Uncertainty contributions in photocurrent linearity measurements of PV devices using a flash solar simulator

This item was submitted to Loughborough University's Institutional Repository by the/an author.

Citation: BLISS, M. ...et al., 2017. Uncertainty contributions in photocurrent linearity measurements of PV devices using a flash solar simulator. 13th Photovoltaic Science, Application and Technology Conference (PVSAT-13), Bangor, UK, 5th-7th April 2017.

Additional Information:
- This is a conference paper.

Metadata Record: [https://dspace.lboro.ac.uk/2134/28290](https://dspace.lboro.ac.uk/2134/28290)

Version: Accepted for publication

Publisher: © The Solar Energy Society

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: [https://creativecommons.org/licenses/by-nc-nd/4.0/](https://creativecommons.org/licenses/by-nc-nd/4.0/)

Please cite the published version.
Uncertainty Contributions in Photocurrent Linearity Measurements of PV Devices using a Flash Solar Simulator

M. Bliss*, B.V. Mihaylov, G. Koutsourakis, T.R. Betts, R. Gottschalg
Centre for Renewable Energy Systems Technology (CREST), Wolfson School Mechanical, Electronic and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK
*Corresponding Author M.Bliss@lboro.ac.uk

Abstract
Especially for reference devices, the linearity of photocurrent over irradiance is an important characteristic that requires a low measurement uncertainty. This work investigates the uncertainty contributions when using a typical flash solar simulator with attenuation masks to determine the linearity characteristics of a device. Due to the complexity in measurement correlations, a Monte-Carlo simulation model was developed to estimate the final uncertainty. Results show that attenuation masks are not necessarily spectrally neutral and, if left uncorrected, this can significantly impact the measurement results. Furthermore, uncertainty in linearity is also dependent on the linearity of the sample under test itself. A shunted, non-linear device can have double the linearity uncertainty in low light conditions than a similar, linear sample.

1 Introduction
The linearity of photocurrent output over irradiance incident on a solar cell is an important factor especially for reference devices. In solar simulator measurements, reference PV devices are used to set and monitor the irradiance incident on the device under test (DUT). Thus, a non-linear reference cell can cause direct undesirable errors on performance measurements. Similarly, a nonlinear monitoring device in the field affects irradiance measurements of the PV system and leads to wrong interpretation of total system performance. International standards require a reference device to be linear over the range of interest [1]. Furthermore, the energy rating standard [2, 3] requires linearity to be measured on tested modules. If found to be linear, spectral response measurements and measurements under varying irradiance and temperature can be significantly simplified. Hence, high levels of uncertainty can lead to higher testing costs or errors in the predicted energy output.

Multiple methods are detailed in the IEC60904-10 [4] standard for linearity measurements of a PV device. The first two methods acquire linearity with use of a reference device under either outdoor sunlight or indoor solar simulated light. The 3rd applies the two lamp method first reported in [5] and does not require a reference. In this work, the solar simulator method was applied using a typical flash solar simulator with attenuation masks to measure linearity of small solar cells up to full sized modules. The specific requirements of light uniformity and spectral stability when changing the solar simulator intensity can introduce some issues when using this method. If these requirements are not met, a device under test (DUT) can quickly be falsely identified as non-linear or its non-linearity corrections will have large uncertainties attached to them. To gain an insight into the measurement uncertainty when using the outlined set-up, a full analysis of the measurement uncertainty has been carried out. Due to the extra complexity of linear fitting to calculate the non-linearity and because of significant correlations between measurements at different light intensity, this work utilises the Monte-Carlo method to estimate the final linearity measurement uncertainty.

The measurement configuration and the employed method with applied corrections are described in detail. The uncertainty contributing factors with the uncertainty model are explained. The impact of uncertainty is discussed on three measurement cases.

2 Measurement Equipment and Method
A Pasan 3B flash solar simulator was used for linearity measurements. The system was modified with an external 16bit data acquisition (DAQ) system. The irradiance is adjusted via four attenuation masks (10, 20, 40 and 70% transmittance) and via ±10% lamp intensity adjustment. Reference cell (RC) and DUT are under the same illumination and are set at a room temperature of 25±1°C. The spectral output of the pulsed light is measured in situ using a CCD spectroradiometer. Each point in the linearity curve is an average of four measurements.

