SAND2015-2582C

Mapping HCPV Module or System Response to Solar Incident Angle

Daniel Riley[1, a)]

[1]Sandia National Laboratories
[a)]Corresponding author: driley@sandia.gov

Abstract. Existing definitions of solar angle of incidence (AOI) present an under defined coordinate system by providing only one of the two required angles in a spherical coordinate system. That is, for a given solar AOI, there are an infinite number of module and sun orientations described by that AOI. Thus, the definition of AOI is inadequate for describing the response of many concentrating photovoltaic systems that respond differently to the same AOI depending on the module rotation. Sandia has proposed adding another angle, the AOI Direction, to generalize the definition of AOI and provide common terms for use across the CPV industry. Furthermore, Sandia has used this new definition to map the electro-optical response of HCPV modules to AOI. The resulting response surface provides a more complete picture of the sensitivity of the module to AOI and can be used to determine the module's acceptance angle, or any optical defects. This paper briefly describes AOI and AOI Direction and presents the results of mapping an HCPV module's electro-optical response.

INTRODUCTION

The response of concentrating photovoltaic (CPV) technologies to solar angle of incidence (AOI) has historically been characterized by the measurement of a module's acceptance angle. The acceptance angle is commonly defined as the solar AOI at which the output power is reduced to 90% of the power at normal incidence [1]. However, this simplistic definition assumes that the module responds symmetrically to solar AOI, i.e. the module responds similarly to a given AOI, regardless of the rotation of the module. Thus, the common measurement of AOI response is dependent upon a device's rotational symmetry. For devices that are not rotationally symmetric, the common characterization by acceptance angle is insufficient to describe AOI response. For example, consider linear focus low-concentration CPV (LCPV) systems such as that presented by [2] that respond very differently along the two device axes. High-concentration CPV (HCPV) systems may also have AOI response that is rotationally asymmetric due to the design of their optics, although HCPV systems usually exhibit more symmetric AOI response than LCPV systems.

We believe that the primary deficiency of the existing definition of solar AOI (in both the flat-plate PV and CPV fields) is the fact that the definition presents an under defined coordinate system. If the module face or aperture is the reference plane of a unit spherical coordinate system, the solar AOI is the polar angle of coordinate system. The definition of solar AOI does not include the second angle, the azimuthal angle, which is required to fully define the coordinate system.

There are current proposals that call for characterization of the AOI response in a module's two primary axes [3], which addresses some of the limitations of the under-defined coordinate system, but still fails to fully characterize the AOI response.

A NEW DEFINITION OF SOLAR AOI

In order to completely address the under defined coordinate system currently used for describing solar AOI, Sandia has proposed modifying the definition of AOI to include a second angle, the AOI Direction [4]. The AOI Direction angle serves as the azimuthal angle of the polar coordinate system, thus the combination of the AOI and the AOI Direction angle fully define the position of the sun relative to the module face or aperture. Figure 1 shows the proposed coordinate system with AOI (θ) and AOI Direction (φ). The definition and methods of calculating AOI and AOI Direction are more fully defined in [4], which also provides an algorithm for determining how to generate a desired AOI/AOI Direction using a two axis solar tracker.

The proposed coordinate system is fully compatible with the existing definition of AOI because the AOI Direction is a simple addition to the existing definition of AOI. That is, the inclusion of AOI Direction simply provides more specific information about the AOI. Also note that the AOI/AOI Direction coordinate system is relative to the module face or aperture, and thus it provides a means to communicate the performance of a CPV module without using earth-relative terms such as "azimuth", "zenith", or "elevation".

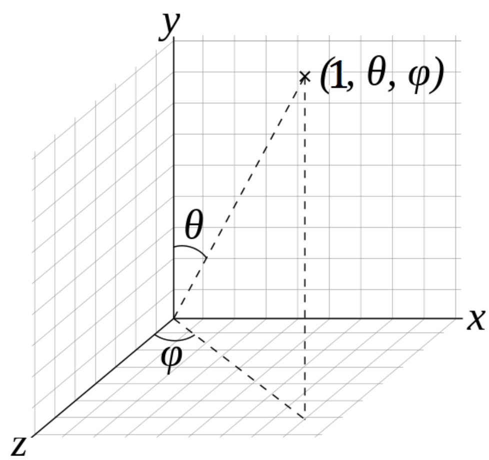

FIGURE 1. A unit spherical coordinate system with labeled AOI (θ) and AOI Direction (φ). In this coordinate system, the module lies in the x-z plane with the top of the module in the positive z direction and the specified vector points toward the sun. The y dimension is normal to the module.

MAPPING CPV RESPONSE TO AOI AND AOI DIRECTION

The newly defined coordinate system creates a unique coordinate for each sun position relative to the module aperture. The unique coordinates of the module relative to the sun then provide a basis for testing, characterizing, and visualizing the electro-optical response of any CPV module. In this paper, we present the method for testing, analyzing, and visualizing the electro-optical response of an HCPV module.

