristics of high-powered cells or modules may, at first, seem like an annoying additional instrument which merely complicates your setup. The following sections, however, describe some of the very real benefits of including a boost supply in your test system, notably: the addition of reverse bias measurement capability, improved system flexibility, and even increased measurement accuracy.

Illuminated and Reverse Bias I-V Curve Characterization

Figure 2 shows the basic configuration for using an eload along with a fixed-output boost supply to capture an illuminated I-V curve of a solar cell and module. You capture the I-V curve by starting at V_{OC} or 0 V (I_{SC}) and sweeping through the entire voltage range while taking voltage and current measurements at each desired point in the curve.

It is often desirable to measure not only the illuminated I-V region of a high-powered cell but also the reverse bias region, as show in Figure 3. Measuring the reverse bias region under darkness allows you to calculate the parallel resistance of the solar DUT and determine where the breakdown region occurs. Solar modules are not commonly tested in reverse bias conditions, but these tests are done occasionally to test a module's tolerance to reverse bias current and to determine protection diode needs.

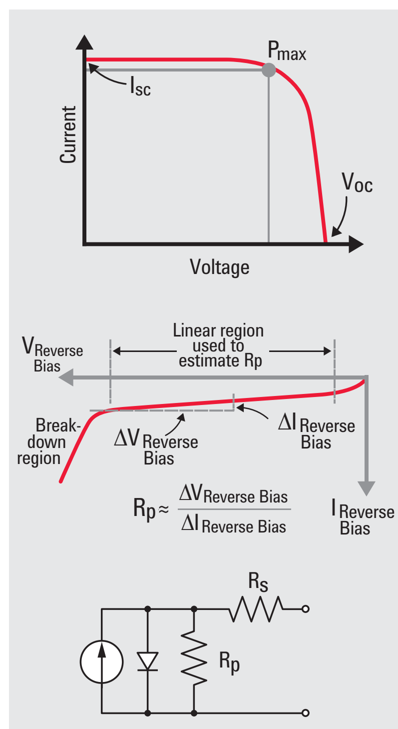

Figure 3. Solar cell I-V curves and equivalent circuit

There are three different ways to capture the illuminated I-V curve and the reverse bias I-V curve of your solar DUT using an eload and boost supply.

Method 1: Stepping both the eload and the boost supply

To illustrate this method, we will use an example where the boost supply is set to 3 V to ensure the eload can deliver full performance specifications. To capture the forward bias I-V curve you must add 3 V to each voltage step of the eload's sweep. Note that if V_{OC} was 50 V, you would start the eload at 53 V. With the eload in CV mode, you sweep the voltage and measure current down to I_{SC} (when the eload is at 3 V and the solar DUT is at 0 V).

To capture the reverse bias region, with the eload at 3 V and voltage at the solar DUT at 0 V, you begin sweeping up the boost supply's output voltage and measuring the current. Keep in mind that the circuit current will be flowing through both the eload and the boost supply, so you could use either instrument to measure the current. Figure 4 shows the configuration. Notice that the eload and the boost supply are both represented as variable, since the eload's voltage is swept to capture the illuminated I-V curve and the boost supply is swept to capture the reverse bias I-V curve.

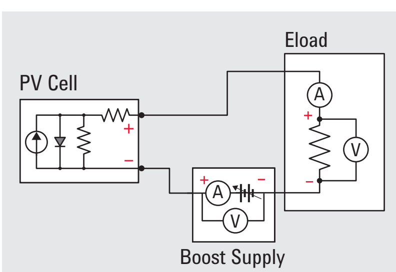

Figure 4. Solar test setup with variable boost supply

Advantages:

- No discontinuity across 0 V
- You lose only three volts from the voltage range of the eload and boost supply.
- The current flows through both the eload and the boost supply, so you can use whichever is faster or more accurate to measure the current.

