SPECTRUM CONTROLLED SOLAR SIMULATOR FOR FACTORY TESTING OF CPV MODULES

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ABSTRACT: The validity of a solar simulator for concentrator PV modules is assessed through a comprehensive characterization of its illumination system: irradiance level and uniformity at the receiver, light collimation and spectral distribution. Methods for adjusting and characterizing the spectrum are described and applied, and a more meaningful way of comparing it with the reference spectrum is proposed, by means of the measurement of component ('isotype') solar cells.
Keywords: characterisation, concentrators, solar simulator, spectrometry.

1 INTRODUCTION

Companies willing to introduce a concentrator PV technology into the market suffer from a lack of appropriate characterization tools. Indoor solar simulators are essential for both prototype development and qualification at the production line. Unfortunately, CPV systems impose some strict constraints on the simulator design: besides the conditions needed for conventional flat modules related to irradiance level, spatial irradiance uniformity and light spectrum, the light has to be collimated for the illumination of CPV modules. In a concentrator, only the light impinging the optical aperture within a small angle is transmitted to the cell, therefore the light source must have an angular size similar to that of the sun, i.e. ±0.275º. Conventional simulators do not fulfil this requirement for module-size systems, since typical PV modules (flat plates) do not have this angular requirement.

IES-UPM has developed a solar simulator for CPV systems with the required light collimation and appropriate irradiance level and spectral distribution. The characterization carried out is presented in this article, as well as some techniques for varying the simulator spectrum and assessing its similarity with AM1.5D reference distribution.

2 SYSTEM DESCRIPTION

The IES-UPM concept for a CPV solar simulator is based on collimation through a parabolic reflector. The parabola is the geometrical figure in which every ray coming from its focus is reflected back parallel to its axis. Thus, if this mirror is illuminated with a small lamp from its focus, it will produce a collimated light spot in reflection, with the same size as the mirror. A CPV module placed normal to its axis will receive light within its acceptance angle.

There are two main difficulties involved in manufacturing such a collimator mirror. First, the large area that has to be illuminated, due to the aperture areas used in current CPV modules, requires a mirror of hundreds of centimeters in diameter. This is completely out of range for most optics manufacturers. Secondly, the long focal distance geometry required means extremely accurate optical quality, which is only available in the prohibitively expensive astronomical telescope industry.

The IES-UPM has developed a mirror in collaboration with the Spanish company JUPASA with high optical quality but at a much lower cost, thus overcoming the aforementioned technological problems. It is a bulk aluminium piece with a diameter of 2 m and a focal distance of 6 m, mounted on a stable metallic structure (see Fig. 1). This allows large CPV modules with any area falling within this circle of 2 m in diameter to be measured.

The first prototype version of the complete solar simulator was installed at Isofotón facilities in 2005. The technology was also transferred to Solfocus in 2007, which has already integrated it in its production line. The company Advanced Soldering has received license for commercializing the technology.

Figure 1. Collimator mirror manufactured at JUPASA.

2.1 Illumination system

The illumination system consists of a Xenon flash bulb and the collimator mirror, which generate a collimated light spot onto the receiver plane. Four basic requirements are defined following the CPV features: appropriate irradiance level and uniformity, collimation of the light and spectral distribution. These have been characterized for the solar simulator in study.

The irradiance level at the receiver is adjustable between the standard levels of 800 to 1000 W/m^2 (direct normal irradiance). A commercial Xenon flash lamp and generator is used, which allows the triggering voltage to be varied. The higher the triggering voltage, the higher the peak power.

The spatial uniformity on the entire receiver surface has been measured by means of a sensor with narrow angular aperture: a single lens-cell concentrator with around +/-1º acceptance angle. The uniformity measured depends on the size of the aperture lens, since the non-uniformities of the irradiance are smoothed as the aperture area increases. For a 3 cm x 3 cm lens, a +/-5% uniformity has been measured, which represents a worst case measurement.

The spatial uniformity measurement given before is a measure of the collimation of the light, since it is given for a narrow angular aperture. Nevertheless, it has been also quantitatively evaluated by means of a CCD camera. The light profile of our Xenon flash lamp has been photographed as seen from the receiver plane, after reflection in the mirror. As it can be seen in Fig. 2, the angular profile has the same geometry as the lamp, i.e. a toroidal flash bulb. This is actually a photograph of the artificial 'sun' incoming the CPV module.

