

# Solmetric White Paper:

# Winning PV Contracts with I-V Curve Testing

---

## Contents

- Introduction.....1
- Background: I-V Curves in Field Applications .....2
  - What is an I-V curve? .....2
  - What is the background of I-V curve tracing in the PV industry? .....3
  - What are the benefits of I-V curve tracing? .....3
  - Why is the Solmetric PV Analyzer (PVA) the best choice for measuring I-V curves? .....4
- Proposal/Contract Language for Array Testing .....5

## Introduction

The value and ROI of a solar PV array is directly tied to its performance. PV array performance testing is typically done during start-up testing, commissioning, operations & maintenance, and troubleshooting. The Solmetric PV Analyzer measures PV array performance faster and in more detail than other methods, simplifies data management, and provides a comprehensive report of commissioning results. This reduces costs and project risk, and helps close projects earlier. Performance measurement capability is a business asset, and the purpose of this white paper is to help you capitalize on this asset during the proposal and contract negotiation phases of new-system or O&M deals.

This white paper has two parts:

1. Descriptive language. This section describes in every-day terms what I-V curve tracing is, why it’s an advantage over other methods, and the particular strengths of the Solmetric PV Analyzer. This language can be used directly in your sales process.
2. Proposal/Contract Language. This section contains wording about the specific procedures, measurement results, and documentation requirements for the I-V curve measurements. This language can be adapted for or included in any appropriate document, including the following:
  - a. Request for Information (RFI)
  - b. Requests for Proposal (RFP)
  - c. Proposal
  - d. Statement of Work (SOW)
  - e. Contractual Agreement
  - f. Performance Agreement
  - g. Operations & Maintenance Agreement

## Part 1: I-V Curve Measurement and the Solmetric PV Analyzer

### What is an I-V curve?

The I-V curve (current versus voltage) represents all possible operating points of a PV module, string or array at existing environmental conditions. The curve starts at the short circuit current and ends at the open circuit voltage (Figure 1). The maximum power point, located at the knee of the I-V curve, is the operating point that delivers the highest output power. It is the job of the inverter's maximum power point tracking circuit (MPPT) to find that point as irradiance and temperature change. The P-V curve (power versus voltage) is zero at either end and a maximum at the knee of the I-V curve.

Any impairment that affects the shape of the I-V curve (Figure 2) will reduce the peak power value and diminish the value of the array. The impact of a mismatch impairment on output power is shown in Figure 3.

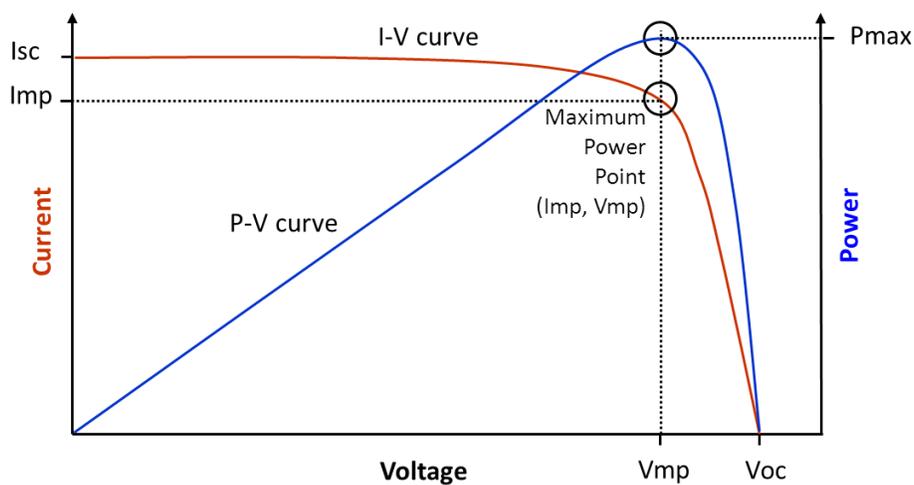


Figure 1 I-V and P-V curves for a PV module or string.

