AN LED-BASED PHOTOVOLTAIC MEASUREMENT SYSTEM WITH VARIABLE SPECTRUM AND FLASH SPEED

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ABSTRACT

Outdoor environmental variability ingenerates the need for indoor systems for PV module characterisation. To combine the advantages of the most commonly used simulators (steady-state and pulsed) and eliminate their disadvantages, an LED-based solar simulator prototype has been developed. The system can produce light at variable flash speeds and pulse shapes or can operate as a continuous light source for long-term measurements. The system achieves one sun intensity at a closely matched, continuous spectrum. Full control of all light sources allows variable intensity and spectral distribution during measurements. A technical description and results of initial qualification tests are given.

Keywords: LED, solar simulator, classification, photovoltaic measurement system

1. Introduction

Due to the natural variability of test conditions outdoors, indoor tests are desirable to carry out tests when required and not when the weather determines suitable measurement conditions. These solar simulators are more controllable than outdoor measurements and a much shorter time is needed for photovoltaic device characterization. Advances in photovoltaic technologies, specifically multi-junction as well as high-efficiency, high-capacity devices, have increased the complexity of indoor measurements and have shown a need for improvement.

Both solar simulator types in use today, steady state and flash, have advantages and disadvantages. For example, a steady state simulator can deliver highly accurate measurements for solar devices with a long time constant, but introduces thermal control issues and has high operation and maintenance costs, largely due to the short life-time of the light sources and the frequent down-times needed to replace them. Flash simulators, on the other hand, influence device temperature to a lesser extent and the operating costs are lower, but care must be taken to avoid measurement artefacts such as capacitive effects [1], which can distort I-V curves and lead to inaccurate power rating. Both types have, in their simple, one-lamp type form, the disadvantage of significant distortion of the spectrum due to the illumination source.

To retain the advantages of both simulator types and eliminating the disadvantages, an LED-based solar simulator can be used such as the prototype reported here (see Figure 1 for physical layout). LED based solar simulators have been reported in the past (see e.g. h.a.l.m. electronics [2], Tokyo university [3] and [4] but to the authors' knowledge this is the first system with quasi-continuous spectrum and also the only one which achieves one Sun intensity. It should be noted however, that in this proto-type development, the near infra-red (NIR) is provided by Halogen lamps. It is planned to replace these with additional LEDs in the final system.