The angular size of the profile can be defined as the angle within 90% of the incoming light power is enclosed, which has been measured to be ±0.43º, similar to the angular size of the sun plus some circumsolar radiation. 50% of the power is within ±0.23º. This demonstrates the simulator to be a valid indoor characterization tool for high concentrator PV modules.

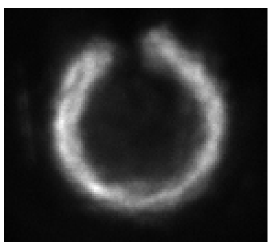

Figure 2. Light source seen from the receiver plane photographed with a CCD camera.

Since multijunction solar cells are the most typical in high concentration PV systems, which are very sensitive to variations in the light spectrum, the spectral distribution of the solar simulator has to be carefully studied in order to assure the appropriate rating of these systems. This characterization is presented in section 3.

2.2 Measurement system

The measurement scheme is based on multi-flash testing [1][2]. The lamp is triggered to illuminate the receiver, and this is biased at a different voltage on each flash pulse, recording different pairs of points (I, V) during the fall of the flash pulse. Every current level corresponds to a different irradiance level (through a reference cell), so a family of I-V curves at several concentrations is obtained. A software programme controls the whole process, triggering the lamp, biasing the device under test and acquiring data. Figure 3 depicts all system elements.

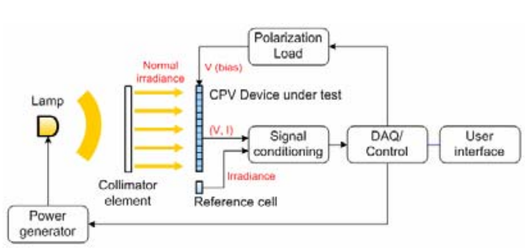

Figure 3. Elements of the multi-flash CPV solar simulator.

The faster the discharge of the flash generator, the higher the radiance of the lamp. A flash lamp without any plateau has been chosen in order to maximize radiance, Flash repetition rate is around 4 seconds. The number of points to be measured for the IV-curve is a trade off between accuracy and speed (throughput of the measured modules). Five points per IV-curve may be enough for in-line module sorting.

3 CONTROL OF THE SPECTRAL DISTRIBUTION

The so-called multijunction (MJ) cells made of III-V materials (e.g. GaInP/GaInAs/Ge) are the most typically used as receivers in high-concentration PV systems. This makes system performance very sensitive to spectrum, since MJ cells are a series-connected stack of two or more sub-cells, each one generating current in response to the light of different spectral bands. The overall current is limited by the subcell with the minimum current. Current matching is defined as the ratio between subcell currents, which in optimal performance equals one.

In order to rate the actual performance of a CPV system, the solar simulator has to provide similar current matching in MJ cells as under reference conditions, therefore its spectral distribution has to be studied.

3.1 Adjusting the simulator spectrum.

The spectral distribution of a Xenon flash lamp is a function of the triggering voltage and the time from the peak in the pulse decay [3]. Increasing the triggering voltage leads to higher equivalent colour temperatures, i.e. blue-richer spectrum. On the other hand the color temperature is reduced throughout the flash pulse decay, i.e. the spectrum gets red rich. One can take advantage of these dependences to accurately adjust the spectral distribution in order to get similarity with that of the sun.

3.2 Characterizing the spectrum.

3.2.1 Fast spectrometer measurement.

A direct measurement of the Xenon light spectra has been made for our flash lamp by means of a HR4000 spectrometer from Ocean Optics, which allows fast measurements with integration times down to 10 μs to be taken. The spectrum is obtained with high wavelength resolution, but the intensity calibration is difficult and the measurement has to be very accurately synchronized with the flash pulse. A direct measurement of the Xenon light source spectrum as a function of time from peak (delay) is presented in Fig. 4. The integration time used is 100 μs, as wells as the time steps. Note that the low-energy light ('red light') decreases much slower than the 'blue' light (higher energy photons), which means that the blue-/red-light balance of the flash light decreases with time from peak.

