Angle of incidence effect on five soiled modules from five different PV technologies

Preprint

V. Rajasekar; S. Boppana; G. TamizhMani

2015 IEEE 42nd Photovoltaic Specialists Conference (PVSC)

2015
Angle of Incidence Effect on
Five Soiled Modules from Five Different PV Technologies
Vidyashree Rajasekar, Sravanthi Boppana, GovindaSamy TamizhMani
Arizona State University Photovoltaic Reliability Laboratory (ASU-PRL), Arizona, United States

Abstract — Higher the angle of incidence (AOI), lower will be the photovoltaic (PV) module performance. The AOI investigation for cleaned modules of five different technologies with air/glass interface has already been reported by our research group. However, the modules that are installed in the field would invariably develop a soil layer with varying thickness depending on the site condition, rain fall and tilt angle. The soiled module will have the air/soil/glass interface rather than air/glass interface. This study investigates the AOI variations on soiled modules of five different PV technologies. It is demonstrated that AOI effect is inversely proportional to the soil density — in other words, the power or current loss between clean and soiled modules would be much higher at a higher AOI than at a lower AOI leading to excessive energy production loss of soiled modules on cloudy days, early morning hours and late afternoon hours. Also, in this study, we show that the critical angle shifts from $57^\circ$ for the clean air/glass interface to $40^\circ$ for the naturally developed air/soil/glass interface in Mesa, Arizona for the fall season.

Index Terms — angle of incidence, interface, soiling, photovoltaic.

I. INTRODUCTION

Reflectance of photovoltaic (PV) module superstrate plays a vital role in determining the amount of sunlight reaching the solar cells. Higher angle of incidence (AOI) drastically affects the short circuit current ($I_{sc}$) of PV modules as it increases the reflectance. As shown in Figure 1, $I_{sc}$ is affected in two ways [1]-[3]: 1. Geometric or cosine loss 2. Reflection loss.

![Fig. 1. Influence of AOI on short circuit current ($I_{sc}$)](image_url)

In a cleaned module, when the incident light is at $0^\circ$ angle of incidence, there is little/no loss due to absorption and reflection on glass surface, whereas a soiled module experiences some absorption and reflection losses due to soiling. When the incident light is greater than $0^\circ$ angle of incidence, there are geometric losses or cosine losses as well as reflection loss. The geometric losses are simply dependent on the angle at which the module is, with respect to incident light for a cleaned module, and can be calculated as the cosine of the angle of incidence. This cosine loss remains the same in the case of a soiled module. However, reflectance losses change for soiled modules from cleaned modules due to a change in interface structure. This phenomenon is important in case of fixed tilt systems that experience a wide range of tilt angles. In a previous study, we reported the effect of angle of incidence on cleaned modules for five different technologies and the critical angle for the cleaned modules was found to be about $57^\circ$ irrespective of the technology type [2]. The critical angle is defined as the angle above which there is a loss of 3% or above as compared to the $0^\circ$ AOI. In another follow-up study on a soiled polycrystalline silicon technology, we reported that the AOI effects change proportionally to the density/thickness of the soil layer [4]. In this study, the effect of soiling on AOI of modules from five different technologies is presented.

II. EXPERIMENTAL METHODS

A. Angle of Incidence Measurements

The study involved performing AOI effect measurement, reflectance measurement and transmittance measurement for various soiling densities of field soiled modules as they naturally get soiled.

Modules from five technologies (monocrystalline silicon, polycrystalline silicon, amorphous silicon, CdTe and CIGS) were used in this study. The modules that were used had glass superstrate. They were placed on a two-axis tracker coplanar to each other. The co-planarity was verified using a sundial.

Before the start of the experiment, a preliminary analysis was done to understand the soil collection rate dependence on the direction of modules facing. The modules on trackers facing true-south and south-west were initially experimented and it was found out that the modules facing south-west had higher and uniform soiling density when compared to the true-south facing modules. As expected the south-west wind is a major contributor to the soiling rate at our site, Mesa, Arizona. So, the tracker was adjusted to face the south-west direction to obtain a higher soiling rate over the test period and to maintain
a uniform soiling layer. A 3DM-GX3-25 miniature attitude heading reference system from Microstrain was used to determine the angle of incidence (AOI), i.e. the tilt of the modules and reference devices on the test tracker from the sun. The experimental methodology described in a previous study was followed [4]. Initially, the modules were cleaned and AOI effect on PV modules were measured to ensure that the relative light transmission plots for all the five modules with glass superstrate irrespective of the technology is nearly identical to indicate that the reflective losses are governed by the air-glass interface of the PV modules [1-3]. After the cleaned AOI effect measurements, these modules were allowed to naturally collect soil by adjusting the tracker to latitude tilt (33° tilt) using an inclinometer facing the south-west direction.

