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A new approach for evaluating flux uniformity for dense array concentrator photovoltaic cells

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ABSTRACT

In this paper, we present two statistical methods to quantify the heterogeneity of the irradiance flux distribution, in a Concentrator Photovoltaic (CPV) dense-array, based on its operation and the optimization of current-matching. Preventing non-uniform flux distribution from design avoids the generation of hot spots, current mismatch and increases the overall efficiency of the system. This new approach considers the effects of the lowest irradiance values in the performance of the complete array, and its performance was corroborated by the simulations of a CPV array modelled in Matlab/Simulink; the irradiance distribution data as an input parameter was obtained from the images taken in a homogenization experiment, in the HoSIER, an 18,000 X solar furnace. The results are interpreted through the new concept of photovoltaic homogeneity, proven that the methodology successfully predicts the flux distributions, which enhances the efficiency of a series connected CPV array. Additionally, we found that the proposed methodology can also be used to optimize the electrical performance of dense-array CPV systems, working under the effects of non-uniformity illumination by rewiring the series connections into series-parallel configurations.

1. Introduction

The main advantage of Photovoltaic Concentration systems compared to flat plate systems is the possibility of reducing the total cost of the system and exceeding the efficiency limits of conventional technologies (Shanks et al., 2016). Thus, two decades after the emergence of the first multi-junction cells that promised a 40% efficiency and whose materials were only affordable for terrestrial applications through HCPV (Horne and SolFocus Inc; USA, (2012)) the innovation in material, trackers and optical devices continues in order to concentrate high homogeneous radiative flux seeking to reduce energy losses and to achieve 45% efficiency in modulus (Mohedano et al., 2016).

A heterogeneous illumination distribution in the Concentrator Photovoltaics (CPV) technology causes a localized increase in current and temperature, deteriorating the materials, decreasing its open-circuit voltage, the fill factor and the overall performance of the system. (Baig et al., 2012). Describing quantitatively the heterogeneity of the radiative flux distribution that affects the active area of a photovoltaic device is fundamental to simulate its behavior in real conditions (Algora et al., 2005), as well as to optimize its design, allowing to improve both the electrical and the thermal performance (Natarajan et al., 2011).

The uniform illumination concept in CPV has been directly imported from imaging optics. Actually, it is one of the most important parameters in both fields (Brown et al., 2015). Recently, the necessity for homogenous flux in CPV systems has created a new upswing of the non-imaging optics. Its terminology and methodologies have not been adapted to describe not only the average light distribution, but also the best radiation conditions and properties to enhance the operation of these specific photovoltaic devices and systems. As a consequence, it is common to see that with each new article of photovoltaic concentration, a new method of evaluating uniformity is proposed, which in turn limits the interpretation to that experiment or prototype in particular and complicates its comparison with other works.

The near future of the CPV industry will also require larger concentrators and an optimization of the interconnection of cells regarding the distribution of the incident flux for the wafer bounded multi-junction solar cells, which has shown a realistic potential efficiency of 50% and can be interconnected from the substrate (Schachtner et al., 2014). This article proposes a methodology specifically designed for CPV arrays and exposes its advantages over conventional methods. It can be reported for general purposes and optimized for the heterogeneous flux sensitivity of a specific array, considering its intrinsic cell characteristics, size or grid design. Also, two non-uniform flux detection and quantification methodologies are presented, as well as the optimal reconfiguration options of electrical connections for series – parallel

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arrays of CPV cells in dense packaging. These methodologies are implemented in the processing and analysis of CCD images of a homogenization experiment of radiative flux in a Solar Furnace with a concentration factor of 18,000 suns.

2. Methodology

Two methods are proposed to evaluate the uniformity of the radiative flux for series connected CPV arrays; The first method named the photovoltaic uniformity, U_{PV}, shows the discrepancy between the incident flux and the operational flux, since in PV arrays the operational flux generates the main electric current flowing in the array circuit, and depending on the operating point, it is usually limited by the minimum short circuit current; the extra current should be bypassed with diodes. This first method takes into account the difference of all the values of flux intensity (F_i) with respect to the minimum value (F_{min}), by the equation:

$$\sigma_{min}(F_i) = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(F_i - F_{min})^2} \quad (1)$$

$\sigma_{min}$is what we call the min standard deviation. In order to increase the accuracy of the method, F_{min} can be adjusted with experimental or simulated cell parameters depending on the solar cell size, simulation mesh or sensitivity to flux heterogeneities due to special grid configurations or intrinsic solar cell characteristics. Then, U_{PV} is calculated by dividing this min standard deviation σ_{min} by the harmonic mean:

$$U_{PV} = \frac{\sigma_{min}}{n}\sum_{i=1}^{n}\frac{1}{F_i} \quad (2)$$

As shown in Fig. 1, analyzing flux distribution with respect to the minimum and not to the average of the values, yields a bigger area under the curve for high heterogeneous flux distributions. The image on the right corresponds to analyze the flux with the conventional method, where the average value of these is taken as a reference; as it is shown, this method minimizes the representativeness of the regions where there is a greater intensity flux with respect to the minimum values.

