Field Applications of I-V Curve Tracers in the Solar PV Industry

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PhotoVoltaic

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Solmetric Solutions

Site Evaluation

PV Design

PV Verification

www.solmetric.com
Topics

• Field portable I-V curve tracers
• Array performance testing
• Measurement conditions
• Data analysis
• Troubleshooting
• I-V curves of partially shaded arrays
Introduction
Trend in PV Incentives

- **Performance based**
  - Net metering
  - Solar Renewable Energy Credit (S-REC) programs
  - Feed-in tariffs
- **Expected performance based (cap/perf hybrid)**
  - State/utility buy-down programs
- **Capacity based**
  - Rebate programs
  - Tax credits

**Goals of performance based incentives**: Incentivize proper system design and installation, improve ROI, and help states meet renewable energy targets.
Array Performance Test Methods
For Startup/Commissioning/Checkups/Alarm response

Inverter readout

String DC measurements

String I-V curve measurements

Monitoring also plays a key role in maintaining performance
Curve Tracers – a Long and Proud History
Making electrical relationships visible

- The Tektronix 575 (c1957) was the first widely used transistor curve tracer
- Curve tracers have been essential tools for PV research and manufacturing
- Today, I-V curve tracers are rugged, simple, and affordable enough for field in commissioning and maintaining PV systems.
Five Classes of I-V Curve Anomalies

Conventional measurements do not reveal many of these effects.
Benefits of I-V Curve Testing

• Most complete performance test possible for PV modules & strings
• Much faster than conventional methods – one connection, one test
• Allows fully testing the array before the inverter comes online
• Provides high-value data for the commissioning or O&M report
Benefits of I-V Curve Testing

• Provides a detailed baseline for comparison as systems age
• Provides authoritative evidence for module warranty return
• Speeds troubleshooting – selective shading method
• Using the “best tools” helps win new business
Curve Tracers for PV Field Applications
Loading the test device

Load can be
• Resistive
• Capacitive
• Electronic

Measure voltage
Measure current

Current vs. Voltage Graph
I-V curve tracing with a resistive load

- Resistors have their own I-V curves
- They are straight lines starting at I=0, V=0
- The lower the resistor, the steeper the line
- Switch in one load resistor at a time
- Each resistor identifies one operating point on the I-V curve
Illustrate charging with an animation. When switch closes the circuit, the capacitor charges from 0V to Voc as shown in graph. I-V curve is swept out from left to right, quickly at first, and gradually slowing above the knee of the I-V curve (the knees of the two curves coincide in voltage).
I-V sweep rate effects in testing high efficiency modules

- High efficiency PV modules store more charge, symbolized by the shunt capacitor.
- If the load changes too fast, the charge does not have time to settle at each new load point.
- This results in overshoot or undershoot of the measured curve, relative to the actual maximum power point.
- The Solmetric PV Analyzer is designed for accurately testing high efficiency PV technologies.
I-V sweep rate effects in testing high efficiency modules

- These curves show the effect of different sweep times and directions
- Overshoot occurs if sweeping too fast from open circuit to short circuit
- Undershoot occurs if sweeping too fast from short circuit to open circuit

Influence of solar cell capacitance on the measurement of I-V curves of PV modules,
Stefan Mau, Thomas Krametz
Measurement throughput
Thermal limitations

• Every I-V curve tracer absorbs a small amount of energy with each I-V curve measurement
• This energy must be managed to control instrument temperature

Resistive load

Capacitive load

Capacitor voltage V_{cap}
Built-in PV models

- Built-in PV models provide an immediate check on the health of the module/string under test.
- Models in use today include the Sandia, 5-Parameter, and simple datasheet models with STC translation.
- The curve tracer may predict the performance at existing conditions, or translate the I-V measurement to Standard Test Conditions (or other user-selected conditions).
Solmetric PV Analyzer
Solmetric PV Analyzer

- 20A, 600V
- 1000V in development
- Wireless interface to your tablet or notebook PC
- Extensive touch features
- Automated data analysis
How it works

Irradiance sensor
Module backside temperature sensor

Your PC

Built-in PV models

Irradiance & temperature

Module, tilt, orientation...

5 points predict the shape of the curve

All wireless

Screen shot

I-V Measurement Unit

WUSB1 WUSB2

Your PC

Solmetric
Typical Measurement Setup

Courtesy of Chevron Energy Solutions © 2011
Wireless Sensor Kit

- Irradiance transmitter
- Temperature transmitter
- Receiver (USB)
- K-type thermocouple
  Omega Part # 5SRTC-GG-K-30-72
Deploying the sensors

** Irradiance **

Mount the irradiance sensor in the plane of the array.

