DETERMINATION OF INDIVIDUAL CONCENTRATOR TOLERANCES FROM FULL-ARRAY I-V CURVE MEASUREMENTS

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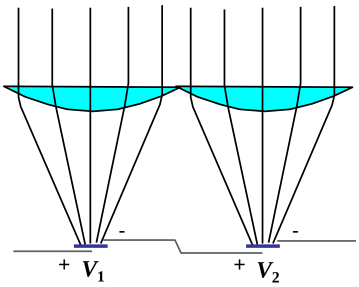
ABSTRACT: When dealing with CPV manufacturing process, tolerances are critical in order to obtain a low cost mass-production system. Usually the efficiency attained by a whole module array is smaller than the average efficiency of every single module. This downside is due to the well-known mismatch losses introduced by the cell series connection. For this reason, we present a novel mathematical method to calculate photocurrent versus pointing angle curves for the single-cell modules, with the only information of photocurrent versus pointing angle measurements for the whole module array. In this way we can estimate the mismatch losses for a given array just by analyzing its full-array I-V curve. Thus, the great breakthrough about this method lies in no single-cell module measurement is needed. The application of this method allows the measurement of the real tolerances of any CPV system.
Keywords: Concentrators, PV Array, Module manufacturing

1 INTRODUCTION

Acceptance angle (tolerance) of an optical concentrator is a key issue when designing CPV systems, since it will allow us to face different tolerance problems dealing with CPV manufacturing process. Among these problems we can outline the following: shape errors and roughness of the optical surfaces, concentrator module assembly misalignment, series-connection mismatch produced when mounting an array, sun-tracking accuracy and solar angular diameter.



$$I_{SC} = \max\{I_{SC1}, I_{SC2}\} \qquad V_{OC} = V_{OC,1} + V_{OC,2}$$

$$I_m \approx \min\{I_{SC1}, I_{SC2}\} \qquad V_m \approx V_{m,1} + V_{m,2}$$

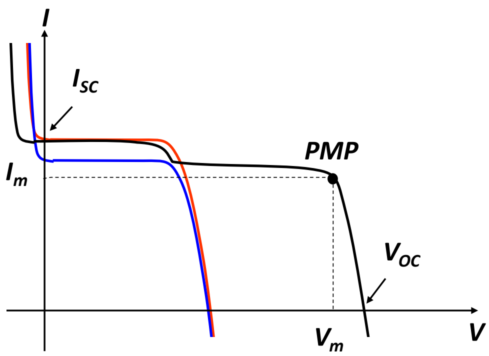


Figure 1 I-V curve for two series-connected solar cells (single cell curves in red and blue colors, series connected set in black) and the equations defining their behavior

In this way, if we knew the specific tolerance budget for a CPV system manufacturing process, we could estimate the optimal acceptance angle needed for its optical concentrator. Although this would be a really useful tool in order to design a well-optimized CPV system, it must be said that this estimation is very difficult to make since it depends on so many factors. This is the reason why in this work we have focused just on undesired effects dealing with series-connection mismatch, caused by single-module and array assembly misalignments.

Even if all the modules in the CPV array are identical, these mismatch losses will appear because of problems in mounting and manufacturing precision. In these situations, where manufacturing precision is below the required one, we can only increase the tolerance (or acceptance angle) of our optical system in order to solve the problem.

When two (or more) cells are series-connected in a CPV array, the resulting I-V curve is as shown in Figure 1, where total I_m (current at maximum power point) is smaller than expected [1]. From Figure 1 it is obvious that total I_m does not equal sum of single I_m, as would be desirable. For this reason, array maximum power is also smaller than expected, and consequently an important part of energy will be lost due to this module pointing mismatch.

This negative effect is mainly due, as stated above, to mismatch connection, produced by dispersion of the maximum I_{sc} and misalignment of the individual concentrators, and depends on the full-array global orientation, θ.

