Indoor measurement of GTE-matrix for energy rating

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Abstract

Energy rating input data acquired indoors is currently based on IV curves measured in a matrix of irradiances (G) and temperatures (T). This can lead to uncertainties in the energy prediction as one needs to make additional corrections for the effects of spectrum (E) and angle of incidence. Energy rating measurements derived outdoors inherently take those variations into account and are more accurate for that reason, but take a long time to acquire and site to site differences might show up more strongly.

This paper demonstrates the first indoor GTE matrix measurements made with an LED-based solar simulator prototype, opening the possibilities of much faster and more accurate energy rating of PV devices. The experimental set-up and measurement method used is explained in detail. Analysis shows a respectable uncertainty of 3.2% (k=2) in maximum power measurements with scope for further improvement.

1 Introduction

Photovoltaic (PV) devices are normally characterised in a solar simulator that measures power rating at static standard test conditions (STC). This gives a very good snapshot of how a device performs under standardised conditions, but real operating conditions are very different and varying, resulting in operating efficiencies outdoors which typically are lower than that at STC. This is why energy rating of PV devices is becoming important for PV users as, unlike power rating under STC, it takes into account variations of environmental conditions. This leads to much better and clearer information of how a device performs in different climatic conditions and ultimately can determine more accurately the financial return of an installation.

Currently, for energy rating, devices are measured outdoors under real conditions or indoors in a matrix of different irradiances (G) and temperatures (T). Energy rating derived from outdoor measurements can be very accurate, but takes a time span of months or years, because many environmental factors are changing only on this time scale and even then, additional specialised measurement need to be undertaken to separate effects and achieve a site-independent rating. If measured indoors, one needs to correct the G-T measurements for the effects of spectrum (E) and angle of incidence, which can lead to large uncertainties in the energy prediction as they are strongly correlated, especially when working with multi-junction solar cells.

To solve this problem, one would need to measure the device in all required conditions of G, T and E as it would experience in real operation, which to date has been only possible outdoors. CREST has developed an LED-based solar simulator that can closely reproduce realistic outdoor conditions with varying spectrum, irradiance and device temperature. Thus, it meets requirements to carry out GTE-matrix measurements required for accurate energy rating. Indoors, this can be done in a much shorter time frame than is possible outdoors and opens possibilities to keep energy rating of photovoltaic devices up-to-date in line with product development timeframes for new devices.

In the following, the first GTE-matrix measurement results with a c-Si solar cell are presented. The measurement uncertainties of the new technique are analysed and explained.

2 Experimental arrangements

All GTE-matrix measurements for energy rating have been carried out using the LED-based solar simulator prototype developed at CREST and previously reported in [1]. The system uses 8 different LED colours and halogen light sources, all separately controllable, thus delivering a very flexible spectral output and light intensity control. Additionally, LEDs allow intensity adjustments with only minimal changes in spectral output, a requirement for accurate intensity changes at the same spectrum. For device temperature control the simulator uses a peltier stage system. This is capable of regulating device temperature from 0°C to 80°C in 0.1°C steps, in reality only temperatures down to 15°C are used due to condensation on the device’s surface.
3 Measurement methodology

As visible in Figure 1, the measurement method consists of 3 main steps; defining measurement ranges, adjusting simulator light output to reference spectra and measuring the GT-matrix at all spectra.

**Define measurement ranges:** sunlight spectra (E), light intensity (G) and device temperature (T)

**Simulator output spectrum adjustment with help of reference cell or test device EQE**

**Measure test device at set variations of intensities and temperatures**

**Test device GTE matrix for energy rating**

*Figure 1: basic measurement method for measuring a GTE matrix*

When defining the measurement ranges it is important to use measurement points in the GTE-matrix that are of most interest and generally seen outdoors. This is important, as the number of measurements can be very large and is dependent on the number of different spectra, intensities and temperatures chosen.

Prior to making a GT-matrix measurement set at a given spectrum, the solar simulator output spectrum must be adjusted by separately altering the intensity of each of the available light sources in the solar simulator. The required intensity of each light source colour can be acquired with help of a fitting algorithm that minimises the deviation between the required sunlight spectrum to the spectrum in the solar simulator. Once the required intensities are known, the light spectrum can be set with the help of the external quantum efficiency (EQE) curve of the device under test or, if a closely matched reference cell is available, with help of the reference cell EQE. If the test device has more than one junction it is important that the junction current balance remains the same as it would experience under the reference spectrum.

Once the solar simulator light spectrum has been adjusted, a light intensity and temperature (GT) matrix can be measured. In this case it is important is, that the light sources in the simulator have minimal change in their output spectra with varying intensity. If this cannot be maintained, a re-adjustment of the solar simulator spectrum is required for each intensity step.

4 Measurement configuration

The first GTE-matrix measurements have been carried out with a non-encapsulated 30x30mm² single junction mono-crystalline silicon solar cell fabricated at CREST. The measurement ranges in the GTE-matrix (see Figure 2) have been defined by using five spectra (as stated in Table I). For each spectrum, the device IV curve was measured in a GT-matrix with five device temperatures (15°C to 55°C) and 12 intensities from 5% to 100% of the maximum irradiance possible (Table I) under the given spectral conditions (Figure 3).

