Solar Simulation Standards and QuickSun® Measurement System

Antti Tolvanen
Endeas Oy
Endeas in Brief

- QuickSun® Solar Simulators
- Technology invented 1996 in Fortum (www.fortum.com)
- Endeas Oy licenses technology 2001
- Endeas today:
  ✓ > 500 simulators delivered
  ✓ turnover ~ 7 M€
Solar simulation

- Measurement of the electrical characteristics (most important $P_{\text{max}}$) of solar cells and modules at comparable and repeatable conditions
- International and national standards specify simulator performance requirements and measurement methods and conditions
- Done mainly to verify quality of solar cells and sort according to power, and to inspect and sort final products in PV module manufacturing. Important also in R&D.
- Standard testing conditions (STC)
  - 1000 W/m²
  - 25°C
  - AM1.5G spectrum
- Correction procedures for temperature and irradiance
Simulator types

- Steady state / constant light
  - Heat load, cooling, high power consumption
- Pulsed light
  - No heating of the sample
  - Fast measurement, no temperature leveling
- Pulsed light, decaying
  - Can measure easily at different irradiation levels
    - Measurement of series resistance
  - High peak irradiance easily reached
  - More refined analysis possible (IDCAM)
Measurement principle

Light flash

Solar module

QuickSun Electronics unit

Monitor cell

Temperature sensor

Irradiance Temperature

Ambient/Module Temperature

Flash trigger
Measurement principle, cont.

- Flash pulse is triggered, irradiance measured with monitor cell.
- When target irradiance level is reached, I-V measurement initiated. Typically at 1200 W/m\(^2\).
- Module is swept from short circuit to open circuit during the following approx. 2 ms. Voltage, current and irradiance signals are recorded simultaneously.
Measurement principle, cont.

- QuickSun hardware measures 4096 data points for each signal; current, voltage and irradiance.
- Data is averaged in groups of eight to obtain 512 raw data points. This reduces measurement noise.
- Measured raw data is corrected for irradiance and temperature to defined conditions.
- From the corrected raw data the I-V curve is obtained, with relevant measurement parameters.

![I/V Data](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>STC Measurement</td>
<td>1000 W/m², 25°C, AM 1.5G</td>
</tr>
<tr>
<td>Isc / Imp [A]</td>
<td>5.296 / 4.937</td>
</tr>
<tr>
<td>Voc / Vmp [V]</td>
<td>0.6189 / 0.5076</td>
</tr>
<tr>
<td>Pmp [W]</td>
<td>2.51</td>
</tr>
<tr>
<td>F.F.:</td>
<td>0.765</td>
</tr>
<tr>
<td>Cell eff. [%]</td>
<td>16.49</td>
</tr>
<tr>
<td>I / P @ 0.50V [A/W]</td>
<td>4.998 / 2.50</td>
</tr>
</tbody>
</table>
International Standards for solar simulation

- Solar simulator performance requirements
  - IEC 904-9 (2nd ed.)
- Cell and module measurement procedure
  - IEC 904-1 (2nd ed.)
- Irradiance and temperature correction procedures and coefficients
  - IEC 891 (2nd ed.)
Other relevant standards

• IEC 904-2 Requirements for reference solar devices
  – requirements for selection, packaging, calibration, marking and care of reference solar cells and modules

• IEC 1215 Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval
  – type approval: visual inspection, performance@STC, insulation test, determination of α and β, NOCT, performance@NOCT, performance@low irradiance...

• IEC 1646 Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval

• IEC 904-3 Measurement Principles for Terrestrial PV Solar Devices with Reference Spectral Irradiance Data

• IEC 904-7 Computation of Spectral Measurement of a PV Device

• IEC 904-8 Guidance for Spectral Measurement of a PV Device

IEC webstore: http://webstore.iec.ch/
Solar simulator performance requirements

- Standard IEC 904-9 describes the requirements for solar simulators.
- The three key aspects of solar simulator performance:
  - Positional non-uniformity
  - Spectral match
  - Temporal instability (short term, long term)
- Can be applied to all PV technologies, but spectral match criteria designed for c-Si
- For performance measurements a class CBA simulator is the minimum
  - (C = Spectrum, B = Non-uniformity, A = STI)
- LTI Specification for Irradiance exposure tests

