Inexpensive Indoor Spot-cell and Spot-light Methods for Angle of Incidence Measurements of PV Modules

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Abstract—Various testing methods have been explored in the past to study the effect of the angle of incidence (AOI) on the short-circuit current (Isc), and hence the power, of a photovoltaic module. In this paper, we are presenting two simple methods for determining the effect of AOI on the short-circuit current, namely the spot-cell method applied on the 1-cell module and the spot-light method applied on the full-size commercial module. The purpose of this work is to design and establish an inexpensive but accurate indoor test setup that can be used by the industry to obtain AOI curves for a cell or a module. This paper provides details on the construction and operation of the test setup. The AOI curves obtained in this work have been compared and validated using the AOI curves obtained as per IEC 61853-2 standard. This paper presents AOI results obtained on crystalline silicon cells and modules with glass superstrates, with and without anti-soiling coatings, and with and without artificially deposited soil layers.

Keywords: angle of incidence, spot-cell method, spot-Light method

I. INTRODUCTION

For years, researchers have explored various indoor and outdoor techniques to understand the influence of the angle of incidence (AOI) from the rays of sun on the performance of the solar photovoltaic (PV) modules [1-6]. The purpose of this work is to design and construct an inexpensive indoor system that can be used by the industry to obtain accurate AOI curves on the 1-cell module and commercial-size module. This paper provides details on the design, construction, operation of the test setup and on the test results obtained with glass superstrates, with and without anti-soiling coatings and artificially deposited soil layers. The AOI curves obtained in this study have been compared and validated using the AOI curves obtained as per IEC 61853-2 standard [5], which is primarily based on the model reported by Martin & Ruiz [4].

In the absence of any reflection of the light from surface of the device with and without cover glass/superstrate, the short-circuit current (Isc) of a PV device obtained from any angle should follow the following equation:

\[ I_{sc}(\theta) = I_{sc}(0) \cdot \cos(\theta) \]  

(1)

In this equation, Isc(0) is the short-circuit current at zero angle of incidence and Isc(\theta) is the short-circuit current at \( \theta \) angle of incidence. The \( \theta \) angle of incidence is the angle between the normal of the module surface and the direction of the incoming light. In the presence of any reflection of light, the relative light transmission into the module \( \tau(\theta) \) [or relative short-circuit current into the module Isc(\theta)] can be approximated as shown in equation 2 [4, 5]. The values for \( A_r \) typically range from 0.16 to 0.17 for commercial modules with clean glass superstrates, and \( A_r \) is about 0.20 and 0.27 for modules having moderate and significant dust, respectively [4, 5].

\[ \tau(\theta) = 1 - \exp\left(\frac{-\cos(\theta)}{A_r}\right) \]  

II. METHODOLOGY

A. Test setup

The designed and constructed test setups are shown in Fig. 1, Fig. 2 and Fig. 3. Two AOI measurement approaches have been implemented in this work, spot-cell method for the 1-cell modules and the spot-light method for the commercial-size modules as shown in the schematics of Fig. 1.

Fig. 1. Schematic representation of Spot-Cell method and Spot-Light method for 1-cell module (left) and commercial-size module (right), respectively

Fig. 2 shows the photograph of the physical desktop test setup for 1-cell module testing with a parallel light source, collimator, sample holder with tilt table inside the black plexiglass box to...
hold the 1-cell module and an ammeter to measure the short-circuit current of the test device. Fig. 3 shows the photograph of the physical test setup for commercial-size module testing with a parallel light source, collimator, module holder with tilt table inside a dark room to hold the commercial-size module and an ammeter to measure the short-circuit current of the test cell (accessed by backsheet cutting) within the module. The parallel light source was purchased from the Dedolight (model DL 150), the collimator was made out of a wider black plastic tubing fitted with a narrow end tubing (dimensional details provided in the forthcoming sections) and a high precision ammeter was purchased from Keithley (model 2700).

![Fig. 2. AOI test setup for the spot-cell method for 1-cell module](image)

**B. Clean device measurements**

**B.1. Spot-cell method on a cell without shading mask**

For the spot-cell method at the 1-cell module measurements, the test setup shown in Fig. 2 was utilized. A tungsten-halogen lamp with built-in parallelizer and a long black tubing (183 cm height) were used to obtain a parallel beam (about 9 cm²) on the test sample placed on a flat platform of tilt table (for changing soil deposition angles) located inside a darkened plexiglass box placed on a study table. In this test setup, a 1 cm² cell with glass/EVA/ cell/ EVA/ backsheet construction was used to obtain the AOI data. A low iron 3.2 mm Solite glass, EVA and backsheet construction with 60x70 mm dimensions was used. These 1 cm² cells were made with black backsheet to avoid the influence of backsheet reflection on the measured AOI data. To maintain light uniformity on the test device, it is critical to align the center of the light spot to the center of the 1 cm² cell at all test angles. This was achieved by horizontally moving the cell-mounted platform (see Fig. 1) so that the cell-center and light spot-center are lined up at every tilt angle. The measured data in this approach requires conventional cosine-loss correction to calculate the reflection loss.