*Figure 2: Measurement points in a GTE-matrix*

<table>
<thead>
<tr>
<th>Solar spectrum</th>
<th>Irradiance comparison of reference sunlight and solar simulator spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM1.1</td>
<td>1019 803</td>
</tr>
<tr>
<td>AM1.5</td>
<td>1000 765</td>
</tr>
<tr>
<td>AM2.0</td>
<td>904 713</td>
</tr>
<tr>
<td>AM3.0</td>
<td>723 655</td>
</tr>
<tr>
<td>AM4.0</td>
<td>599 620</td>
</tr>
</tbody>
</table>

*Figure 3: Reference and simulator spectrum; all output spectra used are within class B*

The test device IV-curves were measured in forward direction with a resolution of 200 points. Total measurement time per curve was 20ms. The solar cell was positioned with thermal conductive gap filler onto the temperature
conditioning stage in the solar simulator for best thermal conductivity and temperature homogeneity.

5 Measurement results

5.1 Spectral behaviour

The measured short circuit current (I_{SC}) over G behaviour at a constant spectrum is linear (Figure 4), which is as expected from a linear c-Si device and also indicates that the irradiance control in the simulator works accurately.

![Figure 4: I_{SC} over G at varying E at 25°C](image)

In regards to variation of the spectrum, it has been observed that with increasing air mass the current generation in the device also slightly increases as visible in Figure 4. This as well is as expected due to the spectrum changing at a higher rate in the ultraviolet to red (300-700nm) low energy region than in the high energy infrared region where the spectral response of the c-Si solar cell has its peak. The same effect can be seen on the efficiency, which is significantly higher in the red rich high air mass spectra (Figure 5).

As visible in Figure 6 and Figure 7, the influencing factor on the increase of efficiency at higher air mass is current at maximum power point (MPP), MPP voltage and fill factor are not affected.

![Figure 7: MPP voltage and current behaviour over irradiance at different sunlight spectra](image)

5.2 Irradiance – temperature behaviour

In Figure 8 the temperature and light intensity influences on the efficiency are clearly visible. As seen on the CREST outdoor measurement system data and reported in [2] efficiency increases sharply in the low intensity ranges and flattens out at high intensity. Furthermore, efficiency decreases linearly with temperature.

![Figure 8: GT-efficiency plot at AM1.5 spectrum](image)

This pattern is largely followed, but slightly different looking at the fill factor (Figure 9). The difference is that the fill factor reaches a maximum point at 400W/m² and slightly decreases at higher irradiances (see also Figure 6). The effects measured are due to the linear MPP current behaviour over irradiance and the nonlinear behaviour of MPP voltage as shown previously in Figure 7.

The temperature coefficients of the recorded IV-curve parameters, illustrated in Figure 10,
are within expected ranges for a c-Si solar cell and as seen on the CREST outdoor monitoring system; the non-linear behaviour at low intensities is clearly visible.

Figure 9: GT-fill factor plot at AM1.5 spectrum

Figure 10: Temperature coefficients of IV parameters extracted under AM1.5 spectrum

6 Measurement uncertainty analysis

To determine the level of confidence in the IV measurements, an uncertainty calculation was carried out according to ISO/IEC Guide 98-3 [3] and with help of [4]. The influencing factors can be grouped into 4 main sections:

- Data acquisition and calibration
- Temperature meas. and conditioning
- Spectrum and irradiance meas. and control
- Device mounting and connections

The uncertainty calculations have been made with respect to the IV curve measurement at AM1.5 spectrum with maximum intensity; the uncertainties at low intensities will be larger (which is a general case). Furthermore, it is important to mention that uncertainty influences due to EQE measurements have not yet been analysed and are thus not included.

Table II shows a summary of the uncertainties in the main IV-curve parameters.

The largest influence on the voltage uncertainty (0.29%, coverage factor k=1) is due to the currently un-calibrated temperature sensor used for measurement and device condition-

Table II: Absolute uncertainty on IV measurements at 765W/m² and AM1.5 spectrum

<table>
<thead>
<tr>
<th>Measurement Parameter</th>
<th>Uncertainty [%]</th>
<th>Combined k=1</th>
<th>Expanded k=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance</td>
<td>± 1.429</td>
<td>± 2.859</td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>± 0.308</td>
<td>± 0.617</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>± 1.517</td>
<td>± 3.034</td>
<td></td>
</tr>
<tr>
<td>Fill Factor</td>
<td>± 0.298</td>
<td>± 0.596</td>
<td></td>
</tr>
<tr>
<td>Pmax</td>
<td>± 1.574</td>
<td>± 3.148</td>
<td></td>
</tr>
</tbody>
</table>

7 Conclusions and future work

A new method for measuring a GTE-matrix indoors for energy rating has been explained and successfully carried out in the LED-based solar simulator developed by CREST. The first ever GTE-matrix measurement results derived indoors with a c-Si solar cell show a good agreement to measured behaviour outdoors, proving that indoor GTE measurements can be carried out accurately in a much faster time than is possible outdoors.

An uncertainty analysis shows that measurements can be trusted. Uncertainties can and will be largely reduced with better calibration accuracies and with better control hardware for the 2nd incarnation of the solar simulator, currently under development.

In the near future, measurements will be carried out on other device technologies as such as amorphous silicon and also on multi-junction solar cells. Measurements will be validated against outdoor data.

Acknowledgements

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References