Evaluation of misalignments within a concentrator photovoltaic module by the module optical analyzer: A case of study concerning temperature effects on the module performance

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1. Module characterization at production line

When developing concentrator photovoltaic (CPV) modules,[1,2] it is essential to indoor characterize both the electrical and optical-angular properties of the module in all the development phases (not only during the design step but also at the production line). In this regard, the appearance of the first commercial solar simulator (the Helios 3198)[3–6] has been key for manufacturers for the indoor electrical characterization of their products.[7–9] However, there are still scarce available instrumentation and procedures to perform the indoor optical-angular characterization of modules in production line. This last evaluation is critical due to the reduced angular tolerance of CPV systems.[10,11]

A novel instrument so-called module optical analyzer (MOA) is proposed to characterize the optical-angular properties of modules in large-scale production scenarios.

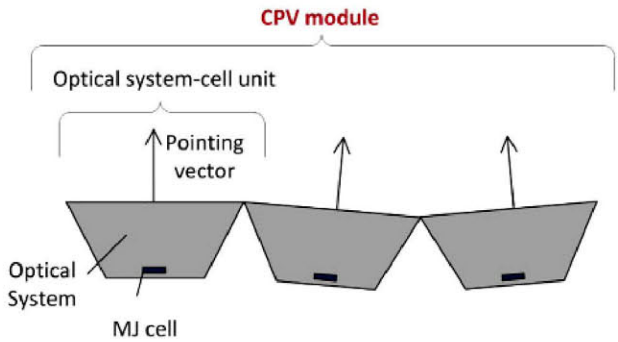

Fig. 1. (Color online) A CPV module is formed by several optical-system cell units series or parallel connected. Differences between the pointing vectors of the units in the module are referred to as the misalignments between units.

1.1 Optical-angular properties of CPV modules: Misalignments and angular transmittance function

The metric commonly used to define the optical-angular performance of a concentrator is the angular transmittance function. It describes the percentage of light flux transmitted to the output of the concentrator when illuminated from its input. The module is uniformly illuminated with collimated light beams whose direction of incidence is defined by two angles: α is the zenith angle, and ϕ is the azimuth angle. The resulting angular transmittance function is therefore a two-dimensional (2D) function described by $H(\alpha, \phi)$.

The angular acceptance (AA) angle is used to summarize the information given by the angular transmittance function. It is defined as the angle at which the angular transmittance reaches 90% of its maximum.

Not only controlling the acceptance angle of the module but also the misalignments between its optical system-cell units (Fig. 1) are essential to avoid some critical problems (e.g., the current mismatch between units may largely decrease the output power of the module).[12] The misalignments between units are defined as the differences between their pointing vectors, and the pointing vector refers to the angular direction of the concentrator (with respect to the optimum alignment with the light source) at which the CPV module best performs. This pointing vector can be calculated from the angular transmittance function as the average value of angular directions in which the angular transmittance is higher than 90% of its maximum value.

1.2 The luminescence inverse method and the MOA

The luminescence-inverse (LI) method is used to fast measure the optical-angular properties of a CPV module without the need of neither illumination system nor module movement. In the LI method, the multi-junction (MJ) solar cell[13] is forward biased to reproduce a Lambertian light source at the exit of the module by electroluminescence.[14–18] Therefore, the performance of the CPV module can be studied based on the principle of reversibility in optics.[19] If the whole cell area emits in all possible angular directions with the same intensity, then the light rays exiting the module in a given angular direction (α, ϕ) will have an intensity that is proportional to the angular transmittance for that direction when the whole concentrator is illuminated by uniform, collimated radiation [i.e., the angular transmission function $H(\alpha, \phi)$ when the module is illuminated with collimated light].

A large parabolic mirror is used to focus the backward light of the module with a given angular direction (α, ϕ) to the same point in the focal plane of the mirror. Therefore, the light emitted by the module is discriminated as function of its angular properties (Fig. 2). Moreover, the light emitted by the module is also evaluated as function of its spatial properties by the MOA.

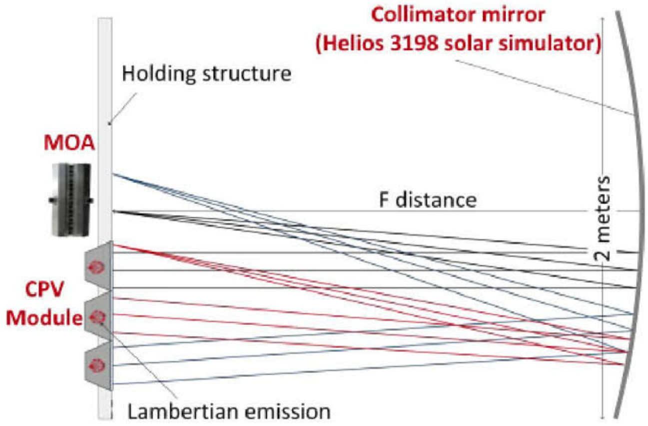

Fig. 2. (Color online) Measurement scheme of the LI method used to evaluate the optical-angular properties of CPV modules.