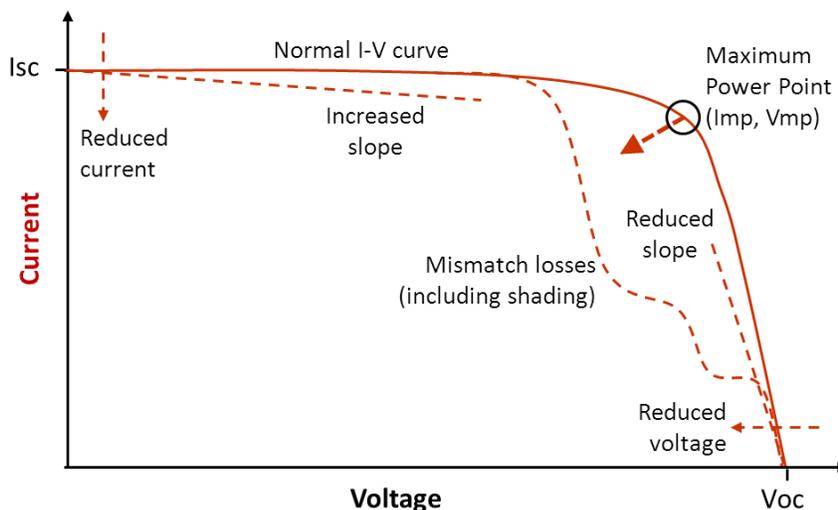
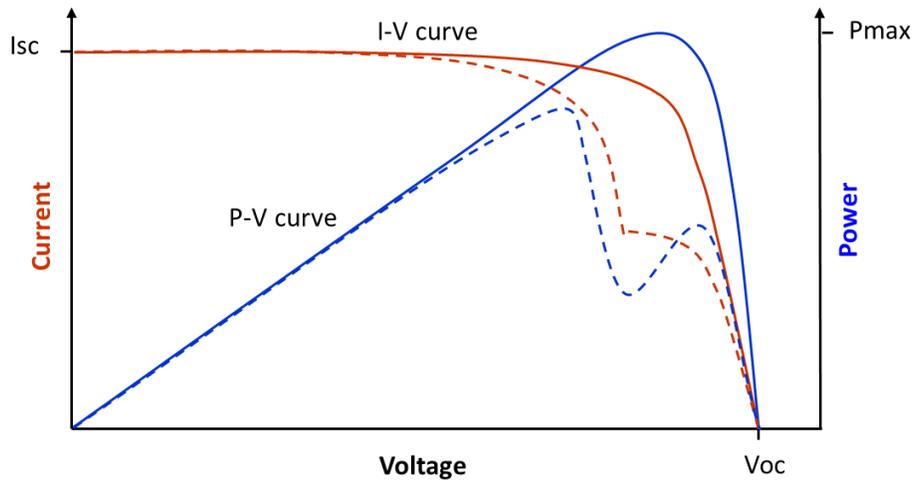


Figure 2 The five types of deviation from normal I-V curve shape.



**Figure 3** I-V and P-V curves under mismatch (shade, cracked cell, etc).

### What is the background of I-V curve tracing in the PV industry?

I-V curve tracing has been used for decades in PV R&D, manufacturing, and field testing. It is the most comprehensive measurement that can be performed on a PV module, string or array. Today, it is the availability of an affordable, compact, rugged, and easy to use curve tracer that has changed the game in PV system testing. The Solmetric PV Analyzer allows the user to compare the measured I-V curve with the predictions of built-in PV models, giving immediate indication of the health of the array. The companion Data Analysis Tool makes quick work of analyzing and displaying the test results for kilowatt to multi-Megawatt PV projects.

Some PV Analyzer users have adopted this test method to reduce their test times, others to gain deeper insight into PV system performance. Together, these are a winning combination.

### What are the benefits of I-V curve tracing?

#### Reduced test time

I-V curve tracing measures array performance with a single electrical connection at each combiner box, and a single measurement per string. After isolating the combiner box from the rest of the array and lifting the string fuses, the curve tracer is connected to the combiner box buss bars. One at a time, the fuses are inserted and the strings measured. Data is saved electronically. A single I-V curve sweep by the PV Analyzer takes less than a quarter of a second, and the cycle time including saving of data takes less than 15 seconds per string. There is no need to return to the array again later to measure operating current on each string, because the I-V measurement has already determined the maximum power and the maximum power current and voltage.