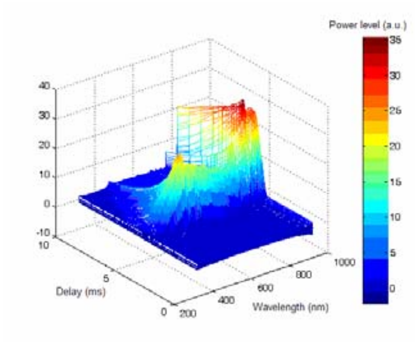

Figure 4. Spectrometer measurement of the Xenon light source intensity as a function of time from peak.

3.2.2 Broad band measurement: multijunction component cells.

An easier way to measure the spectral content available for every subcell in the receiver is to measure the photogenerated currents at every subcell, which are proportional to the incident irradiance. In monolithic MJ cells this is not feasible, but their component cells (also known as 'isotype' cells) can be used. A component cell has the same spectral response as one of the subcells of the MJ stack, usually by growing an optically equivalent semiconductor structure but keeping the other subcells electrically inactive (or *isotype*). If the short-circuit current of everysubcell under reference irradiance is known, then the irradiance available for subcell *i* under the simulator light can be obtained as follows:

$$B_{subcell,i}^{simulator} = B^{reference} \frac{I_{sc,subcell,i}^{simulator}}{I_{sc,subcell,i}^{reference}} \quad (1)$$

where B stands for direct normal irradiance and I_{SC} for short-circuit current. The resolution of this measurement is given by the spectral response of the QE curves of the subcells, so this is a broad band measurement.

3.2.3 Current-matching measurement.

The simulator spectrum can also be characterized with the current-matching which it produces among the different subcells in the multijunction stack. Usually, MJ cells are designed in order to produce the same current at every subcell under the reference AM1.5D spectrum [4]. If such a cell is current matched under a given illumination, its similarity with reference spectrum is roughly checked. An indirect way of measuring this current matching is to record the IV curve of the MJ cell under different blue-/red-light balance of the light. If this is made under the same short-circuit current for every curve, a local minimum in the Fill Factor as a function of the blue-/red-light mixture marks the current matching point [5]. Since the blue-/red-light balance of the flash lamp can be adjusted by means of the triggering voltage, the curve in Fig. 5 has been obtained for our Xenon lamp, where the FF of a 3J cell from Spectrolab is plotted. It is given as a function of the flash energy, which in our generator is related to the triggering voltage. The f-stops magnitude is a 2-base logarithm of the energy scale, i.e. doubling the energy means increasing one f-stop. Note that a local minimum in FF is reached, which corresponds to the current-matching conditions.

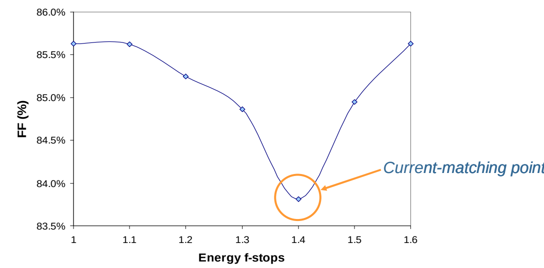

Figure 5. FF of a 3J cell from Spectrolab at constant Isc, as a function of the flash pulse energy. The higher the energy, the more blue-rich the spectrum is.

3.3 Comparing spectra.

The question arising is how to quantify similarity between the simulator spectra and the reference light spectrum (AM1.5D). The standard for flat plate solar simulators establishes fixed integration spectral bands for comparison with reference spectrum [6]. But in a CPV system equipping MJ cells, it makes more sense to study the zones defined by the spectral response of the sub-cells, since spectral likeness should lead to the same current matching. In GaInP/GaInAs/Ge triple-junction cells (most often used in CPV), the Germanium cell is designed to generate about 20% current in excess in operating conditions. If this excess is assured with the flash simulator, only the spectral range covering GaInP and GaInAs subcells has to be studied carefully (see Fig. 6).