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral match (ratio of the actual percentage of total irradiance to the</td>
<td>0.75 – 1.25</td>
<td>0.6 – 1.4</td>
<td>0.4 – 2.0</td>
</tr>
<tr>
<td>required percentage specified for each wavelength range)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-uniformity of irradiance</td>
<td>&lt; ± 2%</td>
<td>&lt; ± 5%</td>
<td>&lt; ± 10%</td>
</tr>
<tr>
<td>Temporal instability, short term, STI</td>
<td>&lt; ± 0.5%</td>
<td>&lt; ± 2%</td>
<td>&lt; ± 10%</td>
</tr>
<tr>
<td>Temporal Instability, long term, LTI</td>
<td>&lt; ± 2%</td>
<td>&lt; ± 5%</td>
<td>&lt; ± 10%</td>
</tr>
</tbody>
</table>

Minimum requirements
Positional non-uniformity

- Class A requirement: \(< \pm 2\%\>
- In practice, measured using the short circuit current of a single solar cell:

\[
\Delta E = \frac{E_{\text{max}} - E_{\text{min}}}{E_{\text{max}} + E_{\text{min}}} \cdot 100\%
\]

\(\Delta E\) = positional non-uniformity of irradiance
\(E_{\text{max}}\) = maximum value of irradiance (maximum \(I_{\text{SC}}\))
\(E_{\text{min}}\) = minimum value of irradiance (minimum \(I_{\text{SC}}\))

- Non-uniformity of QuickSun simulators is routinely checked and easily adjusted and maintained
- The positional non-uniformity of all QuickSun solar simulators is class A
Effects of non-uniformity

- Increasing non-uniformity affects IV curve
- Situation can be identified from elevated FF

- If non-uniformity affects only a part of the module, IV curve is deformed (when module has bypass diodes)

- Current mismatch of cells/strings causes same effects as non-uniform irradiance
- Poor non-uniformity causes problems with irradiance calibration. Module position and orientation affect result.
- If there are no bypass diodes, the effect is always as in left picture
Spectral match

- Defined as the ratio of actual irradiance to the percentage of total irradiance of reference spectrum in distinct wavelength ranges.
- Reference spectrum is AM1.5G
- QuickSun spectrum measured with OceanOptics spectrometer. TÜV using same technology.
- Measurement is triggered at the same instant as the actual I-V measurement, integration time is 3 ms.

![Graph showing spectral match]

<table>
<thead>
<tr>
<th>Wavelength interval [nm]</th>
<th>Percentage of total irradiance between 400 – 1100 nm, AM1.5G</th>
<th>Typical spectrum of QuickSun solar simulator [%]</th>
<th>ratio, class A: 0.75 – 1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 – 500</td>
<td>18.5</td>
<td>17.6</td>
<td>0.95</td>
</tr>
<tr>
<td>500 – 600</td>
<td>20.1</td>
<td>19.0</td>
<td>0.94</td>
</tr>
<tr>
<td>600 – 700</td>
<td>18.3</td>
<td>17.6</td>
<td>0.96</td>
</tr>
<tr>
<td>700 – 800</td>
<td>14.8</td>
<td>13.1</td>
<td>0.89</td>
</tr>
<tr>
<td>800 – 900</td>
<td>12.2</td>
<td>14.5</td>
<td>1.19</td>
</tr>
<tr>
<td>900 – 1100</td>
<td>16.1</td>
<td>18.2</td>
<td>1.13</td>
</tr>
<tr>
<td>400 – 1100</td>
<td>100</td>
<td>100</td>
<td>⇒ Class A</td>
</tr>
</tbody>
</table>
Spectral match, cont.