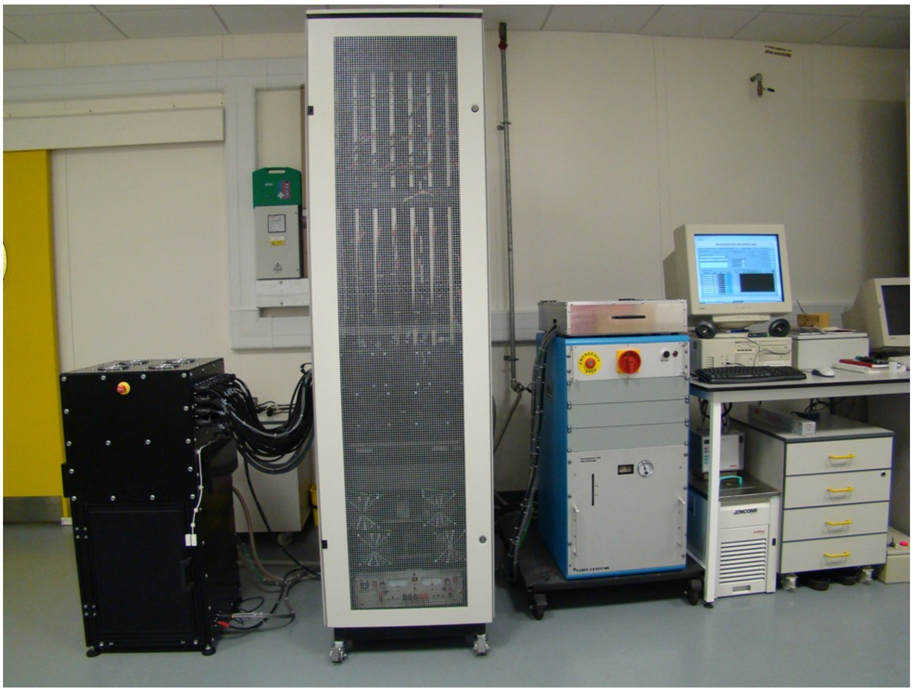

Figure 1: LED based solar simulator

LEDs as main light sources have a much longer lifetime than conventional high-intensity simulator bulbs (up to 100,000h), which reduces maintenance costs to a minimum. This life time is a factor 50 higher than most lamps and modern LED-dies have a comparable luminance to that of e.g. halogen lamps. LEDs can be controlled very accurately and stable output is achieved within microseconds. After this, the junction temperature rises and a degradation of power output is observed. Running them in stable condition for a long time opens possibilities to measure both short- and long-term effects on solar cells in one simulator. The aim of this work is partially to investigate the need for tighter control and to assess whether or not a water-cooled LED array is stable enough for solar PV device characterisation.

The unit is capable of producing variable flash shapes in variable speeds as well as providing a continuous-wavelength light output and achieving more than one Sun intensity over an area of more than 200mm x 200mm. Furthermore, with conventional simulators PV devices are generally measured at one irradiance level, with other intensities achieved by either mechanically adding a neutral density filter of some sort (most commonly used are wire-meshes) or by regulating the current through the lamp. The latter has the disadvantage that the spectrum is changed. Using LEDs removes this problem, as they are spectrally stable over a wide range of output levels. Using different colours with separate controls allows a dynamic adjustment of the spectrum as presented here. This provides a good tool for measuring and characterising multi-junction solar cells, which is one of the main applications for this work. This spectral control is required to remove any effects of spectral mismatch on the fill factor of the device [5] and thus decrease the uncertainty of such measurements.

2. Technical description

The principle construction of an LED-base solar simulator is not too dissimilar from that of conventional multi-lamp halogen solar simulators. As depicted in Figure 2, the main difference is to have differently coloured LEDs on an array of light sources as the main illuminating source. Installing many different narrow wavelength LEDs can provide a quasi-continues-wavelength light output on the solar cell test area.

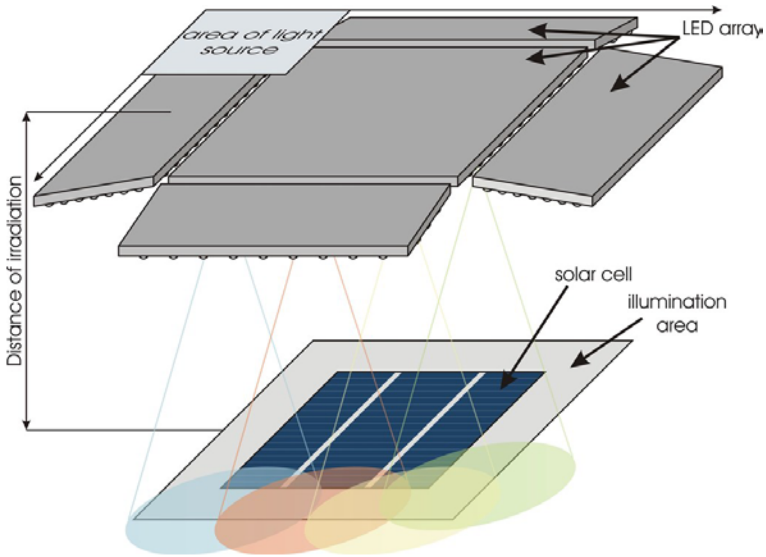

Figure 2: Schematic diagram of an LED-based solar simulator

The newly developed LED-based solar simulator array of light sources consists of several hundred LEDs in 8 different colours, to cover the light spectrum from the ultraviolet at 375nm to the red end of the spectrum 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 type and bin of the LEDs were chosen according to a simulation result based on their data-sheet values for matching the airmass (AM) 1.5G spectrum used in standard test conditions (STC) [6].

The control system, shown in a simplified schematic overview in Figure 3, allows independent control and adjustment 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, closely reproducing the variation seen in realistic outdoor conditions. The light source control allows LED flash frequencies of up to 500Hz in all imaginable flash shapes (see Figure 4). Single or multiple flashes are easily implemented making this a useful tool for scientific investigations of different types of solar cells.