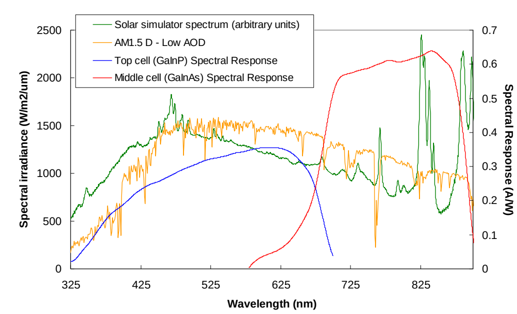

Figure 6. Solar simulator spectrum for a specific triggering voltage at peak power compared to AM1.5D standard spectrum. Also, spectral responses from top and middle junctions in a typical triple-junction cell are shown.

Therefore, reference spectral conditions will be achieved when the same irradiance is available for top and middle subcells as under AM1.5D illumination (provided Germanium subcell generates an excess of current). The light available for every subcell can be measured directly by means of component cells, through their photogenerated current (which is proportional to the irradiance within their spectral range). Alternatively they can be estimated indirectly if the light spectrum is measured and the spectral responses of the subcells are known, and applying Eq. 2:

$$I_{L,subcell} = \int_{\lambda} SR_{subcell}(\lambda) E(\lambda) d\lambda \quad (2)$$

where:

$I_{L,subcell}$ photogenerated current

$SR(\lambda)$ spectral response [A/W]

$E(\lambda)$ spectral irradiance [W/m^2/nm]

If the photogenerated currents of subcells under reference spectrum AM1.5D are known, their ratio can be compared to that under the solar simulator. Typically this value will be given for top and middle junctions in a triple junction cell, and the photogenerated current will be approximated by the short-circuit current (I_{SC}). This way, the magnitude 'Spectral similarity' is defined as in Eq. 3. 'Spectral similarity' equal to 1 means the perfect matching of the spectra.

$$SpectralSimilarity_{Middle}^{Top} = \frac{I_{sc,Top}^{Simulator} / I_{sc,Top}^{AM1.5D}}{I_{sc,Middle}^{Simulator} / I_{sc,Middle}^{AM1.5D}} \quad (3)$$

In the equation, AM1.5D superscript stands for the current measured under these reference conditions, and 'Top' and 'Middle' subscripts refer to the corresponding subcells. This value is not only related to the spectrum itself, but also obviously to the solar cell behavior, so component cells with same technology as those under the concentrator should be used in order to find the best figure for spectral similarity.

Component cells of triple junction cells from Spectrolab have been used in order to measure this spectral similarity between our flash simulator and the reference AM1.5D under which they were calibrated. Matching point ('Spectral similarity' equals 1) is achieved for a wide range of triggering voltage levels if different delays from peak power are considered. Fig. 7 plots this measurement for the solar simulator illumination system (lamp plus collimator mirror) as a function of time, and at a given triggering voltage. In this case spectral matching is achieved at 850 W/m^2, which is usually taken as the reference irradiance level for CPV systems rating [7].

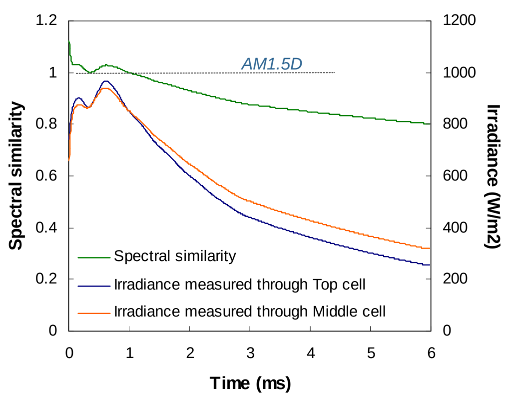

Figure 7. *Spectral similarity* through current ratios of top and middle component cells (GaInP, GaInAs) under solar simulator and reference AM1.5D conditions. It is given as a function of time, during the flash pulse decay. Available irradiance for top and middle cells is measured using Eq. 1

4 CONCLUSIONS

The validity of only CPV solar simulator has been demonstrated through a comprehensive characterization of their illumination system:
- Appropriate irradiance level and uniformity (850 W/m2, +/- 5% - *worst case*)
- Angular size at the receiver similar to that under the sun (+/- 0.4º)
- Spectral distribution matching AM1.5D (using *isotype* cells as sensors)

Methods for adjusting and characterizing the spectrum of a solar simulator have been presented and applied to characterize the solar simulator. Also, a more meaningful way of comparing spectra in MJ-based CPV systems is proposed, through measure of component ('isotype') cells.

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