The MOA is an apparatus that implements the already presented LI method and that has been developed during the course of the project entitled "A new generation of concentrator photovoltaic cells, modules and systems" (NGCPV).[20] The first prototype of the MOA for a production line was developed and installed in 2013 at Daido Steel facilities in Nagoya (Japan).[21]

The MOA consists of a set of scientific-grade camera sensors with attached optics that evaluate the module emission at different angular directions. The system provides images of the CPV module emitting light for different angular direction. These angles can be calculated as function of the focal distance of the collimator mirror, and the distance between the camera sensors and the module.

The identification of the different optical system-cell units comprising the module can be performed if a good spatial resolution is achieved in the photographs given by the MOA system. In Fig. 3, the images corresponding to a module formed by nine units with a spatial resolution of $1.4\,\mathrm{mm{\cdot}pixel^{-1}}$ are presented. It can be observed that units are easily identifiable because each one emits with a particular intensity level and spatial map emission at the different evaluated angular directions. The amount of light emitted for each unit at the different angular directions can be quantified by integrating the value of the pixels involved in each unit representation. Thus, the angular transmittance function (equals to the one measured when illuminating the module with collimated light beams) is generated if plotting the integration values in terms of their corresponding angular directions (Fig. 3).[22,23]

The angular transmittance of every unit comprising the module must be measured first to obtain the angular transmittance properties of the CPV module. In the case the module has units series connected, the angular transmittance function of the module is calculated as the minimum enveloped of all the units functions. On the contrary, the module function is the sum of all the units functions if there are only parallel connections.

1.3 Solar simulator for CPV modules Helios 3198 and the MOA

The Helios 3198 is a solar simulator[3,4] whose illumination system is based on a 2 m diameter parabolic mirror and a

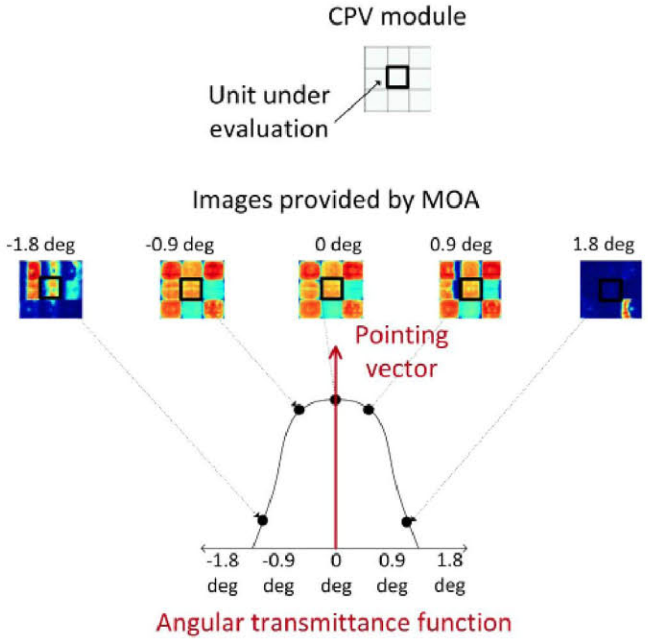

Fig. 3. (Color online) The angular transmittance function and the pointing vector of each unit in the CPV module can be obtained from the images (of the module emitting light at a given direction) provided by MOA.

Fig. 4. (Color online) Scheme of the solar simulator for CPV modules Helios 3198. A xenon lamp is placed at the focus of the collimator mirror to measure the electrical properties of modules (while the module is illuminated with collimated light). The module optical analyzer is installed at the focus of the collimator mirror to characterize the optical-angular properties of CPV modules (while the module is emitting light).

xenon flash lamp placed at the focus of the mirror (Fig. 4). The solar simulator provides uniform and collimated (angular size of 0.4°) illumination over a large area. This equipment is used to characterize the electrical properties (*I–V* curve) of modules in production line. The collimator mirror of the Helios 3198 solar simulator for CPV modules can be adopted in the LI set-up (Fig. 2). Thus, the MOA measurement can be implemented together with the *I–V* curve measurement to fully characterized the CPV module in a production line.

There are few differences in the setups of both the electrical characterization (i.e., *I–V* curve) and the optical-angular characterization (by the MOA). To measure the *I–V* curve at the solar simulator, the module is forward biased (from 0 V to the open circuit voltage V_{OC} of the module) while it is illuminated by collimated light with normal incidence (produced by a xenon flash lamp placed at the focal plane of the parabolic mirror). However to measure the optical-angular properties by the LI method at the solar simulator, the module is forward biased in dark conditions (close to the V_{OC} of the module).