Procedure

The HCPV module is first mounted on a two axis solar tracker with the "top" of the module oriented toward the "top" of the tracker. Thermocouples are placed to measure the temperature of at least three PV cells, preferably as close to the cells as possible. The CPV module is then connected to an I-V curve tracer. The direct normal irradiance (DNI) must be measured by a pyrheliometer on a different tracker.

Prior to beginning the test, it is necessary to establish a test plan with the desired AOI/AOI Direction test coordinates. The set of AOI/AOI Direction coordinates should be carefully chosen to extract the desired level of characterization, for example, a module with an acceptance angle of ±1 degree might be tested to include AOI between 0 and 1.5 degrees in multiple directions. A good test plan should include as many AOI/AOI Direction coordinates as possible in order to create a dense performance grid, however, more test coordinates means that the test will have a longer duration and runs the risk of environmental changes (e.g. irradiance, spectrum, temperature) that must be corrected. Thus it is important to consider the relative importance of the density of the test points and the test duration when designing the test.

The test is then conducted by moving the two axis tracker to orient the CPV module to the desired series of AOI/AOI Direction coordinates using the algorithm in [4]. One or more I-V curves must be measured at each coordinate. The DNI must be measured simultaneously on a separate tracker.

Analysis and Results

The parameter of interest should be corrected for differences in irradiance, temperature, and spectrum (if desired) to adjust the results to a common environmental condition. For this example, we have chosen the parameter of interest to be the current at maximum power (I_{MP}), and a sample adjustment equation is provided as equation 1. Other performance parameters may also be measured such as maximum power (P_{MP}) or short circuit current (I_{SC}) with slightly different correction equations.

$$I_{MP,adj} = I_{MP} \times \frac{E_0}{E} \times \left[1 + \alpha_{Imp} \times \left(T_C - T_{C,0}\right)\right] \tag{1}$$

where:
$I_{MP,adj}$ is the I_{MP} adjusted to the reference environmental condition
I_{MP} is the measured I_{MP} at each orientation coordinate
E_0 is the DNI reference environmental condition
E is the measured DNI at each orientation coordinate
α_{Imp} is the temperature coefficient of the cells in units of 1/C
T_C is the measured cell temperature in units of °C
$T_{C,0}$ is the reference cell temperature in units of °C

The correction function may vary depending upon module type and influencing factors. For example, if AOI values are greater than a few degrees, it may be necessary to also correct for the reduction in irradiance due to incident angle. Also, we recognize that it is difficult to measure or estimate operating cell temperature of a module under natural light, however it may be possible to use measured module temperature and a reference module temperature if the temperature difference between the cell and heat sink is relatively constant as shown in [5].

After adjusting the I_{MP} to a common operating condition, the parameters are normalized by the maximum value obtained during the test, as shown in equation 2.

$$I_{MP,norm} = I_{MP,adj} / \max\left(I_{MP,adj}\right) \tag{2}$$

The grid of normalized I_{MP} values is now plotted in three dimensions as shown in Fig. 2(a). This grid represents the measured points on a surface that describes the CPV module's response to AOI and AOI Direction. By interpolating between the grid points, we form a full surface that may be used for finer analysis. Several interpolation methods are possible (e.g., linear, cubic), and we have found good results with linear interpolation.

Once the response surface is created, many visualizations options are possible. As shown in Fig. 2(b-d), the surface can be viewed in three dimensions as an isometric view, a heat map, or a contour projection. In Fig. 2 the plots have been translated from a polar coordinate system (AOI, AOI Direction) to Cartesian system (cross-elevation, elevation) for ease of understanding.

The test results shown in Fig. 2 are the result of 161 I-V curves at different AOI and AOI Direction coordinates. From Fig. 2(d) it is clear to see that the module exhibits a 10% reduction in I_{MP} at angles of ±0.8 degrees in the "elevation" direction (φ=0° and 180°), ±0.9 degrees in the "cross-elevation" direction (φ=90° and 270°), and ±1.0 degree in a combined elevation/cross-elevation direction (φ=135° and 315°). The response has a slightly rectangular shape due to the optical system of the module.

CONCLUSIONS AND FUTURE WORK

In Sandia's testing of HCPV and LCPV modules, we have found that the existing description of AOI as a single angle is inadequate in describing the response of CPV modules to AOI, particularly for modules that do not exhibit rotationally symmetric AOI response. Current methods of dealing with this inadequacy usually involve the creation of new terms that are only used by one company and are specific to their particular product (e.g. parallel incidence and perpendicular incidence, elevation and cross-elevation). In order to more generally address the inadequacy of a single angular representation of AOI, we present the addition of a second angle, the AOI Direction, that fully describes the spherical coordinate system of AOI. The addition of AOI Direction is compatible with the existing definition of AOI, and requires only the inclusion of a second angular measure and a reference module orientation.

Using this new definition of AOI with AOI Direction, Sandia has successfully mapped the electro-optical response of several HCPV modules in two dimensions. The electro-optical response mapping provides a performance surface that describes the ability of a CPV module to convert direct light from a given AOI/AOI Direction. While we have presented a mapping for a single HCPV module, we believe that the technique could also be used for full HCPV systems on a single tracker.