** Temperature **

Mount the thermocouple away from the cool edges of the module/array. Press the thermocouple into firm contact with the module backside.

** MOCAP MCD-PE 1.75 poly dot
~$80/roll of 1000 dots
customerservice@mocap.com **
Software User Interface
Traces tab
Saving a Measurement Result
Touch location of test device, then save
Environmental Inputs controls

7/19/2012 07:40 - Inverter1-Combiner1-String1

Irradiance: 1054 W/m²
T backside: 36.7 °C

Model: 5 Parameter
Show STC Translation
Environmental Inputs

From IV Data
Wireless Sensor
Manual Entry

Adjust Sensors Cal...
Verify screen

Solmetric PV Analyzer™ - Garage PV system

7/19/2012 07:40 - Inverter1-Combiner1-String1

Performance Factor 97.1%

Power

Target

5000
4000
3000
2000
1000
0

Irradiance 1054 W/m²

T backside 36.7 °C
Table screen

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**Irradiance:** 1051 W/m²

**T backside:** 37.2 °C
Measurement Conditions
Recommended Sky Conditions
For Array Performance Testing

- **Clear sky (for high, stable irradiance)**
  - Height of I-V curve varies directly with irradiance
  - Shape of I-V curve changes at low irradiance
  - Translation to STC is much less accurate from low light conditions

- **4 hour window centered on solar noon***
  - Avoids low-light, spectral, and angle of incidence induced errors

- **Low/No wind (for more consistent module temperature)**
  - Width of I-V curve varies inversely with temperature
  - Temperature is not uniform across an array under any conditions

Good conditions mean **less scatter** in your data, which means:
  - Easier to spot non-conforming strings, and
  - More convincing demonstration of consistent string-level performance

*Solar Noon Calculator:
http://www.esrl.noaa.gov/gmd/grad/solcalc/
Problem Sky Conditions

Cirrus

Scattered

Edge effect
Measurement Process - Commissioning
I-V Measurement Setup
Example: Measuring strings at a combiner box

Attach the thermocouple well away from module edges, using polyimide (Kapton) tape for best mechanical properties at high temperatures.
Measurement Process

Example: Measuring strings at a combiner box

**Hardware setup (do once at each combiner box):**

1. Move the sensors (if necessary to get wireless range)
2. Isolate the combiner box (open the DC disconnect)
3. De-energize the buss bars (lift the string fuses)
4. Clip test leads to the buss bars

**Electrical measurement (repeat for each string):**

1. Insert a string fuse
2. Press “Measure”
3. View and save results
4. Lift the fuse

10-15 seconds, typically
1. Open the DC disconnect for the combiner where you will be making the measurement.
Measurement Process Example

2. Locate and open the combiner

Courtesy of Portland Habilitation Center and Dynaelectric Oregon
3. With a clamp-meter, verify that the load has been disconnected. Then lift all of the fuses.
4. Clip the curve tracer leads to the buss bars.
5. Push down one fuse at a time and make I-V curve measurements.
6. View and save results.
Data Analysis
Displays Generated by the I-V Data Analysis Tool*

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<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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*Optional, MS Excel-based tool, $95
Troubleshooting
I-V Curve Signatures of PV Problems

Any reduction of the knee of the curve means reduced output power.

Conventional measurements do not reveal many of these effects.
Useful diagnostics
Fill Factor, Current Ratio, Voltage Ratio

Fill Factor = \( \frac{\text{Imp} \times \text{Vmp} \text{ (watts)}}{\text{Isc} \times \text{Voc} \text{ (watts)}} \)

\[
\begin{align*}
\text{Current ratio} &= \frac{\text{Imp}}{\text{Isc}} \\
\text{Voltage ratio} &= \frac{\text{Vmp}}{\text{Voc}}
\end{align*}
\]

\[
\begin{align*}
\text{aSi:} & \quad 0.50 - 0.70 \\
\text{xSi:} & \quad 0.75 - 0.85 \\
\text{GaAs:} & \quad 0.85 - 0.9
\end{align*}
\]
String of Field-aged, Early TF Modules
Degraded fill factor, lower output power
High-resistance String

Anomalous slope in string I-V caused by single high-resistance module
Example of a Series Resistance Failure
At solder bond of PV output conductor to ribbon buss bar