Every two weeks, as the soiling layer builds up, AOI and reflectance measurements were carried out so that variations in AOI curves with different soil density layers can be obtained. A total of five rounds, excluding the cleaned one, of measurements were performed as shown in Figure 2.

Fig. 2. Outdoor experimental setup used for five rounds of AOI measurements as the soiling layer was building up

B. Reflectance Measurements

A FieldSpec-4 UV-Vis-NIR reflectance spectroradiometer from Analytical Spectral Devices, Colorado was used for all the reflectance and transmittance measurements. It is a compact, field portable and precision instrument which has a spectral range of 350–2500 nm and a fast data collection time of 0.2 second per spectrum. This instrument is extensively used by the agricultural industry for analyzing soil samples. It has Hi-Brite Contact Probe from ASD Inc. attached to the optical fiber of the spectroradiometer for reflectance measurements. The contact probe includes a halogen bulb light source and the optic fiber of the spectroradiometer measures this to give relative reflectance with respect to a white reference. The contact probe of the instrument should initially be calibrated using a reference reflector, and then is placed perpendicular to the module surface for collecting the reflectance spectra on the soil layers. This instrument allowed us to obtain the reflectance spectra on large commercial modules installed outdoor. These spectra were later analyzed for soil composition and for the wavelength dependent reflectance changes in the solar cell response regions.

C. Module Dedicated for Soil Sampling

In order to collect soil samples to determine the soiling density, it became necessary to use a separate module (shown in Figures 2 and 3), called soil-sampling module, coplanar to the test modules on the same 2-axis tracker. All the three measurements (AOI, reflectance and soil density) on this module were carried in every round of measurements for 8 rounds (three rounds more than AOI measurements rounds).

The soil density was measured using ASU-PRL’s standard operating procedure (SOP): a clean lint roller was weighed using Mettler Toledo (AG285, resolution 0.001 mg); then it was rolled on a pre-determined area on the soil-sampling module to collect soil; then the soiled lint roller was weighed again to calculate the average soil density. The soil density (in g/m²) is calculated using the following formula:

\[
SD = \frac{\text{Weight}_{\text{soil}} - \text{Weight}_{\text{clean}}}{\text{Area}}
\]  

Fig. 3. Soil-sampling module (soil samples were collected on a separate module installed coplanar with the test modules)

D. Transmittance Measurements

As shown in Figure 4, two solar PV glass pieces were also mounted on the same 2-axis tracker coplanar to the modules. A sundial was used to verify the coplanarity. One glass piece was left for soiling while the other was cleaned before every clean transmittance reading. For transmittance measurement, the spectroradiometer is fitted with a Remote Cosine Reflector (RCR) foreoptic, which enables full hemispherical absolute energy measurements. This allows the spectroradiometer to measure the total irradiance that is both direct irradiance and diffuse irradiance, or an artificial light source, as well as the corresponding full hemispherical reflected radiance.
Transmittance through each of the glasses was measured after measuring the direct transmittance of the sun. This transmittance loss through the glass was compared to ensure the spectral loss properties were similar for both the glass pieces. The spectrum was collected for three spots per glass and the average irradiance data was analyzed. All the measurements were performed with minimum delay to eliminate the effect of any possible spectral variation. All the measurements were done at 0° angle of incidence to avoid angle of incidence effects.

**E. Modelling of Soiling Losses due to Effect of Angle of Incidence**

Assuming the soil density is the same throughout the year, annual soiling losses due to AOI effects were calculated for different regions in the United States. Weather data from Solar Anywhere was used for Phoenix while PVSyst weather data based on MeteoNorm was used for other locations in the United States.

