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Initial Solar Cell Characterisation Test And Comparison With A LED-Based Solar Simulator With Variable Flash Speed And Spectrum

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Abstract

A continues-wavelength LED-based solar simulator has been developed to optimise the measurement of solar cells. It achieves more than one Sun intensity over an area of 200x200mm². Use of LEDs as the main light source enabled advanced functions like variable flash speed and shape and variable spectrum.

The simulator hardware is described briefly and simulator classification results are given. Initial measurements with error analysis of a mono crystalline silicon solar cell are presented, proofing that a LED-based solar simulator has potential to outperform today's state of the art solar simulators.

1 Introduction

Advances in photovoltaic technology have increased device complexity and introduced new characterisation challenges. The two main solar simulator types in use for this purpose, the steady state and the flash simulators, each have advantages and disadvantages regarding practicality of use and breadth of applicability. The output spectrum of some solar simulators is only adjustable within very narrow margins. Generally only light intensity and module temperature can be varied, which is mainly due to the light sources used in current simulators.

Due to their unique characteristic, replacing conventional light sources such as Xeon, Halogen and HMI light sources with LEDs opens possibilities for much wider variability of the artificial light conditions and measurement control. The ability to keep LEDs stable for a long time or to control them rapidly, i.e. within microseconds, combines a steady state and a flash solar simulator with additional functions such as variable flash frequencies and flash shape. High power LEDs are available in colours over the whole spectrum from ultraviolet to infrared. With their narrow wavelength output, an AM1.5G spectrum can thus be accurately represented with its intensity and additionally adjustable spectral output is possible. With the up to 50.000h life

expectancy, maintenance costs are reduced to a minimum. Because of those advantages a continues-wavelength LED-based solar simulator prototype (Figure 1) has been developed, achieving more than one Sun intensity over an area of 200x200mm².

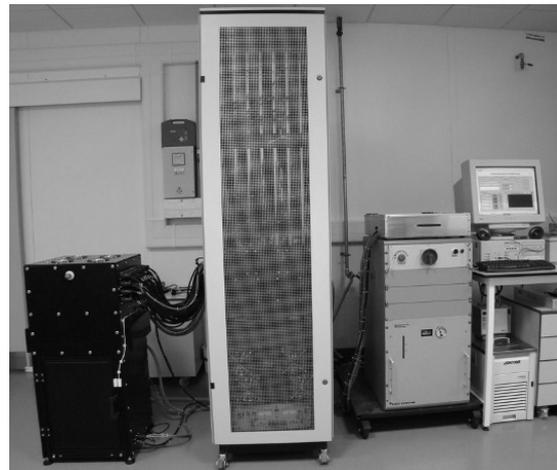


Figure 1: LED-Based solar simulator

2 Simulator hardware

The simulator LED array consists of several hundred LEDs in 8 different colours, to cover the light spectrum from the ultraviolet at 375nm to the red at 680nm. In this prototype, halogen lights are used to cover the infrared part of the spectrum, while developments are ongoing to replace this with LEDs in the final product. The area of the light sources is 380x380mm and the distance to the illuminated test area is 650mm. The LEDs colours were chosen for matching the airmass (AM) 1.5G spectrum used in standard test conditions (STC) [1].

The control system allows independent control of the intensities of all light sources. This makes it possible match the AM1.5G spectrum, as well as to simulate the change from blue rich to red rich spectra, as seen in realistic outdoor conditions. The light source control allows LED flash frequencies of up to 500Hz in all imaginable flash shapes. Single or multiple flashes are easily implemented making this a useful tool for scientific investigations of different types of solar cells.

The I-V curve is traced by an analog 4-quadrant high-speed operational amplifier. Measurement speed is fully adjustable and can be as short as 10µs per measurement point, including regulation delays of the I-V tracer and sampling period.

A PV device temperature control system is capable of regulating the test device temperature from 10 to 80°C.

The simulator is controlled by a computer with in-house developed LabVIEW software.

3 Simulator Classification

The aim was to develop a simulator that is capable of class A. In the following the prototype is assessed as class B, which allows room for improvement for the final system.

3.1 Temporal instability

The long term stability (LTI) of the different light sources (Table I) has been measured with a silicon pyranometer centred in the test area.

Measurement conditions and setup	Meas. Time	Temporal Instability [%]	Class
All LEDs	10ms	±1.14	A
All LEDs	100ms	±2.02	B
All LEDs	1s	±4.03	B
Halogen light	2.5s	±0.28	A
Halogen light	25s	±1.49	A
All light sources (25s warm-up)	24h	±4.72	B
All light sources (15m warm-up)	24h	±0.34	A

Table I: Temporal instability and classification

Irradiance changes during measurement time are mainly due to LED dye temperature rising and warm-up of electrical components in the regulation circuits. With care during set-up a class A LTI can be always maintained for IV measurements.

