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Accurate Soiling Ratio Determination With Incident Angle Modifier for PV Modules

Pramod Nepal, Marc Korevaar, Hesan Ziar, Olindo Isabella, and Miro Zeman

***Abstract*—The deposition of dust, soil, and microfibers resulting from the surroundings, as well as the growth of minute pollens like moss and fungi, contributes toward photovoltaic (PV) module soiling. Soiling is a widely recognized factor that significantly reduces the power production by acting as a barrier for effective light absorption by the module. The estimated loss in the irradiance and power can be determined with the help of a soiling ratio (SR) parameter, which is the ratio of the short-circuit current (I_{sc}) or the maximum power produced (P_{max}) by a soiled module to a clean one. The measured SR is normally not constant throughout a day but changes with the position of the Sun and the amount of dust on the module. This paper proposes an empirical equation to determine the SR at any instant of time of the day based on the Sun's angle of incidence on the module and a single SR value measured at the mid of the day. First, an indoor experiment was done to examine the angular loss dependence of two totally different dust colors for the same SR at normal light incidence. Next, in an outdoor experiment, the SR of an artificially soiled module was measured over the course of the day for three conditions of high, medium, and low daily average irradiance due to variation in cloudiness. Then, an empirical equation is introduced based on an incident angle modifier for soiled and cleaned PV modules. The proposed equation was further used to determine the SR. Finally, the average residuals between the measured and the modeled SRs were determined with the help of root-mean-square deviation. The results showed that the modeled SR was determined with a deviation of $\pm$0.21% and $\pm$0.28%, respectively, for high- and medium-irradiance days, whereas the deviation increased to $\pm$1.04% in the case of low irradiance due to clouds.**

***Index Terms*—Angle of incidence (AOI), angular loss (AL), incident angle modifier (IAM), module soiling, photovoltaic (PV) module, soiling ratio (SR), solar power generation, transmission loss (t_{loss}).**

I. Introduction

THE technological advancement in the field has resulted in photovoltaic (PV) technology becoming one of the leading renewable energy sources currently available. The annual growth of PV installations was reported to be 40% from 2010 to 2016 [1]. Despite this outstanding growth, the performance ratio of PV systems has been greatly influenced due to various environmental factors, such as non-uniform irradiance, wind, rain, module temperature, and soiling.

The accumulation of dust, sand, and biological deposits like the growth of algae, moss or bird droppings, and air pollution is categorized as PV module soiling [2]. It directly obstructs the irradiation falling on the module by forming a thin layer of dust, usually less than 10 μm [3]. The module soiling is considered to be the third major environmental factor after irradiation and temperature, which directly accounts for lower performance statistics of a PV system [4]. The soiling of PV modules majorly depends on two factors: 1) installation design of the PV plant such as tracking mechanisms, tilt, and orientation; and 2) local environmental conditions such as atmospheric dust intensity, relative humidity, wind, and rainfall [5]. Therefore, dust accumulation is a result of the rate of deposition and the rate of removal by the wind and rain event [6]. Thus, based on the location and dust type, the soiling losses might vary. Experiments carried out at different parts of the world suggest that the losses may vary anywhere between 0.1% per day and 20% per day based on the location and rain events [7], [8]. Several experiments also suggested that the average soiling loss in the Middle East regions were more severe compared with other parts of the world [3]. In Egypt, an experiment was performed on 100 different glass samples installed at different tilt angles and azimuth orientations for eight months; the cell at an angle of 45° facing south resulted in a reduction of output power by 17.4% per month [9]. Rainfall event acts as a natural cleaning for the soiled modules. Around 5 mm of rainfall was noticed to completely clean the module in the Arizona region [10].

Besides the location and environmental conditions, module's properties also possess a significant influence on soil deposition. Depending on a PV module's glazing surface and orientation, it is subjected to two types of the angle of incidence (AOI) influences, namely mechanical and optical [11]. The mechanical response is associated with its tilt and orientation and the light source. Based on the AOI, solar radiation is de-rated by a cosine of the angle between the surface normal and the Sun's angle commonly known as "cosine effect" [12]. On the other hand, the optical effect is due to the surface properties of the module. A module with an anti-reflective surface coating is more resilient toward the effect of the AOI than without [11]. Higher AOI increases reflectance losses, thus reducing the amount of solar beam that can be utilized by the module [13]. Several incident angle modifier (IAM) methods, such as Physical, ASHRAE, Sandia, and Martin & Ruiz, have been developed to calculate