3 Uncertainty contributing factors
Uncertainty is considered separately for short circuit current (\(I_{SC}\)), irradiance (\(G\)) and current linearity (\(LI\)). The evaluation of uncertainty in \(I_{SC}\) and \(G\) is not explained in detail. Instead, this work focusses on the specific factors influencing \(LI\) uncertainty (\(ULI\)) because it does not directly translate from uncertainty in \(I_{SC}\) and \(G\) (\(U_{I_{SC}}\) and \(U_{G}\)). It is mostly effected by relative changes in conditions, since absolute uncertainty factors such as RC calibration and current scale are fully correlated and have no impact on \(LI\) itself.

### 3.1 Reference cell non-linearity

Since the RC is used as a linearity reference, it has a direct influence on \(U_{LI}\). In the presented case, the RC \(LI\) was measured using the two-lamp method in a custom set-up with a maximum non-linearity of 0.1\%. This method, as detailed in [4, 5], does not require a reference, but also does not measure a continues curve but only the linearity between two points. The intermittent data points can be translated into a curve that can be used to correct for the non-linearity of the RC (see [6]). However, in this work, the RC \(LI\) has not been corrected, due to its high linearity. Apart from verifying the RC linearity, the results of the two-lamp linearity measurement also provide an uncertainty value.

### 3.2 Spectral mismatch factor (MMF)

During this work it has been observed that the spectral output of the flash lamps changes significantly with lamp intensity, as well as when changing the attenuation masks. This has been corrected for using in-situ spectral measurements. The absolute value of MMF only affects \(G\) and \(I_{SC}\). However, the relative variation of the MMF between measurements at different irradiances does contribute to \(U_{LI}\). This relative uncertainty depends strongly on how well the true value of the MMF is represented overall and on the repeatability of spectral measurements.

### 3.3 Temperature variations

As long as the linearity of the DUT itself is not affected by the temperature, static deviations to the 25°C given in standard test conditions do not contribute to \(U_{LI}\). However, the variation of the RC and DUT temperature between measurement points does affect linearity, depending on the temperature coefficient and degree of temperature change.

### 3.4 Light intensity uniformity

In theory, any static variations of light intensity uniformity affect only current and irradiance measurements of the DUT and RC. However, \(LI\) is directly affected by changes in uniformity between RC and DUT. Those can be introduced when adjusting the intensity using attenuation masks. This effect has been measured on RC sized samples with a 2x2cm active area by swapping the positions of the RC and DUT (see Table 1). For larger samples the uniformity variation can only be estimated using full uniformity field measurements and thus may not be as accurate.

### 3.5 Spectral uniformity

Similar to light intensity uniformity, spectral uniformity affects \(LI\) only if it varies during the linearity measurement. Measurements of the spectrum at various positions over the solar simulator target area demonstrate that spectral non-uniformity worsens significantly when higher density attenuation masks are used, as presented in Figure 2. The spectral variations have been corrected when measuring small devices, but such a correction becomes impractical with larger DUTs and modules due to the size difference in the spectroradiometer detector input and the sample.

### Table 1: Spatial uniformity correction; measured deviation of irradiance corrected \(DUT\) \(I_{SC}\) between swapped RC and DUT positions and correction factor applied.

<table>
<thead>
<tr>
<th>Mask</th>
<th>(\Delta DUT I_{SC})</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Mask</td>
<td>-0.27%</td>
<td>1.0013</td>
</tr>
<tr>
<td>70%</td>
<td>-0.40%</td>
<td>1.0020</td>
</tr>
<tr>
<td>40%</td>
<td>-0.06%</td>
<td>1.0003</td>
</tr>
<tr>
<td>20%</td>
<td>-0.43%</td>
<td>1.0022</td>
</tr>
<tr>
<td>10%</td>
<td>-0.83%</td>
<td>1.0042</td>
</tr>
</tbody>
</table>

### Figure 1: Deviation between spectrum at spectroradiometer and at sample position; a change in spectrum is observed in the 800-1050nm region.

A point-by-point irradiance correction to the average measurement irradiance was applied to the current measurements of the DUT. The contribution to \(U_{LI}\) lies mainly in the irradiance and current signal noise and digitalisation error. The \(I_{SC}\) was extracted by linear regression. The final contribution to \(U_{LI}\) is dependent on the irradiance corrected current signal noise and the number of fitting points used, assuming that the IV curve of the DUT is linear around the \(I_{SC}\) point.
3.7 Signal data acquisition

ULI is unaffected by static signal scale and offset calibration errors. Only if the measurement range is changed within a LI measurement cycle the relative changes in scale and offset contribute to ULI. Another factor to include is the signal drift due to external short term effects such as temperature variation.