The irradiance and current and voltage of the device under test are measured simultaneously as required by the IEC60904-9 edition 2 standard [2], which classifies the short term stability (STI) as class A

3.2 Spectral output

To demonstrate the spectral variability, the spectrum has been measured in the centre of the illuminated area in two different configurations (Figure 1): full intensity with all light sources at maximum output without any further adjustments and optimised (by simplex fitting) for best matching to the AM1.5G spectrum.

The spectral classification according to IEC60904-9 [2] is summarised for the optimised spectral output in Table II. The full intensity case results in a class C characteristic. Adjusting the intensity of the different light sources achieved a class B spectral match.

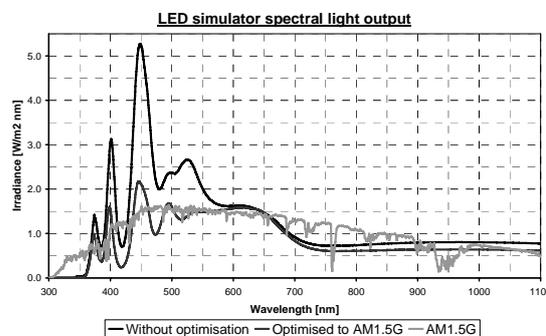


Figure 2: Simulator spectral light output

Wavelength interval [nm]	Measured optimised spectrum	
	Relative Error	Class
400 – 500	0.997	A
500 – 600	1.128	A
600 – 700	1.117	A
700 – 800	0.661	B
800 – 900	0.762	A
900 – 1100	1.213	A
Total	-	B

Table II: Spectral match classification

3.3 Homogeneity

A thermopile pyranometer was used to measure the light intensity over a 220x220mm² field at 20x20mm² resolution, as this detector is not so susceptible to spectral variations. A warm-up time period of electronics and light sources for intensity stabilization was included.

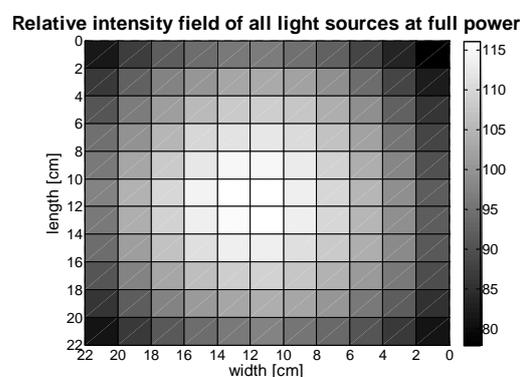


Figure 3: relative intensity field of all light sources at full power

As visible in Figure 3, the non-uniformity classification of all light sources at full power over the full area of 220x220mm² is ±19.6% - well outside the boundary of standard classification. Reducing the test area to 140x140mm² decreases non-uniformity to ±8.0% (Class C). On an area of 100x100mm² we achieve a Class B with ±4.0% [2]. Class A classification with ±1.5% non-uniformity has been achieved in an area of 60x60mm². Further homogeneity measurements of each individual LED colour and the halogen lights have shown that the intensity pattern changes slightly, which means that the spectral output is also changing over the illuminated area. However, due to the electronic system used in the simulator, it is possible to adjust the intensity of each light source separately, which would improve the situation significantly.

4 Solar Cell Characterisation

The test device used for the initial IV-curve measurement test is a calibrated mono crystalline silicon solar cell, normally used as a reference cell. The cell area is 400mm², which means that the homogeneity of light illumination can be classified as class A for this device.

4.1 Measurement methodology

The solar cell has been measured in a single flash set-up with a start-up time of 2.5s for the halogen lights and 2ms for all LEDs to stabilise in prior to the actual measurement time of 12.5ms. Each measurement was carried out in forward and reverse bias with each 50 points to ensure that i.e. no capacitive effects are introduced [3]. For each point a voltage settling time of 100µs and measurement time of 25µs was allowed. During the 25µs measurement period the current, voltage and irradiance was measured simultaneously 15 times and then averaged for signal noise reduction.

Because the reference cell was actually the test device, a K&S SPLite silicon pyranometer was used for irradiance stability measurements. This has a time constant similar to that of solar cells and thus can detect changes of relevance to the solar cell.

The simulator light output spectrum was set to AM1.5G as mentioned in section 3.2.

The temperature of the test device was regulated to 25°C as required for STC [1].

4.2 Measurement result without corrections

The c-Si reference cell was measured 3 times with approximately 1½ minutes time in-between the measurements for normalisation of light source and device temperatures.

Figure 4 shows the uncorrected measurement results in comparison to the real IV-curve extracted from the calibration certificate of the solar cell.

