I-V Curve Tracing of High Efficiency PV Modules

Introduction

This application note will describe the physics of high efficiency modules, what happens during an I-V curve sweep, the challenges of measuring strings of high efficiency modules, proper measurement techniques, and trade-offs of different curve tracing architectures.

High efficiency modules have high capacitance which can cause errors when measuring I-V curves, if not measured properly. The capacitance can also cause a large in-rush current which can pose challenges for curve tracers being able to measure at all. The Solmetric PV Analyzer ("PVA") is specifically designed to measure high efficiency modules accurately and handle the in-rush current of strings of high efficiency modules. Some models of the PVA have limitations associated with module efficiency as shown below.

	PVA-1000, PVA-1500S/V2/V3/V4	PVA-1500HE
Max Current for module efficiency <19%	30A	30A
Max Current for module efficiency ≥19%	10A	30A

The reason for the limitations on the PVA-1000 and PVA-1500S/V2/V3/V4 models is that if the in-rush current is too high, it can trigger an over-current warning in the PVA that prevents the measurement from completing. The in-rush current increases with module efficiency, current, voltage, bifaciality, and irradiance. This is why the PVA-1000 and PVA-1500S/V2/V3/V4 spec limits current to 10A for module efficiencies over 19%. However, this spec is an over-simplification, and there are ways to work with these modules at higher currents.

The Physics of Module Capacitance

In addition to producing the commonly known DC current, PV modules also have AC or dynamic characteristics, chiefly PV cell capacitance, which comes into play when the operating point changes very rapidly like during an I-V curve sweep. There exists a modest amount of parallel plate-type *junction capacitance* in addition to a much higher capacitance associated with excited electrons in the body of the semiconductor layers. This so-called *diffusion capacitance* increases with cell voltage and with irradiance, and it also increases rapidly with cell efficiency, because higher efficiency is gained partly by extending the lifetime of charges within the cell. The magnitude of diffusion capacitance can reach the microfarad range for high efficiency modules. All modules have some capacitance. Modules over 19% efficiency are sometimes categorizing as being "high efficiency", however, in reality it is a continuum.

Where does all this stored charge come from? There is a lot going on inside a PV cell even when there is no external load. An equivalent circuit model for a solar cell is described in the Appendix at the end of this paper. Photons of sunlight are busy exciting electrons free of the semiconductor crystal. With no external circuit to drain off the charge, these charges drift around in the conductive body of the semiconductor layers outside the narrow junction region. These excited electrons have a short lifetime before they recombine, but in high efficiency cells that lifetime is relatively long, resulting in the high amount of temporarily stored (excited) charge.

Capacitive Load I-V Curve Measurements

The Solmetric PVA starts each I-V trace or 'sweep' by switching a fully discharged load capacitor (i.e. the load capacitor is at zero volts) across the terminals of the PV string. This capacitive load architecture enables the PV Analyzer to minimize errors when measuring high efficiency modules and handle the high in-rush current, all while managing the thermal energy inside the instrument. The capacitive load in the PVA is a different and un-related capacitance than the capacitance of the modules.

When an I-V sweep is started, there is a short in-rush current pulse, followed by a more steady current that is the short circuit current (Isc). As the capacitive load accumulates charge its voltage rises until it reaches the open circuit voltage Voc and current stops flowing. During the I-V sweep, the curve tracer circuitry measures and saves a series of current-voltage pairs, starting just after the in-rush current pulse, when the curve crosses 0 volts. Each current-voltage pair represents a possible operating point of the PV source circuit at the existing solar irradiance and PV cell temperature. It then connects those dots in the current-voltage graph to produce the I-V curve.

I-V Sweep Speed

Although module capacitance doesn't impact ordinary solar electric generation, I-V curve tracing *is* affected. As the voltage on the load is increasing during the I-V sweep, the operating point of the PV cells is rapidly changing, which involves a change in the amount and distribution of charge in the semiconductor material. It takes a short increment of time for the charge to equilibrate, so if the I-V sweep is too rapid there will be a time delay between the voltage and the current, distorting the I-V curve such that the maximum power point shifts to higher or lower voltages, depending on the direction of the I-V sweep (i.e. starting from Isc versus from Voc). The time delay arises from the joint effects of the cells' diffusion capacitance and series resistance, and the delay increases with the values of both. This effect was taken into account in the design of the Solmetric PVA. The I-V curve is traced continuously (i.e. not pulsed) and slow enough by the PVA to avoid distortion of the I-V curve.