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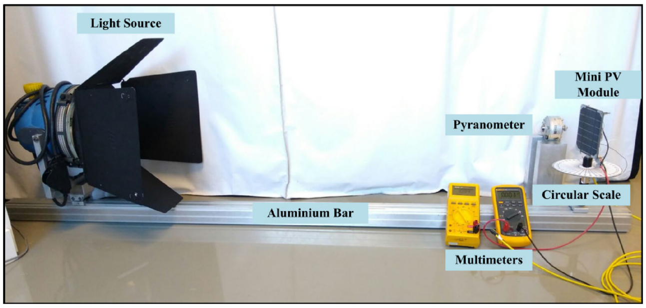

Fig. 1. Indoor experimental setup consisting of a light source, two multimeters, a mini PV module, and a circular scale supported by an aluminum bar. Instantaneous module temperature of the soiled and clean module was measured by a 10-kΩ temperature measuring sensor (thermistor, NTC), applied at the back of the module. Two multimeters were used to measure the short-circuit current ($I_{\rm sc}$) and the thermistor resistance at each AOI interval.

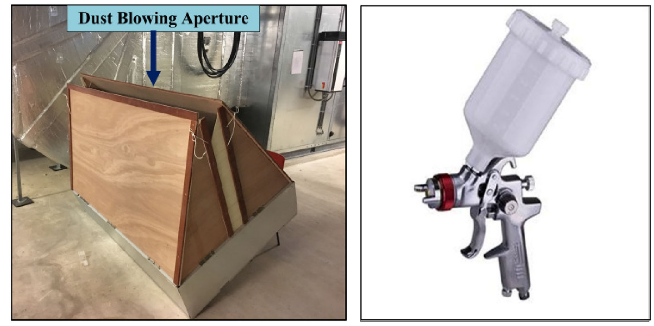

Fig. 2. Wooden–aluminum chamber (1660 $\times$ 1000 $\times$ 900 mm^3) (left) and the paint gun (600 cc) used for soiling (right). The chamber has a small opening at the top (pointed by a blue arrow) that provides a space for the gun filled with the soiling mixture. A pressure hose was connected at the bottom of the paint gun at 1.5 bar to provide enough pressure for soiling.

the optical losses of irradiation due to reflection at the module surface. In 1983, Wilson and Ross found that the cell surface is highly influenced by the surface texture and soling level because of both Fresnel reflection and soil shadowing [14]. A study carried out in Malaga, Spain, has resulted in the fact that the relative irradiance loss of a solar cell increased the AOI of the Sun [7], whereas John *et al.* [15] found that the density of soil significantly lowers its critical AOI of the module, suggesting higher reflection losses compared with clean. Similarly, Martin and Ruiz have gone one step further and characterized the angular losses (ALs) in different module technologies with the help of an outdoor experiment. The experimental and modeled data were used to define a dimensionless parameter called "angular loss coefficient" (a_r) [16]. The optical response of the PV module is a surface characteristic; therefore, solar irradiance is highly influenced due to the presence of the soiling.

In this paper, a mini PV module was tested indoor for two soil colors at the same SR to compare their AL at different AOIs. Next, a commercial-scale module was tested outdoor under two soiling conditions to estimate (a_r) and subsequently the AL. The artificial soiling technique was carried out with the help of a soiling chamber and a spray gun also demonstrated in the work of [17] and [18]. Then, after introducing the soiling ratio (SR) model, the SR curves were constructed with the help of calculated ALs and a single SR measurement done at solar noon for three different scenarios of high-, medium-, and low-irradiance conditions due to different levels of cloudiness. Finally, the measured SR curve was compared with the modeled SR (SR$^{\rm model}$) by calculating the root-mean-square deviation (RMSD).

II. Methodology

A. Indoor Measurement Setup

An incandescent light of 2000 W (Arrilite 2000) was used as a constant light source. A mini-monocrystalline silicon module of $2W_p$ was vertically kept at 1.5 m from the light source, where the irradiance intensity was 1000 W/m^2. The module was supported on a flexible arrangement to allow for movement along two axes, i.e., 0–360° on the horizontal axis and 0–60° for the vertical angle. The experiments were carried out in a dark room to avoid the influence of other lights in the proximity. For each experiment, the module was rotated carefully from –90° to 90° with 10° interval measured with a 360° circular scale at the bottom of the module. The entire experimental setup is shown in Fig. 1.