Disadvantages:

- Need to program and sweep two instruments
- Speed of test depends on programming speed of two instruments

Method 2: Stepping only one instrument

The second method simplifies the test by programmatically sweeping the voltage for one of the instruments. For simplicity sake, we will cover this method in terms of sweeping the eload, although you could sweep either the eload or boost supply. For this test setup you first need to set your 0-V potential level across your solar DUT at a voltage level that will allow you to characterize the illuminated and reverse bias I-V curves of your DUT. For example, we will look at a DUT with a V_{OC} of 50 V and assume that you want the ability to apply a reverse bias voltage up to 20 V. Once again, for our example the eload provides full specifications at 3 V and above. So we need an eload that provides at least a 73-V range, 70 V for reverse and forward bias sweeps plus 3 V boost for full-performance specs. We will assume the eload has at least a 75-V range. The boost supply will be set for 25 V, which will be the 0 V potential level across our solar DUT. If you sweep the eload, you would need only a 25-V fixed-output power supply as the boost supply, which would lower your costs and simplify your setup. When stepping only the eload, we would start out in a constant voltage setpoint at 75 V, which achieves V_{OC} at the DUT (75 V – 25 V = 50 V, which is V_{OC}). Then the eload will be swept down to 25 V, which achieves 0 V at the DUT where the current is L_{SC}. Moving the eload voltage lower than 25 V will put a reverse bias potential on the DUT. Going down to a CV level of 5 V gives us the 20-V reverse bias we desire along with an extra 2 V for flexibility before we reach 3 V, where the eload's performance specification begin to de-rate. Figure 5 shows the configuration. Notice that the power supply is fixed.

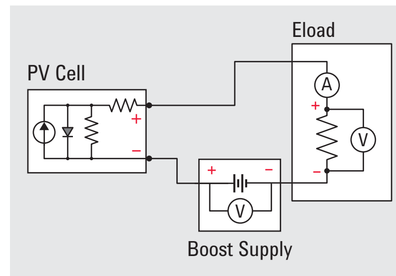

Figure 5. Solar test setup with fixed-output boost supply

Advantages:

- You only have to sweep one instrument programmatically
- You can gain accuracy by sweeping the instrument that has more measurement accuracy and by using a DMM to calibrate the instrument that is not swept to the appropriate voltage level
- No discontinuity at 0 V

Disadvantages:

- The voltage range of the test is limited to the voltage range of the instrument being swept, and it must be shared across the forward and reverse bias ranges.
- The load must dissipate the total power from the solar DUT and the higher-voltage boost supply, so you need a larger load.

Method 3: Short circuiting the eload

The final method is similar to the first method where we set our 0-V potential level across our solar DUT to as low as possible, for our example 3 V. The eload is set for a CV mode at V_{OC} and is stepped down to 3 V, which is where I_{SC} will occur. From there we take the eload out of the remainder of the test using a short circuit condition. By turning the eload into a short circuit, we can carry out the reverse bias test by simply placing the output of the variable boost power supply directly across the solar device. Then you can just step the boost supply up to the desired reverse bias level.

There are two ways to short the eload out of the circuit. The first method depends on the eload you are using and whether or not it has a short circuit mode like the Keysight Technologies, Inc. N3300 family of eloads. This function creates a short through the eload but maintains its ability to measure current. In short circuit mode the eload is still limited by its max current rating. Figure 6, below, shows the configuration with the eload in short circuit mode.

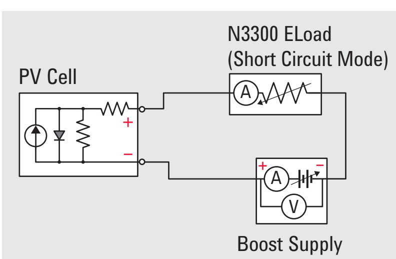

Figure 6. Solar test setup with eload in short circuit mode

The eload will still have some small amount of resistance across it. Depending on your exact testing needs, this small amount of resistance may or may not matter. For instance, the N3300 family of eload's resistance in short circuit mode depends on its exact operating conditions, but it will not be more than 200 mohms. If the added resistance is a factor, you can overcome it by using a power supply with remote sense capability as the boost supply. The boost supply's common remote sense lead should be connected to the positive lead of the solar DUT, and the positive remote sense lead should be connected to the solar DUT's common lead, as shown in Figure 7.