2. Case of study: Variation of the optical-angular properties of CPV modules with temperature conditions

Before being installed at the Instituto de Energía Solar, Universidad Politécnica de Madrid (IES-UPM) experimental field in Madrid, 20 out of 50 CPV "intrepid" modules [dome-shaped Fresnel Köhler (DFK) architecture[24] developed within the NGCPV project[20,25,26]] randomly selected were characterized by the MOA system at IES-UPM laboratory. This characterization was performed after concluding that the modules acceptance angles were significantly lower than expected (0.3° in average if compared with that of the individual optical system-cell unit).

This decrease in angular tolerance is usually mainly caused by misalignments between units. For the 20 modules under study by MOA, a misalignments pattern coincident between them was observed: the alignment of each unit was related to the position of the unit in the module. In general for the vertical direction, those units at the top of the module have opposite alignments than if placed at the bottom of the module. In the horizontal direction, those units at the left side of the module have opposite alignments than the ones at the right side.

These misalignments were proven to be likely to be caused by enclosure deformation rather than the receiver positioning. In fact, the size of the Fresnel lens parquet was discovered to be as much as approximately 0.1% larger than the one at the receiver plate. This difference in size is consistent with the decrease of 0.3° on average for the acceptance angle of the modules under investigation.

In connection with this fact, two different misalignments patterns were distinguished for the 20 modules under investigation: a radial distribution related to the difference in size between lens parquet-and-receiver plate (showed up in 15 out of 20 modules) and a more irregular distribution because of additional deformation due to the enclosure (showed up in 5 out of 20 modules). Based on module manufacturer analysis, the optical-angular improvement in the module could lead to an increase of up to 3–4% absolute points in the FF which justifies the need of quality control alignment processing during manufacturing.

Previous results were obtained when measuring with MOA equipment at 20 °C ambient laboratory temperature. However, the module under operating conditions reaches higher temperatures in both the lenses parquet and the back plate. This increase in temperature can involve a module thermal expansion that modifies its optical-angular properties.[27] To observe misalignments variation with temperature, a MOA measurement was conducted while increasing the temperature of a module to reproduce different outdoor conditions. Several IR bulbs placed at the back side of the module were used to vary its temperature. The module back plate that is made of aluminum was covered with an adhesive black vinyl to increase the light absorption. Several thermocouples were placed between the black cover and the back plate to confirm that the temperature distribution of this surface was rather homogeneous (with variations of 4 °C between the center and the edges of the module). Also the air temperature inside the module is measured with a thermocouple to assure that the MOA measurements are performed under steady-state conditions. It must be noticed that the temperatures used in this experiment are close to the ones already published for a module in operation with slightly lower concentration ratio but similar configuration regarding thermal management.[28]

The optical-angular properties of the modules under investigation do not show any significant variation (average pointing variation lower than 0.03°) while increasing the back plate temperature from 20 to 71 °C. In this experiment, the air temperature inside the module is controlled to ensure stable conditions in the module heating (not only back plate but also lenses parquet). There are differences between the thermal coefficients of the back plate and the lenses parquet of the module under evaluation: the one from poly(methyl methacrylate) (PMMA) lenses parquet depends directly on the process of the lens manufacturing,[29,30] and its value is at least 4 times the one made from aluminum. For this reason, even the aluminum back plate reaches higher temperatures than the lens parquet, the thermal expansion is not larger and thus misalignments remain unchanged.

The previous experiment was also carried out with a very fast temperature increase of the back plate but with not enough time to heat the lens parquet (transient regimen). A MOA evaluation was performed with temperatures from 19 to 66 °C in the back plate and constant ambient temperature (at 19 °C). In this experiment, the air temperature inside the module is not controlled (neither the lens temperature).

In this second experiment, it can be observed that the pointing vectors of all the units in the module slightly decrease (average variation of 0.08°) while increasing the back plate temperature from 19 to 66 °C (without increasing lens temperature). This is consistent with the fact that the back plate is smaller than lens parquet as already stated. If the temperature of the back plate increases, its size does also while the lens remains unaltered (because of the lens temperature is close to the ambient temperature during the whole experiment).

This last experiment shows the capacity of the MOA to analyze the module performance in very short times. However, it must be pointed out that the first experiment in steady-state conditions is the one which reproduces the real outdoor performance conditions of the module. Thus, we can conclude there is no significant change between misalignments for this particular module while varying the temperature conditions.

3. Conclusions

The MOA measures the angular transmittance of a CPV module and the misalignments between its optical system-cell units in short measurement times (seconds). These misalignments between optical system-cell units comprising a CPV module can reveal manufacturing errors or inefficient module design that may decrease the module performance. In this regard, high speed misalignments measurements, enable by the MOA, allow for the characterization of modules under realistic thermal transients.

Acknowledgments

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