**III. RESULTS AND DISCUSSIONS**

**A. AOI Curves for Various Soiling Densities**

AOI curves for soiled modules of different technologies are plotted in Fig. 5. The plot indicates that if there is an identical soil density on the PV modules, then the relative optical response at different AOI i.e. \( f_2(AOI) \) is nearly identical irrespective of the PV technology type. As shown in Figure 6, the relative optical response was obtained as the soil density varies for a mono-Si module which can be considered as a representative example for all other technologies with glass superstrate as observed in this study. Figure 6 indicates that, as the soil density increases, the drop in the \( f_2(AOI) \) beyond critical angle also increases indicating that the reflective losses increase at higher AOI due to soiling. In other words, the power or current loss between clean and soiled modules would be much higher at a higher AOI than at a lower AOI leading to excessive energy production loss of soiled modules on cloudy days, early morning hours and late afternoon hours. The empirical polynomial equations providing the relationship between soiling density and \( f_2(AOI) \) is provided in Table I. The equations for only Mono-Si technology are shown in this table as other technologies have been found to have almost identical equations. For the clean modules (zero soiling density), the empirical equation developed by Sandia can be used [5].

**B. Critical Angles for Various Soiling Densities**

The critical angle for the cleaned module (i.e. 0 g/m² soil density) is 57°; but, as shown in Figure 7, this critical angle exponentially drops as the soiling density increases and reaches a near constant minimum of 40° beyond 0.2 g/m² for up to the maximum measured soiling density of 0.648 g/m². Due to a rain event in late fall season of 2014, the study was unfortunately continued beyond the soiling density of 0.648 g/m². Based on these observations, it can be stated that the critical angle shifts from 57° for the clean air/glass interface to 40° for the naturally developed air/soil/glass interface in Mesa, Arizona for the fall season. It would be interesting to see if and when this near constant minimum of 40° changes with respect to higher level of soiling density.
C. Reflectance Spectra for Various Soiling Densities

The reflectance spectrum in the visible region corresponds to reflectance losses due to soiling, and the Near IR region spectrum gives information of soil moisture and other soil properties. From Figure 8, it can be observed that technologies of similar band gaps exhibit similar reflectance spectra like the crystalline silicon technologies and CIGS. All the technologies show a valley in the corresponding absorption regions. An additional valley/dip was observed at 1700nm in crystalline Si technologies and it is not observed in thin film technologies. This 1700nm valley/dip is due to the absorption by EVA which is present before the cell layers in c-Si technologies. Since EVA is typically present only after the cells, the 1700nm absorption peak is not observed in thin film technologies.

Reflectance soil loss can be calculated as the difference between cleaned and soiled reflectance at a particular spot. Soiling density can be estimated from reflectance soil loss. The average reflectance soil loss over 600-700 nm wavelength band can used to estimate soil density for all the technologies using the equations given in Table II. The reflectance loss has been used, instead of measured reflectance of soiled modules, to account for, if any, localized variations in reflectance spectrum of cleaned modules.

![Fig. 8. Cleaned module reflectance for various technologies](image)

![Fig. 9. Delta plot for mono-Si with various soil densities](image)

![Fig. 10. Delta plot for a-Si with various soil densities](image)

**TABLE II**

SOIL DENSITY ESTIMATION USING AVERAGE REFLECTANCE LOSS OVER 600 – 700 nm BAND

<table>
<thead>
<tr>
<th>Type</th>
<th>Equation for Soil density estimation (in g/m²) based on reflectance loss $x = \text{reflectance difference (Soiled reflectance% - Cleaned reflectance%)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-Si</td>
<td>SD = 58.22x + 0.055</td>
</tr>
<tr>
<td>Poly-Si</td>
<td>SD = 58.09x - 0.046</td>
</tr>
<tr>
<td>a-Si</td>
<td>SD = 68.50x + 0.262</td>
</tr>
<tr>
<td>CdTe</td>
<td>SD = 53.47x + 0.196</td>
</tr>
<tr>
<td>CIGS</td>
<td>SD = 58.53x + 0.052</td>
</tr>
</tbody>
</table>
D. Effect of Soiling on Transmittance

The effect of soiling on transmittance was calculated by finding the difference between transmittance spectrum of cleaned and soiled glass at 0° AOI. Figure 11 gives the transmittance measurement for cleaned and soiled glass along with direct transmittance for a soil density of 0.869 g/m². Only four soil densities were considered in the transmittance study. The transmittance loss was measured between wavelengths of 400 nm and 1100 nm and is shown in Figure 12; considering this is the cell response range of test modules as shown in Figure 8, this range is used in transmittance loss calculations.