2 DESCRIPTION OF THE METHOD

2.1 Objective

We present here a novel mathematical method to calculate photocurrent versus pointing angle curves for the single-cell modules, with the only information of photocurrent versus pointing angle measurements for the whole module array. In other words, with our method we can deduce information about the two main parameters (angular misalignment, ε, and optical efficiency, η) that define the error model of the individual concentrators, from full I-V array curves measured at different θ tracking errors. An example of I-V-θ representation for a 6-module array is shown in Figure 2.

Our method allows the measurement of the real tolerances of the system. This leads to two useful applications of the method. In the first one, for a given manufacturing precision, we will provide an estimation of the minimum concentrator tolerance (acceptance angle) needed to fulfill the maximum desired efficiency drop for the whole array. In the second one, for a given concentrator tolerance, we can estimate the manufacturing precision required for a desired array efficiency drop [2].

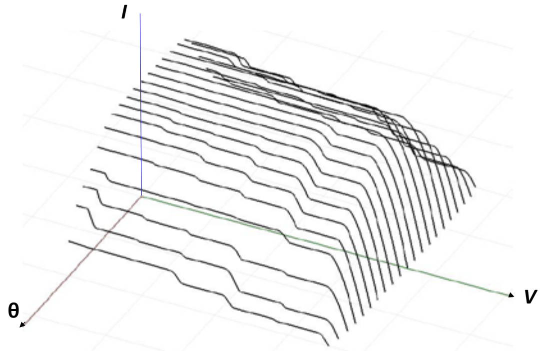


Figure 2 Representation of several I-V curves with different tracking errors θ for a 6-module CPV array

These applications are very helpful since, if tolerance is underestimated, single module photocurrents will be very mismatched among them, resulting in a non-maximal total array photocurrent situation; on the other hand, if tolerance is overestimated, module geometrical concentration factor will be smaller (forced by an acceptance angle increment), leading to a global energy price increase.

2.2 Development

The method is based on the calculation of two basic parameters extracted directly from the array I-V-θ curves (Figure 2). The first one is denoted by A_{Isc} and is the area enclosed by the whole array $I_{sc}(\theta)$ curve; the second one, denoted by A_{Im}, represents the area enclosed by the array $I_m(\theta)$ curve (curve for maximum current projected on the $V=0$ plane).

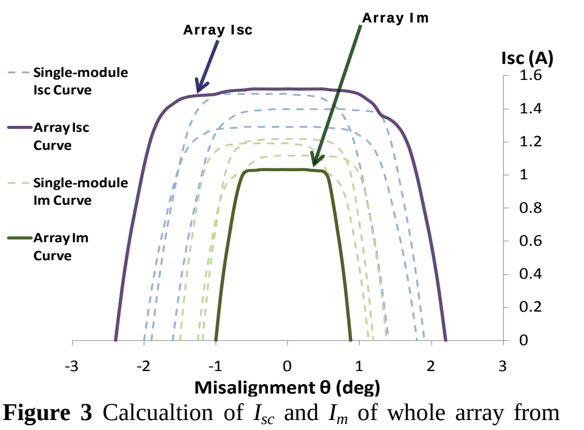


Figure 3 Calcualtion of I_{sc} and I_m of whole array from single-module $I_{sc}(\theta)$ curves

In order to obtain realistic values for these two parameters, we have generated several populations of array I-V-θ curves randomly. These array curves have been built taking into account the series (or parallel) connection of single-module $I_{sc}(\theta)$ curves. These single-module curves have been randomly generated based on two parameters, each one modeled by a different probabilistic distribution. These two parameters will characterize every single-module curve and are the following: angular misalignment ε and optical efficiency η. We have also stated that all concentrator units in our model have identical known relative $I_{sc}(\theta)$ curves.

Figure 3 shows an example of horizontal (caused by ε) and vertical (caused by η) dispersions generating displaced versions of the original relative $I_{sc}(\theta)$ curve. It also shows how array I_{sc} and I_m are calculated, and so their enclosed areas A_{Isc} and A_{Im}.

For our error model, we have chosen a Gaussian distribution for the angular misalignment ε, with null mean value and unknown standard deviation σ_ε. The optical efficiency η, on the other hand, follows a Weibull distribution, with maximum value equal to the reference single-module and unknown standard deviation σ_η.