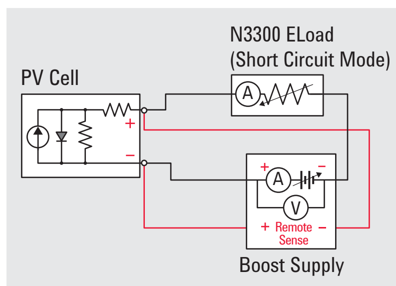

Figure 7. Eload in short circuit mode using remote sense

The second way to short the eload out of the test setup is to use a simple single-pole double-throw switch to switch around the eload, as shown in Figure 8.

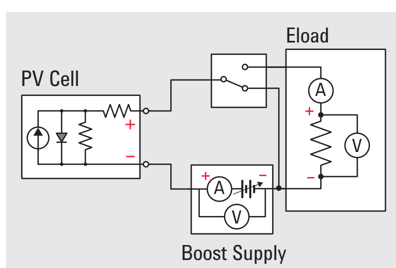

Figure 8. Solar test setup with switched-in short

With the eload out of the test circuit, you now have the boost supply connected in a reverse bias configuration to the cell. Adding a mechanical relay switch to the circuit will add some resistance to the test setup. This resistance could be < 1 ohm or up to 2 omhs, depending on the size and power handling range of the switch. To cancel this resistance out of the test, your boost supply will need remote sense capability, and the boost supply's common remote sense line will need to be connected to the positive contact of the DUT.

Advantages:

- When using the boost supply's remote sense, the effects of the shorted-out eload are removed from the test for increased accuracy for reverse bias testing.
- The whole power range of the boost supply is available for reverse bias testing.

Disadvantages:

- Discontinuity between illuminated I-V test and reverse bias I-V test as the load switches from normal operation to short mode or when the mechanical relay switches
- Need to programmatically sweep two instruments

N3300 eload's speed and measurement flexibility

Keysight's N3300 DC electronic load family consists of modular instruments and includes two different size mainframes. The N3300A is a full-rack-width mainframe with six slots that can sink up to 1,800 watts of power; the N3301A is a half-rack-width mainframe with two slots that can sink up to 600 W. The six plug-in load modules, N3302A-N3307A, power ranges are from 150 W to 600 W. The modular design of the N3300 eload family makes it easily expandable to higher power levels, as the modules can be paralleled together. All modules are controlled by a single GPIB address, which means future expandability requires little or no code changes. The N3300 eload family also is a great solution for durability or burn-in test, because each load module has its own measurement and power sinking hardware, which means testing on each channel can be performed in parallel.

The N3300 eload family has two built-in digitizers per module, which means you can capture the current and voltage from each output in parallel. This is a critical capability for accurately capturing I-V curves, since voltage and current need to be measured simultaneously to cancel out "flicker," or noise that is present in all light sources. The sample period of the built-in digitizers is controlled programmatically and has a maximum speed setting of 10 µs per sample for up to 4096 samples. The N3300 offers synchronization features, triggering options, and measurement offset functions that provide you with a great deal of flexibility to tailor it to your measurement needs.

The N3300's list feature reduces computer and IO latency by putting more of the processing burden on the instrument. The list function allows you to perform high-speed voltage or current sweeps. You can define a list of points and settings, such as slew rate, for a sweep in the N3300's internal memory. When you trigger the list, the N3300 takes over and steps through the list points. This process eliminates the IO latency associated with sending each sweep point from the computer during the sweep, providing the ability to do higher speed sweeps. You can also set up voltage and current measurements using a list, this second list can run in parallel with the sweep list.

There are two ways to program the N3300 eload family to perform a voltage sweep. The first method offers better measurement accuracy at a fairly good ramp rate speed, and the second method provides high-speed ramp rates but with less measurement accuracy.