On the other hand, it should be noted that an I-V curve should not be swept too slowly or there can be error from ramping irradiance. If there are thin clouds moving in front of the sun, this will cause ramping irradiance (i.e. increasing or decreasing irradiance over the period of time it takes to sweep the I-V curve). Furthermore, the irradiance of the sun is often changing a little, even when there are no visible clouds in the sky. There are fluctuations in the atmosphere that can cause it to change over a period of seconds. When the irradiance ramps during an I-V sweep, the curve becomes less useful. For example, if the irradiance is ramping up during a long I-V sweep, the portion of the I-V curve that is sometimes referred to as the flat "plateau" between Isc and Imp may have an upward slope to it.

The Solmetric PVA sweep time is carefully controlled to sweep fast enough to minimize the effects of irradiance ramping, but slow enough to avoid errors due to module capacitance. Most PVA I-V sweeps are controlled to have a duration of 150-300ms in duration.

In-Rush Current

The second impact of diffusion capacitance occurs at the start of the I-V sweep when the free charge surges into the curve tracer. At this instant a short 'spike' of high current surges from the PV string into the curve tracer's load. If this in-rush current is high enough it can prevent the I-V curve from being measured. The PVA will display an 'overcurrent pulse' warning in this situation. Other curve tracers may report that the current is 'unstable'.

All PV cells have some degree of diffusion capacitance that causes a corresponding degree of current surge at the start of the I-V sweep. For conventional module technologies the spike is small, and the curve tracer can easily handle it. But the higher the efficiency of the PV module, the higher the diffusion capacitance and the higher the in-rush current.

PVA-1500HE and In-Rush Current

The PVA-1500HE was designed to manage the in-rush current for single or parallel strings of high efficiency modules up to 30A. The "HE" stands for "high efficiency"!

PVA-1000 and PVA-1500S/V2/V3/V4/T and In-Rush Current

The PVA-1000 and PVA-1500S/V2/V3/V4/T are able to manage the in-rush current for single strings of high efficiency modules up to 10A. In arrays where strings of high efficiency modules are connected in parallel – the 'harnessed' architecture – it's necessary to measure the strings one at a time. Some modules are internally wired with cell groups in parallel (e.g. Canadian Solar BiHiKu and Trina Vertex). These modules can have Isc ratings over 18 Amps and strings of these modules essentially behave like two high efficiency strings in parallel. For this reason, Solmetric specifies that strings of modules over 19% efficiency should be less than 10 Amps when measured with these PVA models.

The 10A limitation is an over-simplification in order to have an easy-to-understand spec sheet. In practice, the capacitive effects of high efficiency modules scale with the total number of modules in a string independent of whether the modules are in parallel or series. So, lower string voltages can allow currents higher than 10 Amps, even with high efficiency modules. The capacitive effects also scale with efficiency, bifaciality, and irradiance. The most challenging strings are those with very high efficiency (e.g. >21%), high Isc (e.g. >10A), high voltage (e.g. >1300V), are bifacial, and are measured under high irradiance (e.g. >1000 W/m^2). Reduce any of these and the string is more likely to be measurable by these PVA models. If you run into the in-rush current problem, you can

1. Reduce string current
   a. Break-up parallel or harnessed strings into individual strings to reduce total string current
   b. Adjust the tracker orientation for lower irradiance
   c. Measure early or late in the day for lower irradiance
2. Reduce string voltage by breaking-up strings into shorter strings

When breaking-up harnessed strings, you can connect the curve tracer to the ends of each individual string, or alternatively, it can be more convenient to connect the curve tracer at the end of the trunk cable (typically in a combiner or load break box) and have a second person plug the strings into the harness one at a time. When using the PVA software, the operator selects a branch of the displayed 'array tree' to save the measurement result. When measuring strings of high efficiency modules of a harnessed array individually, they should be saved to the String layer of the array tree rather than to the Harness layer. And if the measurements will be made from the combiner (or inverter) end of the trunk cable, the wire properties that are entered when setting up the project should be the properties of the trunk cable. However, if the individual strings have long PV jumpers in series with them, it may be more appropriate to ignore the trunk cable wire properties and instead enter the properties of those jumpers. Wire gauges are normally selected for minimal loss, so it's usually reasonable to approximate or enter average wire lengths, but it's important to enter the correct wire gauge. If you are unsure whether to enter the wire properties of the trunk cable or the string jumpers, consult a wire table and calculate and compare their typical resistances. If they are both significant, another approach is to add those resistances and adjust the wire properties to represent that total value of resistance.