Once defined our error model, we just have to create a large family of arrays and calculate the resulting values of A_{Isc} and A_{Im} for each case of the group. We obtain these different cases by varying the two parameters´ standard deviation values: σ_ε and σ_η. Analyzing all these cases, we can set a pair of functions which relates the four desired values:

$$A_{Isc} = F(\sigma_\varepsilon, \sigma_\eta) \qquad (1)$$
$$A_{\mathrm{Im}} = G(\sigma_\varepsilon, \sigma_\eta)$$

For each pair of values σ_ε and σ_η, we obtain a pair of values A_{Isc} and A_{Im}. Nevertheless, it would be desirable to have the inverse relation, i.e. having parameters σ_ε and σ_η being functions of A_{Isc} and A_{Im}. Just by calculating the inverse system of (1), we can obtain two new functions:

$$\sigma_\varepsilon = f(A_{Isc}, A_{\mathrm{Im}}) \qquad (2)$$
$$\sigma_\eta = g(A_{Isc}, A_{\mathrm{Im}})$$

So applying (2) we can obtain important information about angular misalignment and optical efficiency for the single-module units, with the only information of whole array enclosed areas A_{Isc} and A_{Im}.

2.3 Input data considerations

Some considerations regarding the input I-V data have to be taken into account for a proper behavior of our method. First of all, the I-V curve of a reference concentrator unit must be known, including the by-passed state ($V<0$). As explained above, experimental data, as the measured I-V-θ surface of the array and measurement conditions for that surface, are essential. Number of single concentrator units, and interconnection diagram (series, parallel) of the array, must also be known.

3 EXAMPLE OF METHOD APPLICATION

In this section we expose an example of how our method works with a specific case. For this purpose we have fixed some specifications. First of them is the reference concentrator I-V curve for which we have chosen a Fresnel-Köhler (FK) concentrator curve with half acceptance angle of α=±1.3º [3] [4]. Figure 4 shows (in bright blue continuous line) the transmission curve for the FK concentrator chosen.

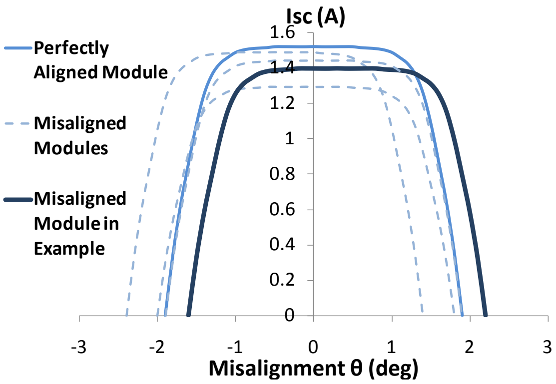


Figure 4 Several $I_{sc}(\theta)$ curves generated by applying different σ_ε and σ_η values to the reference FK concentrator curve. In bright blue continuous line, a perfectly aligned module. In dark blue continuous line, the curve used in the example

Secondly, we have chosen a number of 200 concentrator units connected in series, each of one working with identical triple-junction cells. All these cells present a Schottky by-pass diode.

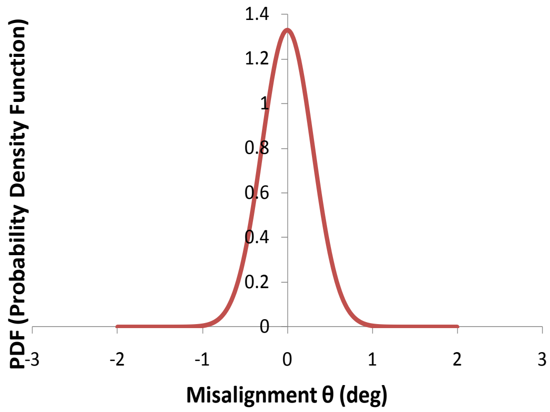


Figure 5 Curve for a Gaussian distribution with σ_ε=0.3. The misalignment produced by the distribution is represented on the horizontal axis

