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

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Overview

Two simple AOI testing methods: Operating principles

AOI testing methods: Construction and operation of test setup

Generation of AOI curves (clean, AS coated, soiled) and comparison with IEC 61853-2 standard AOI curves

Conclusions
Introduction

• Various indoor and outdoor AOI techniques reported in the literature [1-6]

• Purpose of this work is to design and construct an inexpensive but accurate AOI measurement system that can be used by the industry

• In the absence of light reflection loss, the short-circuit current (Isc) of a PV device (or light transmittance) at any angle should follow the following equation:

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

• In the presence of light reflection loss, the light transmittance typically follows the empirical equation shown below for the glass superstrates (Ar typically ranges from 0.16 to 0.17 for clean glass superstrates and from 0.20 to 0.27 for glass superstrates having moderate to significant dust [4, 5].

\[ T(\theta) = 1 - \left[ 1 - \exp \left( \frac{-\cos(\theta)}{A_r} \right) \right] \left[ \frac{1 - \exp \left( -\frac{1}{A_r} \right)}{1 - \exp \left( -\frac{1}{A_r} \right)} \right] \]
AOI testing methods

Spot-cell Method on 1-cell module

Spot-light Method on full-size commercial module

Spot-cell (1 cm²)

- 0° tilt; Circular Shape Light Spot

Spot-cell (1 cm²)

- 60° tilt; Elliptical Shape Light Spot

Circular Shape Spotlight

Elliptical Shape Spotlight
Spot-cell Method on 1-cell module

- PARALLEL LIGHT SOURCE
- COLLIMATOR
- 1-cell module (1cm²)
- TILT TABLE
- TEST STAND
- X-AXIS MOVEMENT FOR LIGHT UNIFORMITY

- Black Plexiglass box to hold test sample
- Ammeter
Spot-light method on full-size commercial module

- Parallel light source
- Collimator
- Axis of rotation
- Tilt table
- Test stand
- Commercial module
- X-axis movement for alignment
Spot-light method on full-size commercial module
Test Setup - For artificially depositing soil layer

Soil deposition chamber placed on the module tilted at 33°

Labeled single-cell PV test modules (left to right):
A) Uncoated (UC) 20.32cm x 20.32cm;
B) AS1 Coated (AS1) 20.32cm x 20.32cm;
C) AS2 Coated (AS2) 20.32cm x 27.94cm
**Study methods comparison**

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

*Spot-cell* method on clean *module*: Validation of measured relative transmission by comparison with IEC standard for clean module (*the spot-cell method for module was abandoned later as spot-light method was determined to be simple and more accurate*)
**Study methods comparison**

**Spot-light method on clean module:** Validation of measured relative transmission by comparison with IEC standard for clean module

**Spot-light method on soiled module:** Validation of measured relative transmission by comparison with IEC standard for soiled (Ar=0.27) module

### 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>
AOI Effect on clean Modules by spot-light method

Comparison between measured-clean module relative transmission and IEC standard values for **AS1**

Comparison between measured-clean module relative transmission and IEC standard values for **AS2**

Comparison between measured-clean module relative transmission and IEC standard values for **UC**

**AS1 = Anti-soil coating 1**  
**AS2 = Anti-soil coating 2**  
**UC = Uncoated**
AOI Effect on Modules Soiled at 0° Tilt angle

Comparison between measured-soiled module relative transmission and IEC standard values for AS1 at 0° soil deposition

Comparison between measured-soiled module relative transmission and IEC standard values for AS2 at 0° soil deposition
AOI Effect on Modules Soiled at 0° Tilt angle

Table 1: The weights of soil on the modules at 0° and 33°

<table>
<thead>
<tr>
<th>Module name</th>
<th>Flat (0°) position soiling</th>
<th>Soil per cm²</th>
<th>33° position soiling</th>
<th>Soil per cm²</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>1.45mg</td>
</tr>
<tr>
<td>UC</td>
<td>0.82g</td>
<td>3.7mg</td>
<td>0.5g</td>
<td>2.3mg</td>
</tr>
</tbody>
</table>

Comparison between measured-soiled module relative transmission and IEC standard values for UC at 0° soil deposition
AOI Effect on Modules Soiled at 33° Tilt angle

Comparison between measured-soiled module relative transmissions for AS1 at 0° and 33° soil deposition

Comparison between measured-soiled module relative transmissions for AS2 at 0° and 33° soil deposition
AOI Effect on Modules Soiled at 33° Tilt angle

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

Comparison between measured-soiled module relative transmissions for UC at 0° and 33° soil deposition

**Comparison 33° AOI soiling AS2-UC**

Comparison between measured-soiled module relative transmissions for AS2 and UC at 33° soil deposition
Conclusion

1) 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 spot-light 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.

2) 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 report 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.
Conclusion

Table 1 and Figures of AOI effect on modules soiled at 33° tilt angle clearly indicated that:

1) 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]

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

4) N. Martin and J. Ruiz, “Annual angular reflection losses in PV modules” Progress in Photovoltaics. 13, 75–84, 2005