**B.2. Spot-cell method on a module with shading mask**

For the spot-cell method at a commercial-size module measurements, the test setup shown in Fig. 3 was used. This approach was complex due to the need of a few test setup adjustments during the measurements, was less accurate due to shading issue of the mask at high AOI and was later abandoned in favour of spot-light method presented in the next section. In this method, the same tungsten-halogen lamp with built-in parallelizer and a long black tubing were used to obtain a parallel beam on the test sample. The test sample in this case was a 72-cell commercial module. One of the center cells served as the test cell and was accessed to measure Isc by cutting the backsheet, and this test cell was aligned to the axis of rotation of a large rotatable platform. Only 1 cm² area/window of the selected cell was exposed, using shading mask, to the light spot of about 9 cm². To avoid the shading issue of the shading mask on the exposed 1 cm² area, an extremely thin black painted aluminium foil was used at shade-casting side of the 1 cm² square window. Other areas of the test cell and all the other cells surrounding the test cell were covered with thin black tape. This 1 cm² surface is located on the axis of the module mounting platform so that, during the rotation of the module, the distance between the illuminated surface of 1 cm² and the halogen lamp light source is constant (about 186 cm). This constant distance adjustment was achieved through the use of a laser light guide with a distance reading capability. To maintain light uniformity on the exposed cell area, it is important to align the center of the light spot (about 2 cm²) to the center of the 1 cm² exposed cell area at all test angles. This was achieved by horizontally moving the light so that the exposed-center and light spot-center are lined up at every tilt angle. The measured data in this approach requires conventional cosine-loss correction to calculate the reflection loss.

**B.3. Spot-light method on the module without shading mask**

This method was found to be the easiest and most accurate method compared to the other two approaches explained above. For the spot-light method at the commercial-size module level measurements, the test setup shown in Fig. 3 was used. The test setup using the spot-cell method at the module level and the
spot-light method applied at the module level are identical except for the following: the light spot area was reduced to 1 cm² by narrowing and extending the light tube close to the surface (1.5 cm above the surface); no part of the module surface, including the test cell surface, was covered/masked with black foil or tape. The 1 cm² circular light spot was first aligned to the axis of rotation and was located close to the right of right-most busbar at zero angle of incidence as shown in Fig. 3. Then the module was rotated, and the light spot shape changed from circular at zero AOI to elliptical at higher AOI and the elliptical shape of the light was covering a larger area of the test cell at high AOI. To ensure the validity of this approach, it is most critical to ensure that the spot-light is contained within the test cell area at all tilt angles of the modules (i.e. at all AOI values). Since this method self corrects the cosine loss, the relative AOI providing the reflectance part of the curve is directly obtained without the need of any mathematical cosine-loss correction.

C. Anti-soiling (AS) coated device measurements with and without soil deposition

Three 1-cell test modules were fabricated at ASU-PRL: on the first module (AS1), an AS coating was applied by the manufacturer directly onto the glass surface of one test module supplied by ASU-PRL; on the second module (AS2), an AS coating material was purchased locally and applied with a commercially available paint roller by ASU-PRL; the third module remained uncoated (UC). A photograph of the test modules with dimensions is shown in Fig. 4.

Fig. 4. Labelled single-cell PV test modules (left to right): A) Uncoated (UC) 20.32 cm x 20.32 cm; B) AS1 Coated (AS1) 20.32 cm x 20.32 cm; C) AS2 Coated (AS2) 20.32 cm x 27.94 cm

Uniform layers of soil on the surface of the AS1, AS2 and UC 1-cell modules were deposited using Arizona road dust (2 grams) at 0° and 33° tilt angles using the deposition technique already established at ASU-PRL [9-11]. The AOI measurements which were performed on clean devices were repeated on the soiled 1-cell modules with and without AS coatings using the above defined spot-cell and spot-light methods. All the soiled 1-cell modules were tested in the test setups shown in Fig. 2 and Fig. 3 (In Fig. 3, the soiled 1-cell module was placed and taped to the surface of a commercial module, so the commercial module was merely serving a support structure for the 1-cell module/coupon with and without soil layer). After that we used the spot-light method to measure the variation of the I_{sc} according to the angle of incidence for each module.

III. RESULTS AND DISCUSSION

A. Comparison and selection AOI test methods
The test results obtained using spot-cell and spot-light methods at both cell and module levels are presented in Fig. 5 to 8. Based on the current experimental results, the spot-light method, at both cell and module levels, appears to be the best method in terms of accuracy (see TABLE 1 for MAE and RMSE), simplicity (no special sample preparation is required, no cosine correction is required, and no shading issue at high AOI is experienced due to the absence of surrounding tape/foil) and measurement duration (more than 60% reduction in testing time). All these measurements have been, so far, carried out using the manual methods. We aim to automate these methods so that the testing repeatability within our lab and reproducibility between multiple labs can be improved.