#### No need to bring the inverter on-line to test PV string performance

Traditional test methods required the inverter to be brought on-line in order to measure the operating current of each string under load. I-V curve tracing eliminates this requirement by measuring the performance of each PV string under all load conditions. This means you test the array once, earlier in the project, avoiding the long wait to bring the inverter on-line.

### **Reduced start-up and commissioning risk**

Testing the array before the inverter is brought on-line means less risk of array-side problems showing up during start-up or commissioning.

### **More detailed measurement results**

I-V curve tracing is the most comprehensive test possible for PV arrays. In addition to measuring the short circuit current and open circuit voltage, it uniquely measures the maximum power point of each string. In fact, the PV Analyzer measures 100 points along the I-V curve. With this resolution, the measurement can detect more physical effects that may be degrading the performance of the system. The PV Analyzer uses a sophisticated PV model to predict what the shape of the I-V curve should be, taking into account the existing irradiance, module temperature, module brand and part number, the sun's incident angle, wire length and gauge, and so on. Any deviation in the shape of the I-V curve compared with the on-screen model gives important clues to the nature of the impairment for troubleshooting purposes.

### **Efficient data management**

I-V curve measurement data is saved electronically, eliminating data recording errors. The Solmetric I-V Data Analysis tool automatically produces a family of displays of array performance across a population of measurements, making it easy to visually demonstrate that PV strings are performing consistently and in line with expectations. If performance issues exist, the tool quickly draws attention to the problem strings.

### **Detailed performance baseline**

PV arrays are extremely robust and reliable but performance does gradually degrade. Occasionally a module will fail. I-V curves captured and stored at start-up or commissioning time give you a detailed baseline against which to compare future measurements over the life cycle of the PV system. Module degradation and failures are easily measured and documented, facilitating module warranty claims. Questions of workmanship or claims about problems dating back to installation time are easily resolved by referring to baseline data.

Taken as a whole, these advantages reduce the costs and risks associated with PV system construction and testing, and provide a baseline for ongoing maintenance.

### **More efficient troubleshooting**

Curve tracing is an invaluable tool when troubleshooting PV strings, detecting excess series resistance, low shunt resistance, module mismatch, or shorted bypass diodes directly from the shape of the I-V curve. To find a bad module in a string, just measure the string repeatedly with a different module shaded in each instance. All of the measured curves will look alike except for the one in which the failed module was shaded. The Solmetric PV Analyzer has features that make these analysis techniques easy.

### **Why is the Solmetric PV Analyzer (PVA) the best choice for measuring I-V curves?**

The Solmetric PV Analyzer combines an affordable, compact, fast, and easy-to-use I-V curve measurement tool with built-in PV performance modeling and STC translation capability, allowing users to immediately determine whether a PV module or string is performing to its potential. If it is not, the shape of the I-V curve provides critical information about potential causes of the performance problem. Advanced data analysis tools make fast work of analyzing data and generating reports for system stakeholders. And if it is ever needed, responsive technical and application support is at your service.

The Solmetric PV Analyzer is also specifically designed to accurately measure high-efficiency PV modules, allowing time for the charge distribution in the modules to shift as the load voltage changes, to avoid distortion of the I-V curve.

## Part 2: Proposal/Contract Language for Array Commissioning

The language below can be included in proposals, contracts, and agreements pertaining to PV performance testing. This text is intended as a guide that you can adapt to your particular needs. See the parenthetical comments “<.....>” and supporting guidance [text] for options to customize the language.

### PV Array Performance Tests

String I-V curve tracing tests shall be performed in accordance with procedures detailed in this section, and test data shall be recorded.

#### String I-V Curve Test

**Purpose:** Measure string-level I-V curves and extract key performance parameters. Compare measurement results across the population of strings in the sub-array or system. Also compare the measurement results with the predictions of a PV performance model, accounting for irradiance and temperature variations. Evaluate the shapes of the I-V curves and the values of key operating parameters derived from the I-V curves, including short circuit current, open circuit voltage, maximum power current and voltage, open circuit voltage, maximum power, and fill factor. Repair any non-conforming strings and retest them. Demonstrate via the resulting data set that the array meets performance expectations.