Two dust samples (produced by KSL Staubtechnik GmbH) mainly characterized by their color were taken for the experiment. Arizona Test Dust (ARIZ-TD (Quartz (SiO_2))) has light-brown color, whereas Prüf-staub (P-030KS16) is black. Two soiling mixtures were prepared by suspending 1.5 g of each dust with 20 ml of deionized water. An equal amount of 8 ml ($\sim$0.0029 g/cm^2) of each soiling mixture was applied on the module with the help of an air gun at an air pressure of 1 bar from a distance of 25 cm (pointing horizontally on a flat lying module). $I_{\rm sc}$ and module temperature was measured again to examine the differences in the SR at each AOI of the light.

B. Outdoor Measurement Setup

The experiment was carried out using a rooftop PV setup installed at the height of 16 m from the ground at Kipp & Zonen BV, Delft, The Netherlands. Two polycrystalline silicon modules (CS6K-270P produced by Canadian solar) installed at a tilt angle of 30° facing south (182°) with an identical mounting mechanism were chosen. One of the modules was uniformly soiled, while the other was kept clean to make a comparison. A soiling mixture was prepared by suspending the Grand Canyon test dust (Eisenoxid-Fe_2O_3, KSL-312) produced by KSL Staubtechnik GmbH with deionized water in 1:10 ratio. To facilitate a homogeneous soiling process by reducing the wind effects, a wooden–aluminum chamber was also built, which can be seen in Fig. 2. The chamber was placed carefully on top of the PV module to be soiled. Finally, module soiling was carried out in twofolds, first light soiling, SR $= 93.2\%$ ($t_{\rm loss} = 6.8\%$) and then after additional soiling, SR $= 86.9\%$ ($t_{\rm loss} = 13.1\%$) with the help of a paint gun at an air pressure of 1.5 bar from a distance of 1 m (pointed vertically).

An instantaneous short-circuit current ($I_{\rm sc}$) from both the modules was recorded by measuring its voltage drop (V_D) over a 10-m-long Technischer Überwachungsverein (TÜV) Rheinland approved solar cable with a resistance ($R_{\rm sc}$) of 63 mΩ (the accuracy of the multimeter to measure the cable resistance is (0.2% of reading $\pm$ 1 reading) $\pm$ 0.126 mΩ [19]). The minute average voltage drop from both modules was logged into a

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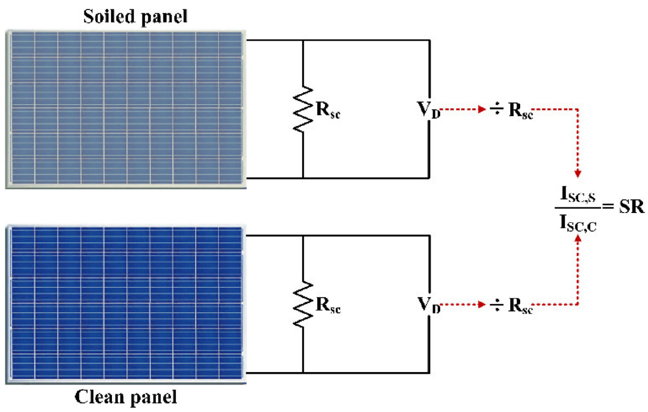

Fig. 3. Circuit diagram representing the short-circuiting technique of clean and soiled modules. In the figure, $R_{\rm sc}$ is a low shunt resistor (63 mΩ) identical for both modules. Voltage drop (V_D) was converted into the $I_{\rm sc}$ by dividing it with the value of the shunt resistor ($R_{\rm sc}$); then, the SR was calculated using the obtained $I_{\rm SC}$ values.

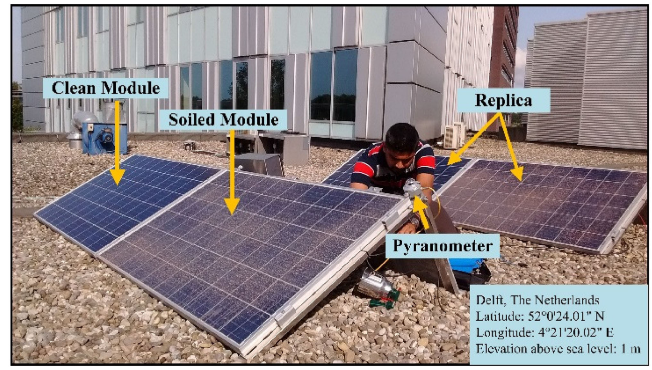

Fig. 4. Experimental setup for SR measurement represented by two co-planar modules in the front row, whereas the rear row represents a duplicate set of modules to later validate the measured data. The experiment was conducted on August 27, 2017 from 10:57 to 17:07. The voltage drop from the modules was recorded with the help of a CR6 data logger placed inside a metal box (at the back of the modules).

