Solar Simulation Standards and QuickSun® Measurement System

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Endeas Oy
Endeas in Brief

• QuickSun® Solar Simulators
• Technology invented 1996 in Fortum (www.fortum.com)
• Endeas Oy licenses technology 2001
• Endeas today:
  ✓ > 200 simulators delivered
  ✓ turnover ~ 4 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/m$^2$
  – 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

Monitor cell

Temperature sensor

QuickSun
Electronics unit

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/m².
- 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 measures 4096 raw data points for each signal; current, voltage and irradiance.
- Data is averaged in groups of eight to obtain 512 I-V graph data points. This reduces measurement noise.
- Measured I-V data is corrected for irradiance and temperature to defined conditions.
- The I-V curve is obtained, with relevant measurement parameters.
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
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 $\alpha$ and $\beta$, 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 required percentage specified for each wavelength range)</td>
<td>0,75 – 1,25</td>
<td>0,6 – 1,4</td>
<td>0,4 – 2,0</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: < ± 2%
- In practice, measured using the short circuit current of a single solar cell:

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

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

<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

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

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

• 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.
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
- 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
Effect of bias voltage and 4-wire measurement
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 guaranteed accuracy of QuickSun irradiance measurement is ± 3 % for silicon solar cells.
Calculation and correction of measured data

- Correction formulas given in IEC 891
- Current:
  \[ I_2 = I_1 + I_{SC} \left( \frac{E_2}{E_1} - 1 \right) + \alpha(T_2 - T_1) \]
  - Irradiance correction
  - Temperature correction
- Voltage:
  \[ V_2 = V_1 + \beta(T_2 - T_1) - R_s (I_2 - I_1) - KI_2 (T_2 - T_1) \]
  - 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
Series Resistance (IEC 891)

\[ R_{s1} = \frac{\Delta V}{I_{SC1} - I_{SC2}} \]
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
- QuickSun 700A Large Area Solar Simulator
- QuickSun 540LA In-Line Solar simulator
QuickSun® 120CA Cell Solar Simulator

- Single flash measurement system
- Class A spectrum
- < 2% 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
QuickSun 700A Large Area Simulator

- Ideal for manual module handling
- Measurement area of up to 160cm x 220cm with non-uniformity < 2%
- Length of flash tunnel only 5.5 m / 4.5 m thanks to proprietary optics
- Throughput depends on area:
  - 60 modules/hour (160x220cm²)
  - 120 modules/hour (130x160cm²)
- Can also be assembled vertically as a tower with module face up
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%
  - Special model for larger modules, max area 205 cm x 135 cm
- Compact, factory footprint saving size (1.6 x 1.7 x 3.0 m³)
- Class A Spectrum
QuickSun® 540LA In-Line Solar Simulator
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 (CSV files) or directly to an external database (Access, MySQL)
- Measurement results can be corrected to other temperatures
- Label printing, barcode reader as an option
- TCP interface to connect to other factory equipment
QuickSun software, cont.
IDCAM

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

\[
I = I_{\text{sun}} - I_{\text{diff}} \left[ \frac{q}{e} \left( V + I R_{\text{ser}} \right) - 1 \right] - I_{\text{rec}} \left[ \frac{q}{2e} \left( V + I R_{\text{ser}} \right) - 1 \right] - \frac{V + I R_{\text{ser}}}{R_{\text{shunt}}}
\]

![Graph showing voltage, current, and irradiance over time](image-url)
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
Solar-Power report by TÜV (2005)

- Goal of the Solar-Power project was to develop harmonized procedures for PV module output measurements.
- SMEs combined efforts to improve their testing methods
- Improve power control
  - sorting in power classes
- Reduce manufacturing tolerances
  - strengthen market position
- Evaluation of solar simulator performance
Solar-Power report by TÜV, cont.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Type</th>
<th>Supplier, model</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPEG</td>
<td>Long-pulse</td>
<td>LEC, FS-PSS</td>
</tr>
<tr>
<td>3S</td>
<td>Steady-state</td>
<td>Tungsten halogen</td>
</tr>
<tr>
<td>Arctic Solar</td>
<td>Long-pulse</td>
<td>ENDEAS, QuickSun</td>
</tr>
<tr>
<td>Bluenergy</td>
<td>Steady-state</td>
<td>H.A.L.M., LED array (planned)</td>
</tr>
<tr>
<td>Millennium</td>
<td>Short-pulse</td>
<td>SPIRE, SPI-SUN</td>
</tr>
<tr>
<td>Solarwatt</td>
<td>Long-pulse</td>
<td>BERGER, PSS-8</td>
</tr>
<tr>
<td>Helios</td>
<td>Short-pulse</td>
<td>Self-development</td>
</tr>
<tr>
<td>Enfoton</td>
<td>Long-pulse</td>
<td>LEC, FS-PSS</td>
</tr>
</tbody>
</table>

Table 5.1.3: Available solar simulator systems in the project consortium

QuickSun only AAA simulator

- Irradiance non-uniformity: **class A**
- Spectral match: **class A**
- Temporal instability: **class A**

all others: BCA

Only QuickSun’s spectrum matches AM1.5G

![Graph showing spectral irradiance of solar simulators in the SME consortium normalised to AM 1.5 reference spectral irradiance.](image)

Figure 5.1.8: Spectral irradiance of solar simulators in the SME consortium normalised to AM 1.5 reference spectral irradiance.
Solar-Power, round robin

- Round robin test on all simulators and PV modules of different technologies
- QuickSun was top performer

Power of UniSolar module outdoors, measured by Endeas
Thank you for your attention

More information: www.endeas.fi

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