**Scope:** Measure <all strings, specified strings:\_\_\_\_\_>

*[Measurement of all strings provides the most complete performance verification. This is a best practice for commissioning new systems. However, for periodic checkups, a sampling basis may be suitable. For repair situations, the repaired strings and a number of neighboring strings should be measured and compared.]*

**Party:** Tests shall be performed by <installer, EPC technical personnel, contracted testing service>.

*[Performance testing for commissioning purposes is often performed by a third party. Alternatively, the testing may be performed by the installer and reviewed by a third party such as the customer’s engineer. ]*

**Schedule:** Tests shall be performed <prior to substantial completion, during startup testing, during commissioning, during O&M>.

#### Equipment/ Materials:

- Rubber insulating gloves and other PPE
- Fuse puller if required
- I-V curve tracer such as the Solmetric PVA-600. If the PV modules under test are the high-efficiency type, use I-V curve tracing equipment that is specifically designed for this application (eg Solmetric PVA-600), to allow the electric charge distribution within the modules to reach quasi-equilibrium at each point along the I-V curve (to avoid distortion of the I-V curve and errors in the maximum power point).
- Test leads with alligator clips

**Procedure:**

- Follow the manufacturer's procedures for use of the I-V curve tracer.
- Electrically isolate the combiner box from other sub-arrays and the inverter by opening its DC disconnect switch.
- Electrically isolate the combiner box buss bars from its PV source circuits by lifting all of the string fuses.
- Connect the curve tracer to the buss bars, observing correct polarity.
- Measure the I-V curve over the range from short circuit current to open circuit voltage, capturing at least 10 and preferably 100 points (eg Solmetric PVA-600) in the I-V curve.
- For each I-V curve, measure and record the irradiance in the plane of the array, the temperature on the backside of a typical PV module, and the date and time. Measure the curve in less than 1 second to assure that rapid irradiance changes have minimal effect on the shape of the curve. Measure the irradiance values within 2 seconds of the I-V measurement and the temperature values within 10 seconds of the I-V measurement, and store these values with the I-V measurement results. Assure that the data is uniquely identifiable, typically by capturing the string, combiner box and inverter numbers.
- Also record the ambient temperature.

**Conditions:**

The characteristics of an I-V curve change with irradiance and temperature. At low irradiance, the shape of the curve changes to an extent that data analysis is less accurate. These limitations apply for all types of performance measuring equipment (I-V curve tracing and conventional measurement methods).

To allow for accurate data analysis, the preferred conditions for PV array performance measurements are clear skies, an irradiance value of at least 700 W/m<sup>2</sup> in the plane of the array, and low wind. In addition, the measurements should be performed within a four hour time window centered on solar noon (see the web site <http://www.esrl.noaa.gov/gmd/grad/solcalc/sunrise.html> to calculate solar noon for your particular date and geographic location). The shape of an I-V curve changes as a function of irradiance, and the change becomes severe below 300W/m<sup>2</sup>. For this reason, testing at irradiance values of less than 300 W/m<sup>2</sup> shall be avoided.

If satisfactory measurement conditions are not available, the tests shall be postponed until the earlier of:

- the date on which such conditions exist, and
- 5 business days following the date on which the test would otherwise have been conducted.

If after 5 business days such conditions are still not available, then the test will be conducted within 5 more days. Any anomalous data apparently due to changing sky conditions shall be re-measured under stable sky conditions.

**Criteria:*****I-V Curves***

Record the measured I-V curves and display them together at the level of each **<combiner box, array>**.