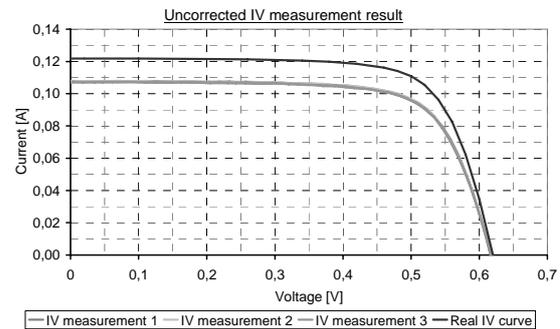


Figure 4: Uncorrected IV measurement result

Stability measurements of irradiance (Figure 5) have shown a temporal instability of less than ±0.1% [2] with a slight drop down to the end of measurement time.

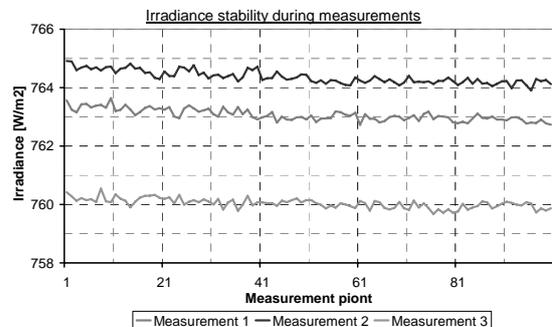


Figure 5: Irradiance stability during measurements

The device temperature, manually measured with a K-type meter, was constant at 24.8°C.

4.3 Spectral mismatch / Irradiance correction

The spectral mismatch between the AM1.5G and the simulator output spectrum was calculated according to the BS 60904-7 [4] standard using the spectral response measurement data from the test device calibration certificate and the spectral data of the simulator output and the AM1.5G spectrum [3]. Calculated was an I_{SC} of the reference cell under AM1.5G spectrum of 124.8mA and under simulator spectrum of 107.6mA. This results in spectral mismatch of -13.81%. Main reason for the spectral mismatch for being so high is the difference in total irradiance, which was measured at 685W/m² until 1100nm and not 802W/m² as prescribed in the standard AM1.5G spectrum. Also the I_{SC} of 121.8mA given in the calibration certificate differs from the calculated value.

Since an un-calibrated silicon pyranometer was used for irradiance stability measurements and the reference cell was measured, it is not possible to calculate the irradiance correction according to IEC 60891 [5] with the measured I_{SC} and the I_{SC} under STC. For this reason the current correction was carried out using the theoretical I_{SC} calculated from the spectral response curve of the reference cell and the incidence spectrum of the simulator. Figure 6 shows the result of the current and voltage irradiance correction. Temperature correction was not required.

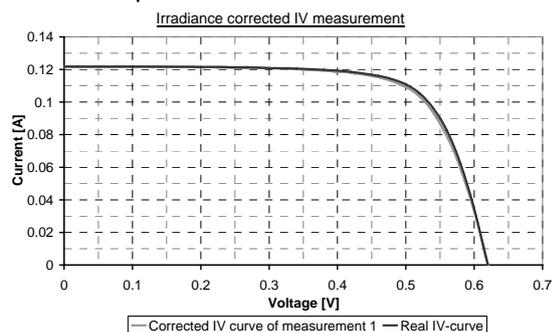


Figure 6: Corrected IV measurement

Table III shows a comparison between corrected values from the measurement and real values from the calibration certificate of the solar cell.

Value	Corrected values	Calibration values	Deviation
VOC [mV]	620.6	620,0	0.10%
ISC [mA]	121.8	121,8	0.00%
VMP [mV]	501.0	500,4	0.12%
IMP [mA]	109.3	110,8	-1.35%
PMAX [mW]	54.75	55,44	-1.24%
FF [%]	72.4	73,4	-1.30%
Eff. [%]	13.7	13,9	-1.53%

Table III: Comparison of values

4.4 Error analysis

Despite the fact that no calibrated reference device was available during the measurement and the irradiance and spectrum was estimated to be as measured before with a spectroradiometer the error is quite small, bearing in mind that spectroradiometer calibration and accuracy also has an impact on the total error.

Errors occur in voltage and current measurements as well, whose accuracies are not within the specified range of $\pm 0.2\%$ [6], because of introduced noise, albeit work is going on to meet standard specifications. Furthermore, the 4-wire measurement connection could not be made directly on the busbar of the reference cell test device, which

introduces series cable resistance and has mainly impact on maximum power output, fill factor and efficiency.

5 Conclusions

An initial PV device measurement test has shown that even with shortcomings of a calibrated reference device for irradiance stability and correction the overall error was in the range of 1.6%.

Improvements will be made as far as possible on the prototype to provide highly accurate measurements also for unknown test devices.

The shortcomings of the prototype will be improved upon in the final unit. Furthermore, the rapid improvement of LEDs will make the overall energy delivery, spectral matching and control even better.

The LED-based simulator opens many possibilities for the analysis of PV devices. The prototype is not yet ready to outperform state-of-the-art solar simulators, but with the amount of improvements possible for this and the next version and the high flexibility in measurements it provides the ideal base.

Acknowledgements

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