Campbell Scientific CR6 data logger with an average sampling time of 5 s. A schematic diagram for module short-circuiting and SR calculation is represented in Fig. 3.

Instantaneous irradiance was recorded every minute with the help of CMP-21 pyranometer by Kipp & Zonen installed at the plane of array. Minutely average temperatures of soiled and cleaned modules were also measured using two temperatures sensors (negative temperature coefficient (NTC) thermistor of 10 kΩ) applied at the backside of each module. The experimental setup consisting of cleaned and artificially soiled modules is presented in Fig. 4.

C. Soiling Ratio Calculation

The SR is defined as the ratio of irradiance utilized by a soiled (G_s) to a cleaned module (G_c) to produce the corresponding short-circuit current ($I_{\rm sc,s}$ and $I_{\rm sc,c}$) or power [20]. Using the translation method explained in IEC-60891, the measured short-circuit currents ($I_{\rm sc,s'}$ and $I_{\rm sc,c'}$) were subjected to temperature correction to account for net irradiance loss only due to soiling [see (1)]. A temperature coefficient (0.053%/°C) mentioned in the datasheet of the PV module was considered for temperature correction [21]. The short-circuit current of the two co-planar modules was normalized with the help of calibration factors when both modules were clean and at the reference temperature (25 °C) condition. The duplicated modules were used for calibration to account for manufacturing defects, differences in the cable resistance, or any other abnormal behavior that might lead to varying current and power production at an identical condition. The expanded SR equation with calibration values and the translation method for temperature correction can be written as [20], [22]

$$\mathrm{SR} = \frac{G_S}{G_C} = \frac{I_{\mathrm{SC},S}}{I_{\mathrm{SC},C}} = \frac{I_{\mathrm{SC},S'}\left(1-\alpha\left(T_{m,S}-T_{\mathrm{ref}}\right)\right)}{I_{\mathrm{SC},C'}\left(1-\alpha\left(T_{m,C}-T_{\mathrm{ref}}\right)\right)} \times \frac{C_C}{C_S} \quad (1)$$

$$t_{\mathrm{loss}} = 1 - \mathrm{SR}. \quad (2)$$

In (1), $I_{\rm sc,s'}$ and $I_{\rm sc,c'}$ are measured short-circuit currents from soiled and cleaned modules, respectively, whereas $I_{\rm sc,s}$ and $I_{\rm sc,c}$ are short-circuit currents after temperature correction. Similarly, α is the temperature coefficient, while C_c and C_s are calibration constants for cleaned and soiled modules, respectively, which were computed by comparing the short-circuit currents of both the modules. Similarly, $T_{\rm m,s}$ and $T_{\rm m,c}$ are the measured temperature of soiled and cleaned PV modules, respectively, whereas $T_{\rm ref}$ is the temperature of the module when the ambient temperature is 25 °C. $t_{\rm loss}$ in (2) is the transmission loss due to the presence of soiling. The following SR calculation was performed for three days characterized by their average irradiances (due to different levels of cloudiness) throughout that day: high irradiance (758 W/m^2), medium irradiance (559 W/m^2), and low irradiance (276 W/m^2). In this experiment, the SR was calculated from the short-circuit method; however, it should be noted that the SR could also be estimated by the maximum power point method, which might give a slightly different result.

D. Photovoltaic Module Angular Losses

ALs for PV modules are generally calculated referencing a normal incidence of radiation at either cleaned or soiled condition [23]. The complement to the unity of ALs is known as the angular factor ($f_{\rm I\alpha}$) [24]. The angular factor at any AOI represents the relative optical response of a module for that angle. The experimental value of the angular factor ($f_{\rm I\alpha}$) (for an arbitrary AOI of θ) can be obtained as the ratio of the cosine-corrected short-circuit current at the angle θ ($I_{\rm sc}|_\theta$) to the short-circuit current at normal incidence ($I_{\rm sc}|_{\theta=0}$°) represented as [24]

$$f_{I\alpha} = \frac{I_{\mathrm{SC}}(\theta)}{I_{\mathrm{SC}}\,|_{\theta=0^\circ}\,\cos\theta}. \quad (3)$$