*[Overlaying of I-V curves is an excellent way to demonstrate performance uniformity and to identify any non-conforming strings. The comparison is most useful when the irradiance and temperature are relatively constant across the family of measurements. For a large system, the conditions are usually stable for the time period required to measure the strings in a single combiner box. For a small system, the conditions may be stable enough to compare the I-V curves of the entire system.]*

Identify and troubleshoot any substantial deviations from normal I-V curve shape. Look for relative differences in slope in the horizontal and vertical legs of the I-V curve, and for any steps or notches in the shape of the curve. For guidance in evaluating I-V curves, refer to the Solmetric Application Note *Guide to Interpreting I-V Curves* <http://resources.solmetric.com/get/Guide%20to%20Interpreting%20I-V%20Curves.pdf>.

### **Maximum Power**

Compare the maximum power (Pmax) values obtained from the measured I-V curves to the predictions of an advanced PV model such as the Sandia PV Array Model or 5-Parameter Model. These models take into account the irradiance and module temperature at the time of measurement. The measured Pmax value for each string shall be within  $\pm$  **<5 to 10>** % of the value predicted by the PV model.

*[A number of factors should be taken into account in setting the level of agreement expected between the measured and predicted system performance. These include the age and level of degradation of the system, the level of irradiance in the plane of the array, the stability of irradiance and temperature during the measurements, the time of day and associated solar angle of incidence, the degree of soiling present, the effect of reflected light (albedo effect), and the details of sensor deployment. Typically, irradiance measurement uncertainty is the largest error term.]*

Also compare the maximum power values across the population of strings in the **<combiner box, array>**. Individual string Pmax values shall be within  $\pm$  **<2 to 3>** % of the average value of the population after translating the individual string results **<to the average irradiance and temperature values of the measurement session, or to STC>** .

*[Translating results STC typically introduces more error than translating to average conditions. However, it is a common practice to require STC translations for commissioning purposes].*

### **Open Circuit Voltage**

Compare the open circuit voltages (Voc) obtained from the measured I-V curves to the predictions of the advanced PV model. The measured Voc value for each string shall be within  $\pm$  **<2 to 5>** % of the value predicted by the PV model.

*[The level of agreement between measured and predicted Voc depends on the uniformity of temperature across the array, which is in turn a function of time of day, wind speed (and variations thereof), and the mounting details of the array. For example, the edges of the array typically run cooler.]*

Also compare the Voc values across the population of strings in the **<combiner box, array>** . The individual string Voc values shall be within  $\pm$  **<2 to 3>** % of the average value of the population after translating the individual string results **<to the average irradiance and temperature values of the measurement session, or to STC>** . Translation to STC typically introduces more error than translating to average conditions.

*[Translating results STC typically introduces more error than translating to average conditions. However, it is a common practice to require STC translations for commissioning purposes].*

### **Short Circuit Current**

Compare the short circuit current (Isc) values obtained from the measured I-V curves to the predictions of an advanced PV model such as the Sandia PV Array Model or 5-Parameter Model. The measured Isc value for each string shall be within  $\pm$  **<5 to 10>** % of the value predicted by the PV model.

*[See the guidance under Maximum Power regarding the level of agreement to expect between measured and predicted values. ]*

Also compare the Isc values across the population of strings in the **<combiner box, array>** . The individual string Isc values shall be within  $\pm$  **<3-6>** % of the average value of the population after translating the individual string results **<to the average irradiance and temperature values of the measurement session, or to STC>** . Translation to STC typically introduces more error than translating to average conditions.

*[Translating results STC typically introduces more error than translating to average conditions. However, it is a common practice to require STC translations for commissioning purposes].*

#### **Resolution of issues:**

If the performance of a string deviates from the limits set forth in the preceding sections, flag the string for further analysis. Analysis steps include:

- Verify that results were translated, if required, and that the translation was done correctly.
- Re-test the string and troubleshoot the issue down to the PV module.

After any necessary repairs are completed, re-test the repaired string and **<#, all>** strings in the same **<combiner box, array>** and verify that the performance limits set forth above have been met.

*[Given that irradiance measurement error is typically the largest component of measurement uncertainty for any PV performance measurement equipment, it is important that post-repair testing compare the performance of the repaired string with that of the neighboring strings. This assures that any irradiance measurement errors affect all of the measurements equally].*

#### **Documentation:**

A report describing the test results and issue resolutions shall be provided. The data for each string shall be identified by string, combiner box and inverter numbers.