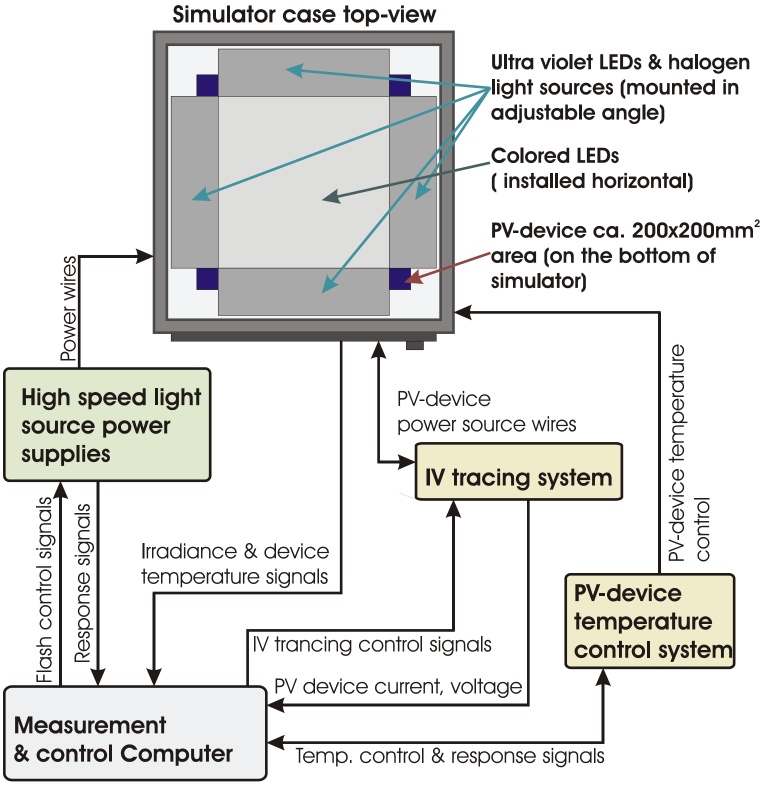

Figure 3: Simplified schematic overview

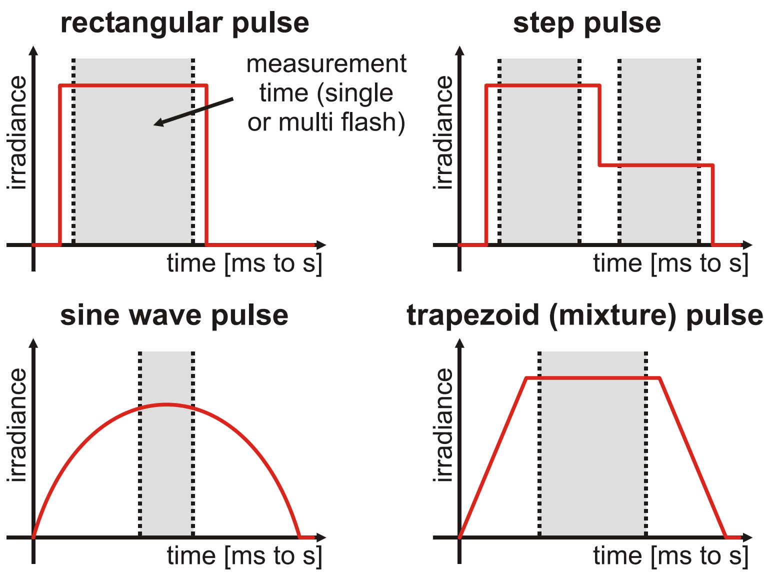

Figure 4: Possible flash shapes

The I-V curve is traced by an analog 4-quadrant high-speed operational amplifier. The irradiance and current and voltage of the device under test are measured simultaneously as required by the IEC60904-9 edition 2 standard [7] and any variation in the light is corrected for increased accuracy using the irradiance correction given in IEC60891 [8]. 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 also embedded in the simulator, capable of regulating the test device temperature from 10 to 80°C. The temperature control consists of a remotely operated Julabo heating and cooling unit circulating the thermal transfer liquid through a custom made cooling block and regulating the temperature of the block independently.