- Spectral effects can be corrected with Mismatch factor

\[ M = \frac{I_{\text{ref, AM1.5G}}}{I_{\text{ref, Simulator}}} \frac{I_{\text{Cell, Simulator}}}{I_{\text{Cell, AM 1.5G}}} \]

\[ I_{\text{ref, AM1.5G}} = \int SR(\lambda)E(\lambda)d\lambda \]

- Typically, the correction is small, only performed at institutes for reference measurements

- In practice, effects eliminated by using a matched reference cell/module
Temporal instability

- Short term instability (STI) refers to the change in light intensity during the acquisition of single data point.
- If irradiance is measured simultaneously with current and voltage, STI is class A.
- Long term instability (LTI) on pulsed solar simulators refers to the change in light intensity during the measurement of IV graph.
- Only STI of class A is required for performance measurements of solar devices.
- LTI specification is required for irradiance exposure tests.
Cell and module measurement

- Specifications in standard IEC 904-1
- Current and voltage measurement accuracy ± 0.2 %
  - In QuickSun systems data point averaging and software calibration improve accuracy
- 4-wire measurement
  - Standard feature of QuickSun
  - Measuring with only 2 wires causes a loss in Pmp
- Temperature measurement accuracy ± 1 °C
  - QuickSun measures monitor cell and ambient temperature with a precision IC sensors with 0.1 °C resolution and ± 1 °C accuracy
- Temperature within 25 ± 2 °C, if not, a correction to be made
  - Always corrected to desired temperature
- Bias voltage to enable measurement of true short circuit current
  - QuickSun measurement starts at zero voltage
  - Lack of bias can cause measurement errors in non-ideal modules
Effect of bias voltage and 4-wire measurement

Current [A] vs. Voltage [V]

- Without bias
- No 4-wire measurement

Solar module diagram:
- 4-wire measurement
- 2-wire measurement

AT 17
October 25, 2011
Cell and module measurement, cont.

• Calibration of the irradiance signal dominates the total accuracy in cell and module measurements.
• Absolute accuracy is determined by the accuracy of the $I_{SC}$ of the reference cell/module.
• Usually $I_{SC}$ measured by an institute (such as NREL, ISE, JQA, ESTI) has an accuracy of only 2 % (at best)
• Spectral response varies ⇒ Each cell type requires own reference
• The irradiance level is set and calibrated in the QuickSun system with better than 1 W/m$^2$ resolution
• With factory calibration the accuracy of QuickSun irradiance measurement is ± 3 % for silicon solar cells.
Calculation and correction of measured data

- Correction formulas given in IEC 891
- Current:

\[ I_2 = I_1 + \frac{G_1}{G_{SC}} I_{SC} \left[ \frac{G_2}{G_1} - 1 \right] + \alpha(T_2 - T_1) \]

  - Irradiance correction
  - Temperature correction

- Voltage:

\[ V_2 = V_1 + \beta(T_2 - T_1) - R_s (I_2 - I_1) - K I_1 (T_2 - T_1) \]

  - Temperature correction
  - Series resistance
  - Curve correction

- \( V_1, I_1, E_1, T_1 \) are actual measured voltage, current, irradiance and temperature
- \( V_2, I_2, E_2, T_2 \) are the corrected characteristics
- \( \alpha \) and \( \beta \) are temperature coefficients for current and voltage
- \( R_s \) is the series resistance
- \( K \) is the curve correction factor
QuickSun Compliance with IEC standards

- **IEC 904-9**
  - QuickSun simulators comply with AAA classification
  - Performance report is given with every simulator
- **IEC 904-1**
  - Measurement uncertainty complies with standard
  - Special requirements are standard features (e.g. 4-wire measurement, bias voltage)
- **IEC 891**
  - Correction is performed automatically
QuickSun Solar Simulators

• QuickSun 120CA Cell Solar Simulator
  – 120CA-HC for automated high capacity cell testing
  – 120CA-XL for mini-module testing

• QuickSun 200A String Solar simulator

• QuickSun 540LA In-Line Solar simulator
  – 540LA-XL for larger modules
  – 540LA-XLi measurement at production line height

• QuickSun 800-Series Module simulators
  – Test area/throughput depends on model
QuickSun® 120CA Cell Solar Simulator

- Single flash measurement system
- Class A spectrum
- ~ ±1 % typical non-uniformity
- Throughput:
  - Manual model 360 cells/hour
  - Automated model 1200 cells/hour
- Average flash lamp lifetime 500 000 flashes
- IDCAM option for detailed cell analysis
- Heating option for temperature coefficient measurements
- Option for Dark IV at reverse voltages
- 120CA-XL test area 40cm x 30cm for mini-modules
QuickSun 200A String Solar simulator