The optical response of any module with or without antireflective coatings can be determined with the help of an analytical equation presented as follows [24]:

$$\mathrm{AL}(\theta) = 1 - \frac{1-\exp\left(\frac{-\cos\theta}{a_r}\right)}{1-\exp\left(\frac{-1}{a_r}\right)} \quad (4)$$

$$\mathrm{IAM}(\theta) = 1 - \mathrm{AL}(\theta) \quad (5)$$

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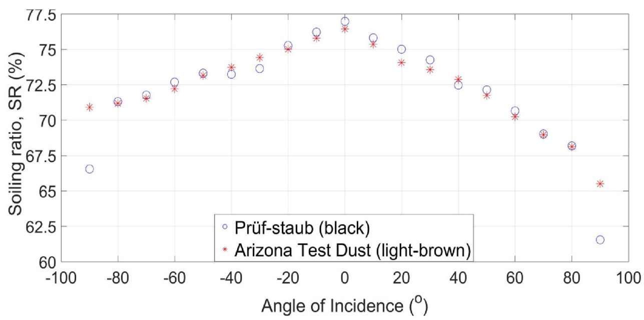

Fig. 5. Measured SR values for Prüf-staub dust and Arizona Test Dust for –90° to +90° AOI. At normal incidence ($\theta = 0°$), the SR value for Prüf-staub represented by blue circles is 76.9%, whereas for Arizona Test Dust represented as red star, it was around 76.5%. This value for Arizona Test Dust was achieved by depositing additional amount of the dust and measuring the $I_{\rm sc}$ till the value was reached.

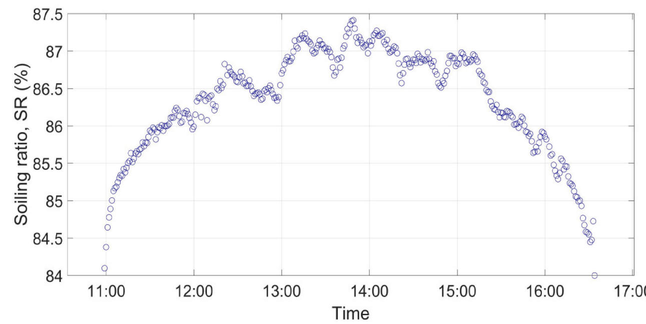

Fig. 6. Measured SR on August 27, 2017 for a high-irradiance day (758 W/m^2). The SR during morning and evening periods is significantly lower compared with the mid of the day. Solar noon on this day was noticed at 13:45, which represents the SR value of 86.9%.

where a_r is a dimensionless parameter known as the AL coefficient, which depends on a particular PV module technology or the front cover [24]. For every AOI of the Sun (θ) and a fixed a_r value, the AL in a PV module is determined by (4). In [23], the analytical model [see (4)] was found to accurately describe the ALs of all analyzed PV configurations with a high value of determination coefficients (R^2). Equation (5) represents the IAM, which is the complement for ALs with a maximum of 1 and a minimum of 0. It signifies the degree of module performance for any AOI of light with a maximum value when the lowest AOI is 0 (perpendicular light incidence). For our calculations, the generated short-circuit currents from each module were first scaled up by linear translation after module temperature correction to the same reference irradiance as it was during solar noon. Then, the angular factor ($f_{\rm I\alpha}$) in (3) was determined for different AOIs of the Sun and different levels of soiling. The calculated angular factors at each soiling level were further plugged into (4) to determine the AL factor (a_r) at an AOI of 5°, 10°, 15°, 20°, 25°, and 30°. Finally, an average a_r value was again substituted into (4) and (5) to calculate the IAM of the module at every AOI from 0° to 90°.

III. Results and Discussion

In this section, the results of the indoor and outdoor experiments have been discussed. First, the measured SRs for two dust colors at different AOIs of the artificial light source were plotted together. Next, the SR measured from outdoor setup was plotted for a course of a day. Then, the ALs as a function of the SR and the AOI were calculated. Finally, using the empirical equation proposed in this paper, the SR over the day has been determined and compared under three irradiance conditions.