The simulator is controlled by a personal computer with in-house developed LabVIEW software. Routines for long and short time measurements can be easily configured and are carried out fully automated.

3. Qualification

The aim was to demonstrate the possibility of obtaining a purely LED illuminated system that is capable of class AAA as defined in IEC60904-9 edition 2 [7]. In the following, the prototype is assessed as class B, which is largely due to shortcomings of the halogen illumination rather than the LED sources. However, there are also clear avenues for improving on this which will be implemented in the device developed in the next stage of this project.

3.1 Temporal instability

The stability of the different light sources has been measured with a silicon pyranometer K&Z SPlite centred in the test area. This has a time constant similar to that of solar cells and thus can detect changes of relevance to solar cell calibrations.

Table 1: Measured temporal instability and classification at different measurement times and conditions of LEDs and Halogen lights only and with all light sources together

Measurement condition and setup	Meas. Time	Temporal Instability [%]	Class
All LEDs (250us start-up)	1ms	±0.77	A
All LEDs (250us start-up)	10ms	±1.37	A
All LEDs (250us start-up)	100ms	±2.30	B
All LEDs (250us start-up)	1000ms	±3.76	B
All LEDs (250us start-up)	2500ms	±4.93	B
All LEDs (25s warm-up)	10s	±0.57	A
All LEDs (25s warm-up)	25s	±0.86	A
All LEDs (25s warm-up)	50s	±1.21	A
Halogen light (2s start-up)	2.5s	±0.44	A
Halogen light (2s start-up)	25s	±1.75	A
Halogen light (25s warm-up)	75s	±1.78	A
All light sources (5s start-up)	24h	±8.35	C
All light sources (15min warm-up)	24h	±1.32	A

Table 1 summarises the results of this characterisation for different time steps. Irradiance changes during short time measurements with only the LEDs switched to full power output. This is mainly due to the negative temperature coefficients of LEDs but could be removed with further control. The intensity of the LEDs decreases until the operation temperature stabilizes, which takes approximately 40 seconds. Light intensity variation of the halogen light happens mainly because of warm-up of electrical components in the regulation circuits. During this time the light intensity of the halogen lights drops slightly. The complete warm-up and stabilization process of the light intensity takes around 15 minutes. As seen in table I in the 24h test, the intensity changes after this period are only minor and the simulator can be classified with a class A [7] temporal instability during 24h duration.

It should be noted, that the given stability is the stability without any feedback, which could be implemented relatively easily. However, depending on the application it is virtually always possible to maintain the two percent required to achieve class A.

3.2 Spectral output

As mentioned in the technical description, it is possible to adjust the spectral output of the simulator. To demonstrate this, the spectrum has been measured in the centre of the illuminated area with an AstraNet spectroradiometer. Two configurations are tested: full intensity with all light sources at maximum output without any further adjustments and optimized (by eye) for best matching the AM1.5G spectrum. The results of this test are given in Figure 5.