The first method requires you to define a list of discrete voltage steps or points that have some constant dwell time. From there, the built-in digitizers are triggered to capture the voltage and current value during the dwell time of each voltage step.

For the second method, you need to define only two points or steps of the voltage sweep, V_{OC} and the 0 V point (or vice versa). The sweep or ramp rate is then defined by the programmed slew rate. The N3300 eload family is able to perform voltage ramps and measure the I-V curve data at rates as fast as 10 ms for a zero to full-scale ramp. The exact value of the I-V curve test time depends on the power range needed, measurement accuracy needed, and number of points that need to be taken. The limiting factor of the sweep speed is the internal measurement speed. For instance, let's say you need to do a 50-V sweep to capture an illuminated I-V and you want to take a measurement every 500 mV (101 measurement points) at the maximum measurement sample rate of 10 µs. This means you could complete the sweep in 101 x 10 µs = 1.01 ms. Faster ramps rates are possible with the N3300 eload, but since the digitizer is limited to no faster than 10 us per sample, faster ramps will mean capturing fewer points during the ramp. So, to capture more points during faster ramps, you would need additional faster external digitizers for capturing the I-V curve.

The following two examples highlight each sweep method using the N3300 eload. For each example we used a solar module that had the following parameters: V_{OC} = 50 V, I_{SC} = 4 A , P_{max} = 150 W.

N3300A

Discrete voltage step sweep

The boost supply is set for 3 V so I_{SC} will occur when the eload reaches 3 V. The voltage step sweep is started at 53 V (corresponding to a V_{OC} of 50 V). The sweep consists of 50 voltage steps, and each voltage step is set for a dwell time of 20 ms. The voltage and current digitizer measurements are set to trigger at each voltage step. An offset of 3 ms is set for the beginning of each measurement trigger to allow the voltage step level to settle. The voltage and current measurement time is set for 16.67 ms at each step. This time was used to cancel out power line noise (1/60 Hz = 16.67 ms). Figure 9 shows a diagram of a single voltage step from the sweep.

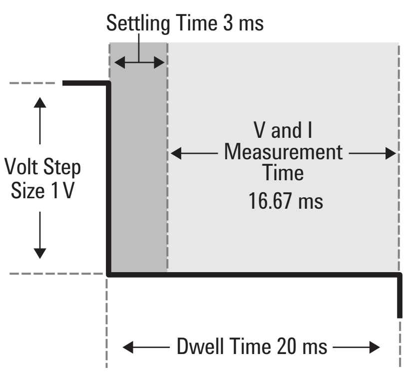

Figure 9. Voltage step diagram

Figure 10 shows the voltage step sweep and current response of the solar DUT measured by the N3300, and Figure 11 shows the I-V curve of the sweep.

With a dwell time of 20 ms for each step, the total time to complete the sweep is 1 s. This method gives you a great deal of flexibility when you choose sweep speed and measurement accuracy. You can increase measurement accuracy by upping the step dwell time to perform measurement times over multiple power line cycles. Of course the reverse is also true: you can achieve higher sweep speeds by reducing the measurement time and step dwell time.