- Test area 20 x 200 cm²
- 360 measurements per hour
- Class CAA solar simulator (spectrum C, can be upgraded to A)
- Measures full IV curve
QuickSun® 540LA In-Line Solar Simulator

- In-line simulator with high throughput, 180 modules per hour
- Modules measured face down for easy production line integration
- Non-uniformity of the 190 cm x 110cm test area < 2 %
  - 540LA-XL for larger modules, max area 205 cm x 135 cm
- Compact, factory footprint saving size (1.6 x 1.7 x 3.0 m³) (H x W x L)
  - 540LA-XL slightly larger (1.8 x 2.1 x 3.4 m³)
- Class A Spectrum
QuickSun® 540LA-XLi
Inverted In-Line Solar Simulator

- Simulator installed on top of the production line
- Modules measured face up
- Size (2.7 x 2.1 x 3.4) m
- Specifications as 540LA-XL
QuickSun 800-Series Module Simulators

- Ideal for manual and semi-automatic module handling
- Measurement area between 1-6 m² with non-uniformity < 2%
- Length of flash tunnel reduced thanks to proprietary optics
- Throughput depends on model, 150 – 60 modules per hour.
- Can be assembled horizontally as a tunnel or vertically as a tower with module face up
- Longer flash pulse with add-on flash generator

<table>
<thead>
<tr>
<th>800-Series model no.</th>
<th>810A</th>
<th>820A</th>
<th>830A</th>
<th>850A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max module size [cm x cm]</td>
<td>80 x 125</td>
<td>120 x 200</td>
<td>150 x 220</td>
<td>220 x 260</td>
</tr>
<tr>
<td>Testing capacity [meas/hr]</td>
<td>150</td>
<td>120</td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td>Flash tunnel [m x m x m]</td>
<td>3.9x1.6x2.5</td>
<td>4.7x2.4x2.5</td>
<td>5.6x2.5x2.7</td>
<td>6.5x2.8x3.2</td>
</tr>
</tbody>
</table>
Common features of QuickSun simulators

- Single flash measurement
- Class AAA simulator (spectrum, non-uniformity, STI)
- Irradiance level adjustable, 200 – 1200 W/m², 1 W/m² resolution
- Current and voltage scales adjustable to any value, internal hardware optimizes measurement accuracy accordingly
- Good measurement reproducibility (< 0.25 %)
- Measurement of series resistance
- Proprietary 2-diode analysis option (IDCAM)
- User friendly Windows® software
Features of the QuickSun software

- Database for measurement product information (measurement data correction coefficients, module size, performance characteristics)
- Storing of multiple measurements in single file
- Printing of data sheet of measurement results
- Measurement data easily exported to other applications (text files) or directly to an external SQL database (Access, MySQL,...)
- Measurement results can be corrected to other temperatures
- Flexible sorting based on any measurement parameter ($P_{mp}$, $I_{sc}$, $V_{oc}$...)
- Label printing, barcode reader as an option
- TCP interface to connect to other factory equipment
- Option for PLC control
QuickSun software, cont.
IDCAM

- Irradiance Decay Cell Analysis Method
- Cell parameters of 2-diode model can be extracted from a single measurement

\[ I = I_{\text{sun}} - I_{\text{diff}} \left[ \frac{q}{e} \left( \frac{kT}{V + IR_{\text{ser}}} \right) - 1 \right] - I_{\text{rec}} \left[ \frac{q}{e} \left( \frac{kT}{V + IR_{\text{ser}}} \right) - 1 \right] - \frac{V + IR_{\text{ser}}}{R_{\text{shunt}}} \]

Graph showing voltage, current, and irradiance over time.
IDCAM, cont.
IDCAM, temperature analysis

Measured and calculated IV curves at 26.2 °C, graphs B. The same measurement data corrected to +75 °C and –25 °C; graphs A and C, respectively.
IDCAM, analysis cont.

Calculated and measured IV graphs at 1000, 800, 600 and 400 W/m².

Case A  Case B
Thank you for your attention

More information: www.endeas.fi

Antti Tolvanen
Endeas Oy
antti.tolvanen@endeas.fi