The relative digitalisation error and signal noise increases with reduction in signal and adds to ULI due to its random nature. The digitalization error is in many cases much smaller than noise, but can have a much larger impact on low resolution DAQ systems (i.e. 12 instead of 16bit). The Linearity of the measurement signal conversion itself does impact ULI, but is normally negligible compared to other effects.

3.8 Linearity measurement repeatability:

Even though the repeatability of linearity measurements should be fully represented when an uncertainty calculation is complete, it is useful to add the measured repeatability into the calculation to make sure factors not considered are included. The repeatability uncertainty is the variation in the mean value over the measurements taken.

4 Determining final uncertainty

Because it is difficult to estimate the final uncertainty contributions on linearity by direct calculation and due to its dependence on the actual DUT linearity, the Monte-Carlo method was applied. The measurement process was modelled with the uncertainty sources introduced at the point at which they are generated. Figure 3 shows the complete model flow chart. Inputs of the model are the uncertainty specifications, measured RC irradiance and DUT Isc and other conditions such as mask type, spectral uniformity correction factor and measurement repeatability. The outputs are the final uncertainty for Isc, G and L1.

5 Case Study Results

To demonstrate the behaviour of ULI in different cases, results of three samples are presented. The first DUT is a 600nm long pass filtered reference cell to highlight measurement deviations induced by spectral changes in the light. The second is a highly non-linear shunted cell of the same size than the first DUT to observe uncertainty in extreme cases. The third is a full size poly-crystalline PV module.

<table>
<thead>
<tr>
<th>Factor (U k=1)</th>
<th>Small DUTs</th>
<th>Module</th>
<th>Distr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isc Static [%]</td>
<td>0.25</td>
<td>0.25</td>
<td>Gauss</td>
</tr>
<tr>
<td>G Static [%]</td>
<td>1.3</td>
<td>1.3</td>
<td>Gauss</td>
</tr>
<tr>
<td>MMF [%]</td>
<td>0.1</td>
<td>0.2</td>
<td>Gauss</td>
</tr>
<tr>
<td>Temp. [°C]</td>
<td>1</td>
<td>1</td>
<td>Rec</td>
</tr>
<tr>
<td>RC L1 [%]</td>
<td>0.1</td>
<td>0.1</td>
<td>Gauss</td>
</tr>
<tr>
<td>Uniformity [%]</td>
<td>0.2</td>
<td>0.4</td>
<td>Rec</td>
</tr>
<tr>
<td>Isc Noise [µA]</td>
<td>42</td>
<td>600</td>
<td>Gauss</td>
</tr>
<tr>
<td>Isc Offset [µA]</td>
<td>200</td>
<td>6600</td>
<td>Rec</td>
</tr>
<tr>
<td>Isc Digital [µA]</td>
<td>10</td>
<td>330</td>
<td></td>
</tr>
<tr>
<td>G Noise [W/m²]</td>
<td>0.2</td>
<td>0.2</td>
<td>Gauss</td>
</tr>
<tr>
<td>G Offset [W/m²]</td>
<td>1</td>
<td>0.1</td>
<td>Rec</td>
</tr>
<tr>
<td>G Digital [W/m²]</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Isc Points</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Nu meas.</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Uncertainty factors and distribution for RC size DUTs and full modules used in Monte-Carlo simulation model.

Table 2 details the uncertainty parameters used for ULI simulations. The main difference between small DUTs and the module is that for

![Figure 2: Monte-Carlo simulation flow chart for calculating final Isc, G and L1 uncertainty.](image-url)
small samples, data was additionally corrected for light intensity and spectral non-uniformity. Due to the size of the DUT, those corrections are not possible for the case of the PV module. Furthermore, the spectral response (SR) of the small samples was measured in a dedicated system and the SR of the module was measured in the solar simulator using a spectral fitting method, described in [7]. This increases uncertainty in MMF calculations.

6 Conclusions

This work details the uncertainty contributing factors when measuring photocurrent linearity using a solar simulator with attenuation masks. An uncertainty calculation model has been developed that uses the Monte-Carlo method to estimate the final linearity measurement uncertainty.

Linearity measurement results show that it is critical to correct for spectral variations that occur in a solar simulator when adjusting the intensity using attenuation mask or by changing the lamp power. The uncertainty in current and irradiance does not directly translate to linearity uncertainty. Furthermore, uncertainty in linearity is dependent on the device linearity itself. Thus, it is recommended to assess uncertainty especially for highly non-linear devices separately. This increases trust in measurements and in linearity correction.

Acknowledgements

The research work leading to this article was carried out within the EMRP ENG55 project Towards an Energy-based Parameter for Photovoltaic Classification. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

References