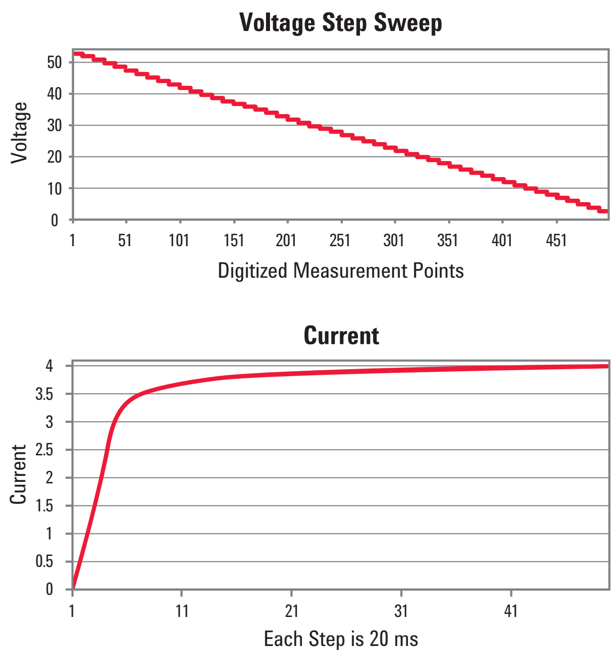

Figure 10. N3300 voltage sweep and current response

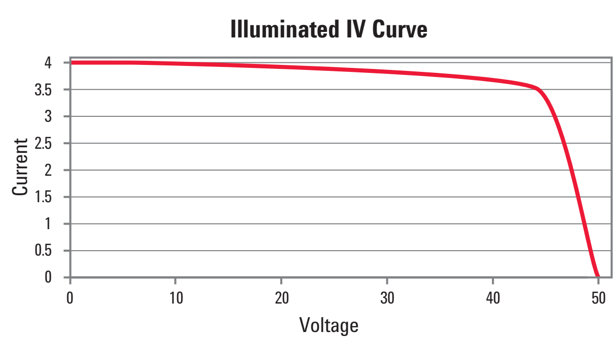

Figure 11. Stepped sweep I-V curve

Optimize for speed: Use continuous voltage sweep

The best way to optimize an I-V curve for speed using the N3300 eload is to use a continuous voltage sweep. With this method you need to define only two points in your voltage sweep: V_{OC} on the DUT and 0 V on the DUT. Then you simply step from your first voltage point, for this example V_{OC}, to the second voltage point, which is the 0 V potential or I_{SC}. The speed of the voltage sweep that the step creates is controlled by setting the slew rate of the N3300 eload. Figure 12 is a diagram of the continuous voltage sweep.

The N3300 eload also has an external programming input that allows you to perform voltage (CV mode) and current (CC mode) ramps with an external waveform source. The input has a 10-KHz bandwidth, and 0 V to 10 V represents the full scale voltage or current range of the N3300 eload. This feature allows you to create and control sweeps, either stepped or continuous, using a device like a function/arbitrary waveform generator, adding flexibility to your test setup.

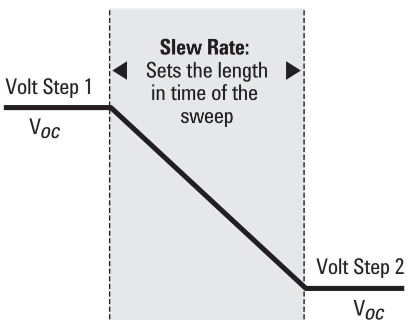

Figure 12. Continuous voltage sweep diagram

In the following example, the boost supply is set for 10 V, so in the example Step 1 is set for 60 V (V_{OC}) and Step 2 is set for 10 V (I_{SC}). The slew rate for this example was set to ramp down the voltage of the eload at a rate of 1 V every 200 µs which means the 60-V to 10-V voltage sweep and I-V curve were completed in about 10 ms. Figure 13 shows the voltage ramp from V_{OC} to 0 V (I_{SC}) curve.

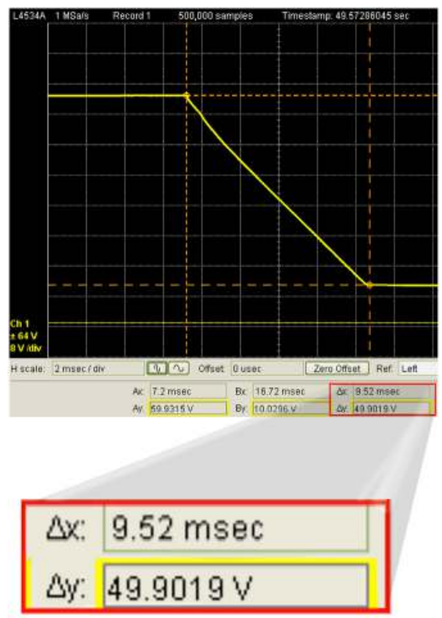

Figure 13. Sweep interval of the N3300 eload, time interval and voltage range circled in red