Probably failure mode:
Heat cycling → bond degradation → resistive heating
Example of catastrophic bond failure

- Stress induced failure
- Failures of this type tend to occur at buss bar bonds and at connections of PV output cables to ribbon conductors
- I-V curve tracing can detect this problem before it becomes catastrophic
Dropped Cell String

- Shorted bypass diode, or
- Mismatch causing diode to turn on when current starts flowing
I-V Curves of Shaded Arrays
Bypass Diode Function
Bypass Diodes

Purpose:
• Prevent damage
• Preserve performance under mismatch conditions
Bypass diode turns on when the shaded cell(s) can no longer pass as much current as the non-shaded cells.
Shade One Cell
Example: 72-cell PV Module

Bypass diode turns on when the shaded cell(s) can no longer pass as much current as the non-shaded cells.
I-V Curve of a Partially Shaded String

- Multiple ‘knees’ → multiple ‘local’ power peaks
- Peaks evolve as shading configuration changes
- Inverter tries to find and track the highest peak

Power

Current

Voltage

Isc

Voc

Bypass diode turns on
Bypass diode thought experiment

Inverter operating at MPP

All cells:

In the next slide we’ll shade this cell
Bypass diode thought experiment

Inverter operating at MPP
Bypass diode thought experiment

Inverter operating at MPP
Shading an Unprotected Cell
Bypass diode failed ‘open’

Conditions:
- All 3 BP diodes removed
- Single cell shaded
- Output short circuited (worst case)

Heatong of a Single Shaded Cell
Backside temperature with no bypass diodes

Rise of 1°C per second
I-V Curve of a Partially Shaded String

- Multiple ‘knees’ → multiple power peaks
- Peaks evolve as conditions change
- Inverter tries to find and track the highest peak
‘Modular’ view of shading

3 cell strings/module
‘Modular’ view of shading

Signature of shading one full cell anywhere in the actual array

3 cell strings/module

I

V
Partially shaded residential array
Measure the single string mounted along lower edge of roof
I-V Curve of the partially shaded string
Single string mounted along lower edge of roof

Approximately 40% reduction in string’s output power
Shade 2 cells in the *same* cell-string

Single module with 72 cells and 3 bypass diodes

Shading one cell string drops 1/3 of PV module voltage and power
Shade 2 cells in adjacent cell-strings
Single module with 72 cells and 3 bypass diodes

The same amount of shade, oriented differently, drops 2/3 of PV module voltage and power.
Line Shade – Narrow
Shade one of two series connected modules

Pmax: 98%
Line Shade – Medium
Shade one of two series connected modules

Pmax: 91%
Line Shade – Thick
Shade one of two series connected modules

Pmax: 77%
Tapered shading
From adjacent row, parapet wall, railing, etc

- This effect produces an I-V curve deviation similar to that of shunt loss
- The tapered sliver of shade causes a slight current mismatch across cell groups and modules
- In tilt-up system, the impact of this shade is felt only early and late in the day, at low sun angles
- In general, inter-row shading losses are greater if rows are ‘crowded’ to increase peak capacity
Shade ‘taper’ across a cell-string
Single module with 72 cells and 3 bypass diodes
Intimate Shading
Solution: Rent a goat
Soiling
Soiling

- **Uniform**
  - Dust or grime, evenly deposited
  - Decreased irradiance, lower PV current

- **Non-uniform**
  - Dust ‘patterns’, debris, bird droppings
  - Mismatch effects, steps in the I-V curve
Examples of uniform & non-uniform soiling
Edge soiling (dirt dam)
Common in low-tilt arrays

The dirt dam hurt performance as much as all of the uniform soiling.
Troubleshooting Techniques
Selective Shading

Photo courtesy of Harmony Farm Supply and Dave Bell (shown)
Initial string measurement:
Step at 15% of normal current, 10-12 volt wide
Infrared imaging of PV arrays
IR signature of bypassed cell string

Cardboard shading a cell to force the bypass diode ‘on’

Measured using the FLIR i7 infrared camera

Center two columns of cells are slightly hotter
Module Inspection
Hot Spot on Module Buss Bar
Aerial Thermography
860kW System at Portland Habilitation Center, built by Dynalectric

Image courtesy of Oregon Infrared
http://www.oregoninfrared.com/
Field Applications of I-V Curve Tracers in the Solar PV Industry

IEEE Santa Clara Valley
PhotoVoltaic

November 14, 2012

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