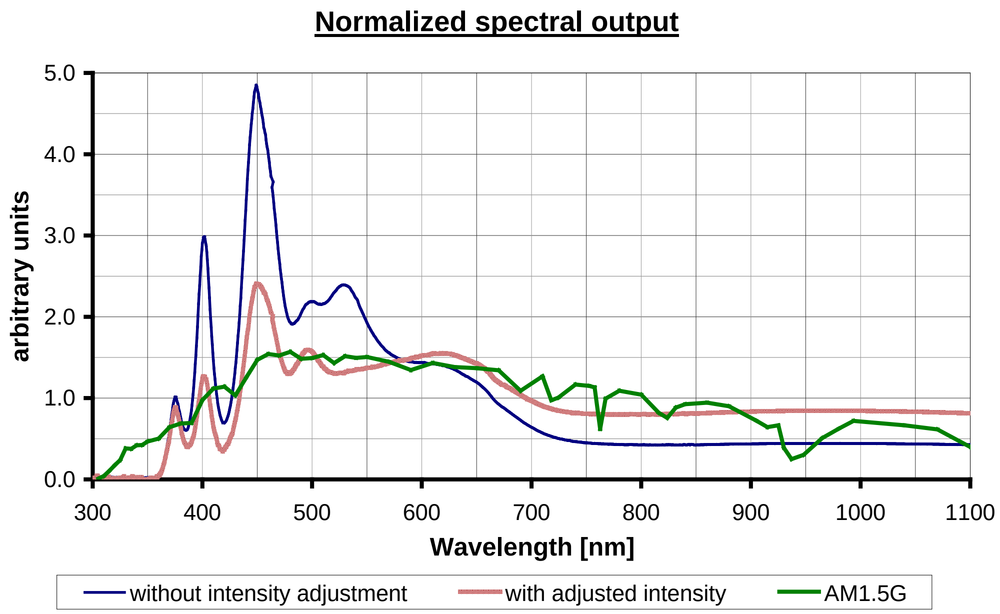

Figure 5: Simulator light source output spectrum, both spectral curves are normalised to the irradiance of the AM1.5G spectrum

The spectral classification according to IEC60904-9 [7] is then summarised in Table 2. The full intensity case results in a class C characteristic of the spectral match. Adjusting the intensity of the different light sources achieved a class B spectrum. Minor improvements may be achievable by using numerical methods to optimise the spectrum but it is questionable if a class A classification could be achieved in the current arrangement. This is entirely due to the choice of halogen lights ('warm halogen lights') and does not affect the possibility of an LED-only simulator achieving class A. In the current setup, the spectrum could be improved by either adding another set of LEDs in the 700-800 nm range or exchanging the halogen lights to dichroic ones. Unfortunately, the latter is not possible: Because of space constraints Osram Ministar axial reflector lamps were used and these are currently not available in a dichroic version.

Table 2: Spectral match classification

	Full power		Closest AM1.5 match	
Wavelength interval [nm]	**Relative Error**	**Class**	**Relative Error**	**Class**
400 – 500	1.86	C	1.01	A
500 – 600	1.31	B	0.93	A
600 – 700	0.84	A	1.01	A
700 – 800	0.44	C	0.75	A
800 – 900	0.47	C	0.87	A
900 – 1100	0.75	B	1.40	B
Total		C		B

3.3 Homogeneity

A thermopile pyranometer was used to measure the light intensity over a 220x220mm^2 field at 20x20mm^2 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 in every test.

As visible in Figure 6, the non-uniformity classification of all light sources at full power over the full area of 220x220mm^2 is ±19.6% - well outside the boundary of standard classification. Reducing the test area to 140x140mm^2 decreases non-uniformity to ±8.0% (Class C). On an area of 100x100mm^2 we achieve a Class B with ±4.0% [7]. Class A classification with ±1.5% non-uniformity has been achieved in an area of 60x60mm^2. Further homogeneity measurements of each individual LED colour and the halogen lights have shown that the intensity pattern changes slightly (see Figure 7), 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. Work is ongoing to calculate the calibration factors to optimise the homogeneity over the illuminated area, while minimizing spectral changes.