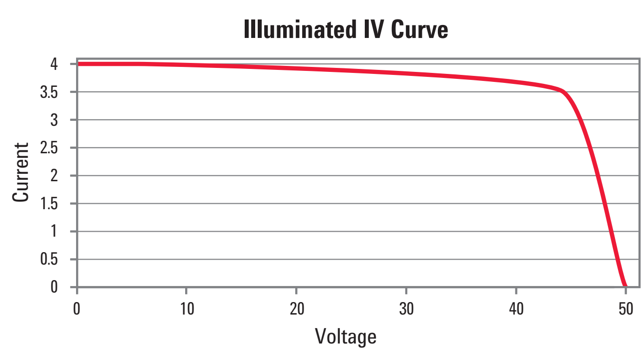

Figure 14. Illuminated I-V curve of continues voltage sweep

Increasing measurement accuracy

One way to increase measurement accuracy in an N3300 eload-based solar test configuration is to add DMMs. You will need one DMM for each measurement you want to make at each I-V curve point. For instance, let's look at a scenario where you are taking four measurements at each point on the I-V curve: solar DUT current, solar DUT voltage, reference solar cell current, and temperature.

Typically, you would want to make each of the four measurements simultaneously to avoid measurement error caused by light source noise. When capturing I-V curves under artificial lighting or under sunlight, the light source is the most inaccurate component in the test because of constantly varying irradiance levels. This is why it is critical to the accuracy of your I-V curve to take each measurement at the same time to ensure each measurement is taken at the same irradiance level. To accomplish this, you would need each DMM or measurement device in the test setup to perform its measurement on a common trigger source. For better accuracy, an external hardware-based trigger would be a better choice than a software-based trigger. For better measurement accuracy when you measure cell or module current, use a DMM set up to measure the voltage drop across a precision current shunt, rather than using the current measurement function of the DMM. The DMM provides more voltage measurement ranges than current measurement ranges.

Keep in mind that adding a current shunt to your test setup essentially adds a known element of series resistance to the measurement. Be sure to take into account the voltage drop across the precision shunt when you calculate the I-V curve. Keysight's 6 ½-digit DMMs (including the 34401A, 34410A, and the 34411A) are great fits for increasing the accuracy of your I-V curve measurements.

Learn more about the accuracy, speed and cost of Keysight DMMs at www.keysight.com/find/dmm.

Another way to add measurement accuracy to an eload-based test setup is to use a high-resolution multiple-channel digitizer. The digitizer provides flexibility in the test setup because it allows you to set the number of points you would like to capture and the speed to use for capturing the points. Multiple channels reduce the complexity of your test setup by making the challenge of triggering each measurement simultaneously much easier and far more accurate since each channel is in the same mainframe. You want the digitizer channels to be floating (common not tied to ground) to allow you to measure current across a precision shunt. Keep in mind that a digitizer adds programming complexity, because post processing is required on the raw digitized data.

Keysight's L453xA family of 20-MSa/s digitizers is a good fit for high-voltage solar measurements. The L4532A is a two-channel version and the L4534A is a four-channel version. The channels are floating (not tied to ground) and isolated from each other. Because each channel is floating, they can be connected across a high-precision current shunt to make high-accuracy current measurements. The channels can operate in parallel and have a voltage range of ± 250 V.

Learn more about Keysight high-resolution digitizers at www.keysight.com/find/digitizers.

Choosing a boost supply

The type of power supply you choose for the boost supply depends on how you want to use it. For instance, will you be sweeping the boost supply voltage in the test? Will you be making measurements with the boost supply? If your answer to both of these questions is no, you can use a fairly basic variable- or fixed-output power supply as the boost supply. The only specification you should be concerned about is the transient response after a load change. Make sure the boost supply you are using is fast enough to keep up with the current changes taking place during your I-V curve sweep. When you use a basic fixed-output or variable power supply, you most likely would want to check its boost voltage level with a DMM at test system turn-on or after each test to ensure voltage measurement accuracy for the I-V curves.