The second method named the interquantile uniformity, U_{IQ}, is descriptive and complementary to the previous one, since this probabilistic approach emphasizes the difference between the values of maximum and minimum intensity flux within a proportional range which divides the irradiance distribution data into N equal and ordered parts. To carry out this method, an interquantile range (IQR) is generated, in which $Q_{(N-1)/N}$ represents the median of the values corresponding to the upper quantile and $Q_{1/N}$ the median of the lower quantile; both intervals have the same number of elements,

$$IQR = Q_{\frac{N-1}{N}} - Q_{\frac{1}{N}} \quad (3)$$

Again, the Uniformity is calculated by dividing the interquantile range by the harmonic mean:

$$U_{IQ} = \left(\frac{IQR}{n}\right)\sum_{i=1}^{n}\frac{1}{F_i} \quad (4)$$

This method makes evident the frequency with which a low or high irradiance value appears in the range specified, in order to detect if the uniformity flux distribution calculated with the previous method will present zones with possibility of current returns, and consequently generation of hot spots, that reduce the efficiency of the array (Bosco et al., 2011).

Fig. 2 shows on the left, a light distribution profile analyzed by quartiles ($N = 4$), and on the right, it is analyzed by quantiles that divide the distribution into 50 equal parts (N = 50). The number of divisions used for this method will depend on the mesh size for the case of ray tracing simulations and for images taking case, on the dimensions of the image and the noise they present. If the images contain impulsive noise, a smaller number of divisions are preferable for the analysis. If the noise is Gaussian or uniform, the implications in this method are not significant, as long as the noise is kept in acceptable levels.

For the accurate implementation of both methods, in the analysis of data from photodetector images or ray tracing simulations, a low uncertainty in the flux intensity data is required, especially for the case of the photovoltaic uniformity; whereas in the interquartile uniformity, the number of divisions or quantiles should be adjusted, according to the uncertainties presented by the maximum and minimum values. In practice, the flux of uniformity is usually calculated from the data of images obtained with the use of CCD cameras. These cameras, as it is well known, are susceptible to different types of noise (European Machine Vision Association, 2012), whether for damages in the device, ignorance of operating parameters, limitations of the equipment itself and factors of the experimentation, among others.

The U_{PV} method is the most affected by the data noise, since it is totally dependent on the minimum value. This case is shown in Fig. 3, where the uniformity of a radiative flux distribution profile taken by a CCD camera is analyzed; the calculation of this is affected by the intrinsic noise of the CCD camera. Eliminating the noise is important in any method used for analysis of images and can be done through the use of the correct filters (Faraji & MacLean, 2006). Since there are several types of noise as well as several types of filters, their implementation must be carefully based on the specific characteristics of a particular camera model as well as the thermal and optical conditions recommended by the manufacturer for its operation. On the right of the figure, the same flux distribution was postprocessed applying it a Gaussian filter, thus to apply the method correctly.

3. Experimental setup. (Irradiance profile characterization)

The methodologies are implemented in the characterization of the flux homogenized by the high concentrated flux homogenizer with cooled internal reflective walls (HOFRAC-PR, by its Spanish acronym). This device was installed in the high-flux radiative Solar Furnace of the

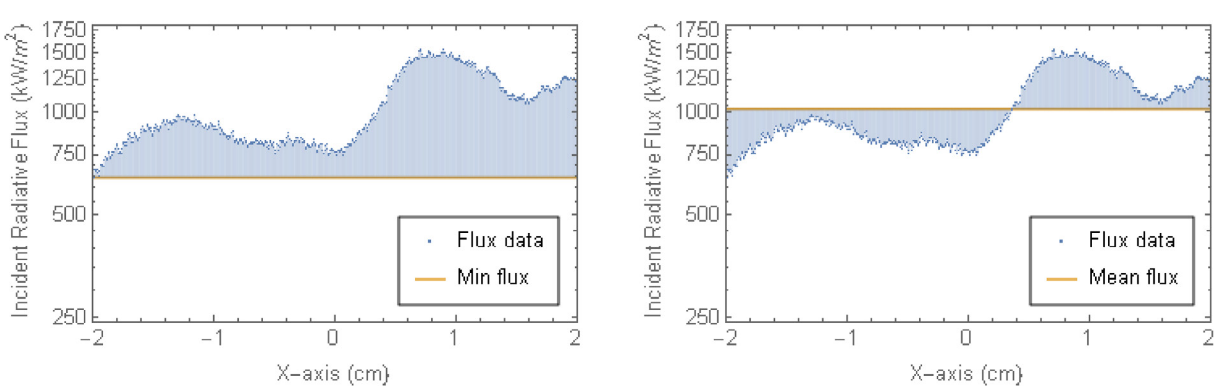

Fig. 1. Left: radiative flux distribution and its relation to the minimum value. Right: Its relation to the average.