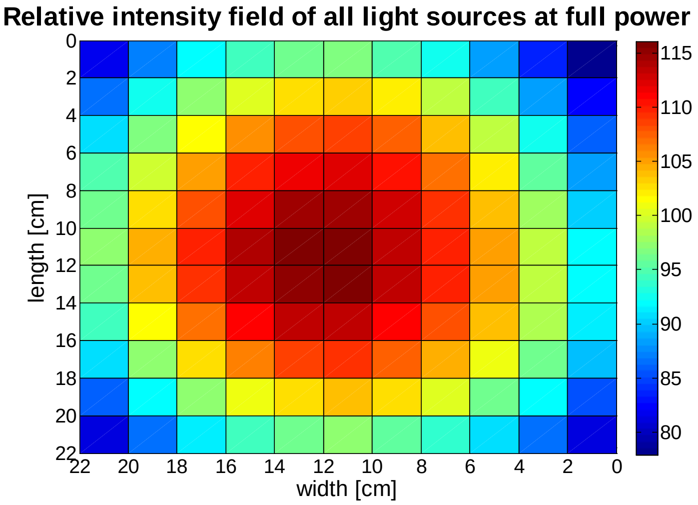

Figure 6: Relative intensity field of all light sources at full power

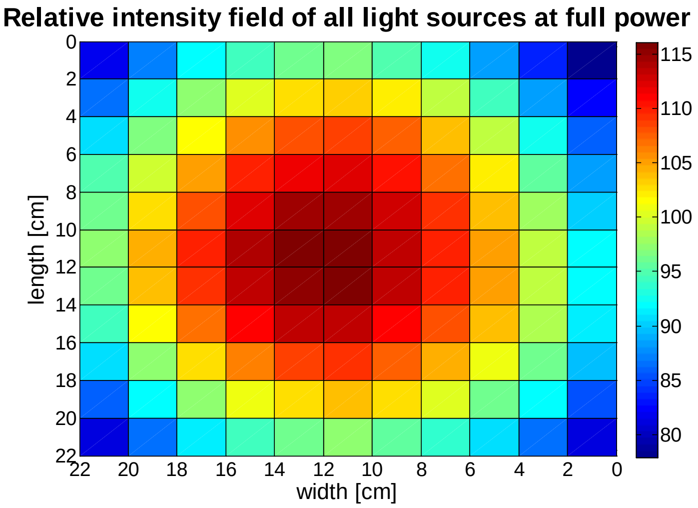

Figure 7: Relative intensity field of only ultraviolet LEDs

3.4 Total irradiance

The total irradiance has been measured with thermopile pyranometer responding linearly from 310nm to 2800nm. At full power output of all light sources an irradiance of 1.5Suns has been measured in the centre of the illumination area. Adjusting the Spectrum to match the AM 1.5G Spectrum reduces the maximum irradiance to 1.2Suns. When using only the LEDs an irradiance of up to 590W/m^2 can be reached.

4. Conclusions

The analysis of a prototype LED simulator has shown that it has the potential to deliver quality PV device measurements. Flexible control electronics in the simulator allow measurement by single or multi flash at variable speeds and flash shapes or in steady state mode.

Qualification results show that achieving the required intensities and qualities of a class AAA solar simulator is possible. 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 will open many possibilities for the analysis of PV devices.

ACKNOWLEDGEMENTS

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REFERENCES

[1] C. Monokroussos, R. Gottschalg, A. N. Tiwari, G. Friesen, D. Chianese, S. Mau, The effects of solar cell capacitance on calibration accuracy when using a flash simulator, *Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion (IEEE Cat. no. 06CH37747),* pp. ROM, 2006.

[2] R. Grischke, J. Schmidt, H. Albert, A. Laux, A. Metz, U. Hilsenberg, J. Gentischer, 5BV.2.47 LED Flasher Arrays (LFA) for an Improved Quality Control in Solar Cell Production Lines, *EUROPEAN PHOTOVOLTAIC SOLAR ENERGY CONFERENCE,* vol. 2, pp. 2591-2594, 2004.

[3] S. Kohraku, K. Kurokawa, New methods for solar cells measurement by LED solar simulator, *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion (IEEE Cat. no. 03CH37497),* pp. 80, 2003.

[4] S. Kohraku, K. Kurokawa, A fundamental experiment for discrete-wavelength LED solar simulator, *Solar Energy Materials and Solar Cells: An International Journal Devoted to Photovoltaic, Photothermal, and Photochemical Solar Energy Conversion.,* vol. 90, pp. 3364, 2006.

[5] M. Meusel, R. Adelhelm, F. Dimroth, A. W. Bett, W. Warta, Spectral Mismatch Correction and Spectrometric Characterization of Monolithic III-V Multi-junction Solar Cells, *PROGRESS IN PHOTOVOLTAICS,* vol. 10, pp. 243-256, 2002.

[6] IEC 60904-3: Measurement Principles for Terrestrial PV Solar Devices with Reference Spectral Irradiance Data, 1989.

[7] IEC 60904-9 Ed. 2: Photovoltaic devices - Part 9: Solar simulator performance requirements, 2007.

[8] IEC 60891: Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic devices, 1995.