For solar test configurations where you are sweeping the boost supply for reverse bias I-V curve measurements, a higher-performance supply is necessary. For high-speed testing you want a power supply with fast command processing speed, fast programming speed, and a short settling time. These three specifications ensure the boost supply has the ability to quickly respond to a software command, such as step voltage, and has a fast settling time so an accurate measurement can be made shortly after the voltage level transition. Also, most high-performance power supplies come with high-accuracy voltage and current measurement capabilities. These capabilities reduce the complexity of your test setup because they eliminate the need to monitor the boost supply's output with a DMM.

Keysight Technologies offers hundreds of power supplies that differ in power ranges, speed, measurement accuracy and price. Keysight's N6700 modular power supplies offer high programming speed and high measurement accuracy, making them a great fit for eload-based solar test setups that require reverse bias I-V curve measurement capability. The N6700 family consists of a mainframe that can support up to four plug-in power supply modules. There are 22 plug-in modules for you to choose from, so you can configure it to meet your needs. With up to four channels per mainframe, the N6700 is a great solution for high-channel-count tests such as life and durability testing. The four supply channels can also be paralleled together or placed in series for increased power output capabilities. Since the N6700 power supply and the N3300 eload are both modular, multichannel, and high speed, they are a good match for a complete I-V curve measurement solution. For more information on the N6700 modular power supply, go to www.keysight.com/find/N6700.

To learn more about other Keysight power supplies, go to www.keysight.com/find/power.

Conclusion

In today's high-current solar cells, solar cell concentrator systems and solar modules, output power levels are out of reach for many four-quadrant power supplies on the market. Four-quadrant power supplies that can handle high power levels often lack measurement accuracy or come with a high price tag. For these high-powered solar DUTs, a DC electronic load and a single-quadrant boost supply make a flexible, high-powered and cost-effective solution. This type of solar test solution gives you the ability to capture the illuminated I-V curve of your solar DUT and provides the flexibility to perform reverse bias I-V measurements.

Using Keysight's N3300 DC electronic load family provides you with the flexibility to trade off between measurement speed and measurement accuracy to fit your exact test needs. The N3300 modular design also provides expandability in both power handling capability and channel count to meet your solar test needs. The single-quadrant boost supply needed for this solution can range from a basic low-cost, fixed-output power supply to a high-performance programmable power supply. If your solar testing needs demand a high-performance supply the N6700 modular power supply is an excellent solution because of its high measurement speed and accuracy.

Keysight N6700 modular power supply

Related Keysight Literature

Publication	Publication type	URL
Keysight DC Electronic Loads Models N3300A-N3307A	Technical specifications	http://literature.cdn.keysight.com/5980-0232E.pdf
34401A Digital Multimeter	Data sheet	http://literature.cdn.keysight.com/5968-0162EN.pdf
34410A and 34411A Multimeters	Product overview	http://literature.cdn.keysight.com/5989-3738EN.pdf
Keysight High-Resolution LXI Digitizers	Data sheet	http://literature.cdn.keysight.com/5989-9636EN.pdf
E4360A Modular Solar Array Simulator	Data sheet	http://literature.cdn.keysight.com/5989-8485EN.pdf
N6700B Low-Profile Modular Power System	Data sheet	http://literature.cdn.keysight.com/5989-1411EN.pdf
Solutions for Solar Cell and Module Testing: Keysight 663XB Power Supplies Connected in Anti-Series to Achieve Four-Quadrant Operation for Solar Cell and Module Testing	Application note	http://literature.cdn.keysight.com/5990-3949EN.pdf
Solutions for Solar Cell and Module Testing: How to decrease costs and increase flexibility in a rapidly changing test environment	Application note	http://literature.cdn.keysight.com/5990-3262EN.pdf

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