Fig. 5. Spot-cell method on 1 cm² clean cell: Validation of measured relative transmission by comparison with IEC standard for clean module

Fig. 6. Spot-cell method on clean module: Validation of measured relative transmission by comparison with IEC standard for clean module
Fig. 7. Spot-light method on clean module: Validation of measured relative transmission by comparison with IEC standard for clean module

Fig. 8. Spot-light method on soiled module: Validation of measured relative transmission by comparison with IEC standard for soiled (Ar=0.29) module

Fig. 9. Comparison between measured-clean module relative transmission and IEC standard values for AS1

Fig. 10. Comparison between measured-clean module relative transmission and IEC standard values for AS2

Fig. 11. Comparison between measured-clean module relative transmission and IEC standard values for UC

C. AOI effect on modules soiled at 0° tilt angle

The results obtained after soiling each of the three modules at 0° are shown in the TABLE 2 and by the Fig. 12 to 14.

### TABLE 1. Comparison of MAE and RMSE between three AOI methods

<table>
<thead>
<tr>
<th>Methods</th>
<th>Spot-light/Module</th>
<th>Spot-cell/Cell</th>
<th>Spot-cell/Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAE</td>
<td>0.0017</td>
<td>0.0052</td>
<td>0.0068</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.0029</td>
<td>0.0075</td>
<td>0.0113</td>
</tr>
</tbody>
</table>

B. AOI Effect on AS1, AS2 and UC clean modules by spot-light method

Before studying the effect of the anti-soiling coating on the soil deposition for the three types of AS coated modules, we studied the angle of incidence effect for AS1, AS2 and UC clean modules by the spot-light method. A comparison of the measured data with the IEC standard data are shown in Fig. 9 to 11. These figures indicate that there is no AOI change due to AS1 or AS2 coating on the glass surface.

Fig. 12. Comparison between measured-clean module relative transmission and IEC standard values for AS1

Fig. 13. Comparison between measured-soiled module relative transmission and IEC standard values for AS2 at 0° soil deposition
Table 2: The weights of soil on the modules at 0° and 33°

<table>
<thead>
<tr>
<th>Module name</th>
<th>0° (flat) position soiling</th>
<th>Soil per cm² at 0° tilt</th>
<th>33° position soiling</th>
<th>Soil per cm² at 33° tilt</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS1</td>
<td>0.71g</td>
<td>3.2mg</td>
<td>0.39g</td>
<td>1.8mg</td>
</tr>
<tr>
<td>AS2</td>
<td>0.43g</td>
<td>1.95mg</td>
<td>0.32g</td>
<td>1.5mg</td>
</tr>
<tr>
<td>UC</td>
<td>0.82g</td>
<td>3.7mg</td>
<td>0.50g</td>
<td>2.3mg</td>
</tr>
</tbody>
</table>

Higher the Ar value mean higher the soiling level. The Ar value in the model was increased until the measured and modelled AOI curves were matching. As can be seen in Fig. 12 through Fig. 14, AS2 seems to be better than AS1 and UC with lowest Ar value.

D. AOI effect on modules soiled at 33° tilt angle

The comparative results obtained after soiling of AS1, AS2 and UC modules at 0° and 33° (latitude angle of Phoenix, Arizona) are shown in the Table 2 and by the Fig. 15 to 17.

AS1 (Comparison Flat 0° and 33° soil deposition)

AS2 (Comparison flat 0° and 33° soil deposition)

UC (Comparison flat 0° and 33° soil deposition)

As indicated in Table II and as expected, the extent of soiling on the tilted modules was lower compared to the horizontal modules. This table also indicates that the highest level of soiling occurs on the UC module and the lowest level on the AS2. These tabulated observations are consistent with the results shown in Fig. 15 through 17 – higher the tilt angle lower the soiling and AS2 coating appears to be better than AS1 and UC.
Table II and Figures 15 through 17 clearly indicated that:

i) higher the tilt angle of the module, lower the soil deposition amount on the module surface and it is consistent with our field observations [7];

ii) AS2 performs the best at both tilt angles and it is consistent with our previous findings [8, 9].

IV. CONCLUSIONS

In this study, two unique AOI measurement methods are presented. AOI data obtained using these two methods are compared with the IEC 61853-2 modelled data for clean, soiled and anti-soiling coated modules. Of these methods, the spotlight method is determined to be the best in terms of equipment cost, accuracy, simplicity and testing duration. This simple, inexpensive AOI method can be used to quickly evaluate the anti-reflection/anti-soiling coated commercial modules and field-soiled commercial modules with cemented soil layer. This method currently involves manual operation of the test setup. An automated operation of this setup is being planned to be implemented in the next step.

The use of anti-soiling coating is very important to reduce the quantity of dust on the surface of the modules and to increase the energy production of the module. We have reported that AS2 is better than AS1 for the fresh coatings, but it is important to evaluate and compare the effectiveness and durability of these AS coatings after prolonged UV exposure in the field or accelerated testing. This will be a topic of future research of this research group.

REFERENCES


3. D. King, “Measuring angle of incidence (AOI) influence on PV module performance” Private communication (this communication is reproduced in Appendix A of reference 1), 2013