Comparison to Other I-V Curve Tracer Architectures

As discussed above, the Solmetric PVA continuously sweeps the load on the PV string by switching in a bank of capacitors across the string and allowing the capacitors to charge up. Other curve tracers switch resistive loads across the array or use an active linear-mode transistor across the string. When a resistive load or an active load is used, the amount of time that the load is applied must be kept very short to minimize power dissipation within the load inside the instrument. This architecture can be more compact and lower cost, but if the instrument dwells too long at any given point on the I-V curve, then the instrument can quickly overheat. For this reason, these kinds of curve tracers typically either sweep the entire I-V curve continuously very fast (e.g. in a few milliseconds) or they pulse the load on and off for each sample in the I-V curve one point at time. But sweeping the full I-V curve quickly exacerbates the errors when measuring high efficiency strings, as discussed above. When load pulsing is used, the load is switched on for a very short time (e.g. less than 1 millisecond) and a single current and voltage operating points is measured. Then, the load is removed, bringing the string back to Voc for a long time (e.g. around 100 milliseconds), in order to allow the curve tracer circuit to cool off. Then, this pulse and sample cycle is repeated for the next point. For a 150 point I-V curve, the cycle is repeated 150 times. This is why curve tracers that pulse the load typically take 15-20 seconds to sweep the I-V curve. But pulsing the load on and off quickly exacerbates the errors when measuring high efficiency modules as discussed above, or in many cases, makes it impossible to measure high efficiency strings at all. In some cases, the capacitive surge caused by a single fast pulse is so large that the data is meaningless and the curve tracer simply gives up. It is more accurate to sweep the load of high efficiency modules continuously and more slowly, but this is impossible in a compact active-load curve tracer because it will overheat.

On the flip side, an I-V curve should not be swept too slowly or there can be error from ramping irradiance, as discussed earlier. For this reason, the PVA typically completes its I-V sweep in around 100-300 milliseconds. This balances the desire to not sweep too fast, minimizing the errors when measuring high efficiency strings, with the desire to not sweep too slow, minimize the errors from irradiance ramping. The Solmetric PVA is able to walk this fine line because of its capacitive measurement architecture. In contrast, curve tracers that use a pulsed active load technique take the individual samples too fast for accurate high efficiency string measurements, but the total sweep time (i.e. time to take all of the individual samples in the curve) is too slow to avoid errors from irradiance ramping.

Also, if a curve tracer sweeps the I-V curve of a high efficiency string from Voc to Isc, there is a larger error in the I-V measurement for a given sweep time than if the sweep is from Isc to Voc. This is one reason that the PVA sweeps from Isc to Voc. Pulsed active load curve tracers typically sweep in the less favorable direction from Voc to Isc.

Conclusion

High efficiency modules require care when measuring their I-V curves due to their high capacitance. The high capacitance can lead to errors in the I-V curve if swept too fast, and the in-rush current can prevent measurements all together if not measured properly. I-V curve tracers that use a capacitive measurement technique are preferred when measuring high efficiency modules and strings because of their ability to sweep the I-V curve slow enough to avoid the errors, but fast enough to avoid solar ramping--all while avoiding overheating. For the most flexibility with high efficiency strings use the PVA-1500HE.

For help dealing with measurement of strings of high efficiency modules in the harness architecture or in any configuration, contact Solmetric Technical Support at 707-823-4600 or support@solmetric.com .

Appendix

This is the formula for diffusion capacitance from the article *Measurement of inrush current waveforms for modeling reactance characteristics of PV modules*, Hiroshi et. al., in the 26th European Photovoltaic Solar Energy Conference:

$$C_{diff} = C_0 \exp\left(\frac{qV_{Cell}}{nkT}\right)$$

where Co is a base capacitance value, Vcell is the cell voltage, T is the temperature, n is the ideality factor, and n, and k are physical constants.

This is the equivalent circuit of a PV cell showing the cell capacitance, from the article *Influence of solar cell capacitance on measurement of I-V curves of PV modules*, Stephan Mau & Thomas Krametz:

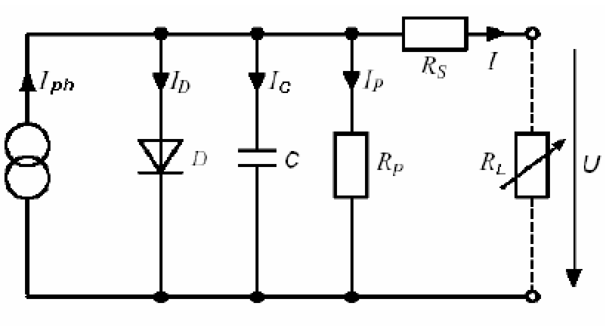

Figure 1: Schematic diagram of the solar cell including load resistance

where the light-dependent current source is at the left, the diode represents the diode nature of the solar cell, C is the cell capacitance, Rs and Rp are the series and shunt (parallel) resistances, and U is the terminal voltage of the cell.