Transmittance loss_{soiling} = T_{soiled glass} - T_{cleaned glass} \% \quad (2)

\[ TL_{\text{Glass}} \% = \frac{\text{Irradiance}_{\text{Direct}} - \text{Irradiance}_{\text{Glass}}}{\text{Irradiance}_{\text{Direct}}} \times 100 \quad (3) \]

Where Irradiance is the cumulative sum of irradiance for 400 nm – 1100 nm band.

For Mesa soil types, soiling loss at 0° AOI increases by 0.0544% for 0.263 g/m² soil density based on the equation in Fig. 12 and maximum measured loss was 4.93% at 0.869 g/m². This includes reflectance and transmittance losses at 0° AOI.

E. Modelling Soil Losses using PVsyst

The angle of incidence related losses for a particular tilt for a cleaned module have been estimated using Sandia's polynomial with PVsyst. Similarly, the angle of incidence related losses for soiling modules have been estimated to be 0.263 g/m² AOI polynomial with PVsyst. The calculation has been done for all tilt angles from 0° to 35° in increments of 5°, and for the latitude tilt of the location. The difference between two losses, i.e. AOI related Soiling losses, ranges from a minimum of 3.9% for 35° to a maximum of 5.86% at 0° for Phoenix as shown in Figure 13. The estimation was done using SolarAnywhere weather data for the year 2014.

Similar analysis was done for other locations like New York, San Francisco, Boston, and Miami, along with Phoenix, as given in Figure 14 based on MeteoNorm weather data. It was observed that the losses were higher in these locations when modules are mounted at corresponding latitude tilt as compared to Phoenix. This could be attributed to the presence of a larger percentage of diffuse irradiance in these locations as compared to Phoenix. However, it is to be noted that the relative optical response could differ based on the soil type of the location, and the soil density is not constant throughout the year. The soil density of 0.263 g/m² was observed after two days of field exposure in Mesa. Therefore, while these values can be considered as the minimum expected soiling losses, actual soiling losses are completely dependent on the specific location.
TABLE I
EMPIRICAL EQUATIONS FOR AOI CURVES OF VARYING SOIL DENSITY ON PV MODULES

<table>
<thead>
<tr>
<th>Rounds</th>
<th>Soil Density (g/m²)</th>
<th>Critical angle (degree)</th>
<th>Empirical Formula ($f_2$(AOI)) (Formulated using Excel Spreadsheet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.016</td>
<td>52.5</td>
<td>$f_2$(AOI) = -0.0006(AOI)² + 0.0009(AOI) + 1.0357</td>
</tr>
<tr>
<td>2</td>
<td>0.263</td>
<td>42.5</td>
<td>$f_2$(AOI) = -0.0002(AOI)² + 0.0022(AOI) + 1.0067</td>
</tr>
<tr>
<td>3</td>
<td>0.345</td>
<td>42.5</td>
<td>$f_2$(AOI) = -0.0002(AOI)² + 0.0022(AOI) + 1.0087</td>
</tr>
<tr>
<td>4</td>
<td>0.447</td>
<td>40</td>
<td>$f_2$(AOI) = -0.0002(AOI)² + 0.0042(AOI) + 0.9777</td>
</tr>
<tr>
<td>5</td>
<td>0.648</td>
<td>40</td>
<td>$f_2$(AOI) = -0.0002(AOI)² + 0.0095(AOI) + 0.9434</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

- If there is an identical soil density on the PV modules, the soiling loss will be nearly identical irrespective of the PV technology type.
- The power or current loss between clean and soiled modules would be much higher at a higher AOI than at a lower AOI leading to excessive energy production loss of soiled modules on cloudy days, early morning hours and late afternoon hours.
- By using the empirical formulae presented in this work, the soiling loss for any AOI can be estimated if the soil density is known/measured.
- Based on the results obtained in this study, it can be stated that the critical angle shifts from 57° for the clean air/glass interface to 40° for the naturally developed air/soil/glass interface in Mesa, Arizona for the fall season.
- Using an average reflectance measurement in the 600-700 nm bandwidth, the soil density on any module can be estimated.
- Using the empirical formula presented in this work and the soiling density, the soiling loss for any specific AOI can be estimated.
- If the soil density is known and the Mesa, Arizona soil type is assumed to be present in all sites, the angle of incidence related losses for the whole year for any site can be modelled using PVsyst.

REFERENCES