The response mapping can display several interesting characteristics about an HCPV module or system. The surface can easily be analyzed to determine acceptance angle in any direction and provide a more complete picture of the sensitivity of the module or system to AOI. The response may also serve a diagnostic purpose by uncovering misaligned optics within a module, misaligned modules within a tracker, or other optical defects present in a module or system.

Most HCPV modules exhibit nearly AOI response that is nearly rotationally symmetric, and thus the AOI response surface of such an HCPV module would be a simple "round hill" as in Fig. 2(b). However, LCPV modules with directionally-selective optics, such as linear concentrators, exhibit extreme rotational asymmetry in response to AOI. With some slight modification to the analysis steps presented here, this method can be adapted to provide response surfaces for LCPV modules.

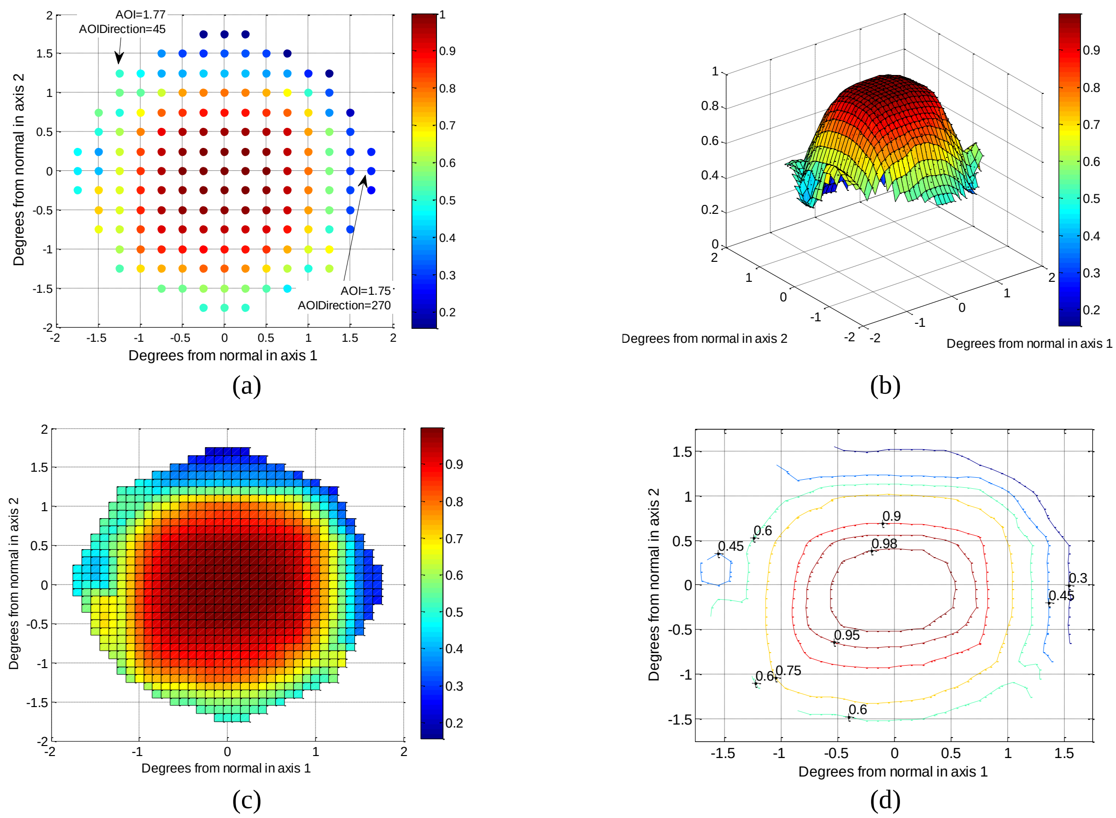

FIGURE 2. (a) The grid of measured normalized I_{MP} points. (b) A three dimensional visualization of the AOI/ AOI Direction response surface. (c) A heat map visualization of the response surface. (d) A contour projection of the response surface.

REFERENCES

1. S. Kurtz, et. al, "Key Parameters in Determining Energy Generated by CPV Modules," *Progress In Photovoltaics: Research and Applications,* 2014, accessed October 8, 2014, DOI: 10.1002/pip.2544
2. R. Varieras, et. al, "System Performance Considerations for Low Concentration Linear-Focus Silicon-Based Photovoltaic Modules," *IEEE Journal of Photovoltaics*, **3**(4), 2013. DOI: 10.1109/JPHOTOV.2013.2270340
3. IEC 62670-3 Draft, Nov. 2014.
4. D. Riley, C. Hansen, "Sun-Relative Pointing for Dual-Axis Solar Trackers Employing Azimuth and Elevation Rotations," *ASME Journal of Solar Energy Engineering*, **137**(3), 2014. DOI: 10.1115/1.4029379
5. M. Muller, et. al, "Determining Outdoor CPV Cell Temperature," *Proc. 7th International Conference on Concentrating Photovoltaic Systems*, 1407, pp. 331-336, 2011.