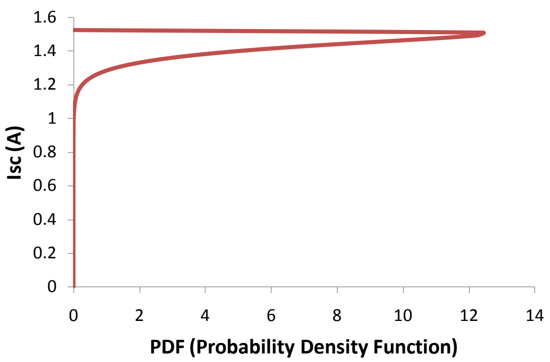


Figure 6 Curve for a Weibull distribution with σ_η=0.05. The variation of I_{sc} (and efficiency) produced by the distribution is represented on the vertical axis

The dark blue continuous curve in Figure 4 represents a modified version of the perfectly aligned module $I_{sc}(\theta)$ curve. This modified version is the result of applying a Gaussian distribution with σ_ε=0.3 (as that represented in Figure 5) and a Weibull distribution with σ_η=0.05 (shown in Figure 6). The lateral displacement of the $I_{sc}(\theta)$ curve is caused by the Gaussian distribution, while the vertical reduction of the curve is due to the Weibull distribution. Note that the maximum of the Weibull distribution shown in Figure 6 (I_{sc}=1.52A) is the same value of the perfectly aligned module maximum value.

Final results derived from the application of our method are shown in Figure 7, where inverse functions are represented. In this way, we can calculate both distribution deviations just by knowing A_{Isc} and A_{Im} values. As shown in Figure 7, for a pair of values (σ_ε,σ_η), there is only a solution (A_{Isc},A_{Im}). We only represent here a certain number of solutions, but a larger range of values of A_{Isc} and A_{Im} could be represented. As can be seen, some of the curves in the top graphic are truncated since, for those values of A_{Im}, values over certain value of A_{Isc} have no physical sense.

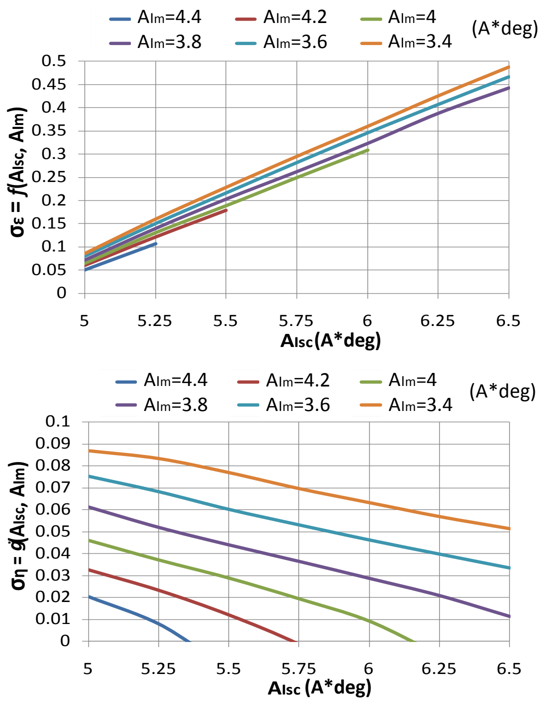


Figure 7 Inverse functions σ_ε=$f(A_{Isc},A_{Im})$ (top), and σ_η=$g(A_{Isc},A_{Im})$ (bottom). Horizontal axis represents A_{Isc}, while A_{Im} is taken as a parameter

4 CONCLUSIONS

We have proposed a mathematical model to estimate the dispersion of the maximum I_{sc} value (i.e. efficiency dispersion) and misalignment of the individual different concentrators from whole array I-V-θ measurements. As pointed above, the great advantage about this method lies in no single-cell module measurement are necessary.

Our model will generally depend on the concentrator $I_{sc}(\theta)$ module architecture chosen, i.e. its transmission curve. For our example, we have used the FK concentrator, but it can be applied to any concentrator architecture. Further work will be presented on this method since the hypotheses we have taken into account for the model need to be contrasted with the application to measured I-V-θ data.

5 ACKNOWLEDGMENTS

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