A. Indoor Soiling Ratio

The measured short-circuit current at different AOIs was temperature corrected to calculate the SR using (1). The SR measured at normal incidence ($\theta = 0°$) for the soil type of Prüf-staub (black) was 76.9%, whereas for Arizona Test Dust (light-brown), it was 87%. The higher light absorption nature of the black dust might be the reason behind larger transmission loss. Next, the attenuation of SR values at different AOIs was compared. To do this, Arizona Test Dust was deposited 1.72 times than previous ($\sim$0.005 g/cm^2) to reach the same SR value at normal incidence as it was given by Prüf-staub dust ($\sim$76.9%). The SR of Arizona Test Dust and Prüf-staub dust at each AOI is presented in Fig. 5.

Apart from few outliers at a larger AOI, no significant difference in the SR value was noticed between Prüf-staub (black) and 1.72-times-deposited Arizona Test Dust (light-brown) dust. The ALs, and consequently SR, for two types of dusts were almost the same for every AOI. The results also suggest that any dust color with the same SR for AOI $= 0$ possess a similar SR at all AOIs. Therefore, ALs and hence SR do not depend on the dust color, but only on the amount of the dust (g/cm^2) deposited on the module. This result can be further validated from the work of [13], where the soiling loss pattern in two different modules at the same soil density or SR was found to be similar at every AOI of the light source.

B. Outdoor Soiling Ratio

The SRs were measured for a shade-free window of around 5.5 h from 10:57 to 16:30 on each day to avoid partial shading on the PV modules caused by nearby objects. Fig. 6 represents a high-irradiance day, which showed that the SR was not constant throughout the day but changed with the position of the Sun. The SR was seen to be the highest during mid of the day [$\pm$1 h from 13:45 (solar noon)] fluctuating between 86.5% and 87%. Therefore, the overall transmission loss in the soiled module was estimated to be around 13–13.5% using (2). During morning and the evening time, it reached the lowest value due to a larger AOI of the Sun. At a larger AOI, the dust on the module is believed to cast larger shadow resulting in higher losses compared with midday. The SR was also seen to be varying by around $\pm$ 1% even during the midday. This was probably because of the dynamic shading on the modules caused by passing clouds. Fig. 6–8 show the result of SR measurements for high-, medium-, and low-irradiance conditions, respectively.

This characteristics nature of a soiled module's dependence on the AOI of the light can also be noticed from the indoor SR experiment in Fig. 5. For the larger AOI, SR values were smaller, while they increased and reached the maximum as the light source was perpendicular to the module's surface. The

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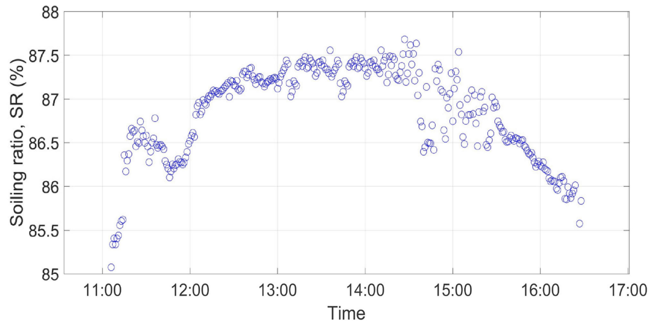

Fig. 7. Measured SR on August 23, 2017 for a medium-irradiance day (559 W/m^2). The SR pattern is similar as in Fig. 6 with some additional SR fluctuations. The value of the SR at the solar noon was 87.5%, which is higher than for a high-irradiance day. This is probably due to additional deposition of the atmospheric dust in-between those four days (August 23–24, 2017), resulting into lower SR (higher losses).

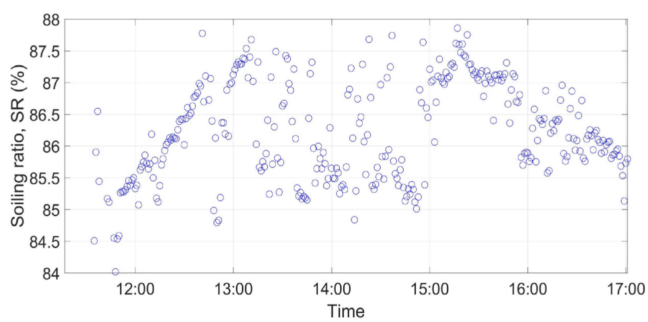

Fig. 8. Measured SR on August 24, 2017 for a low-irradiance day (276 W/m^2). The SR pattern cannot be clearly observed due to higher amount of SR fluctuations at cloudy condition. The value of SR at the solar noon was 86%.

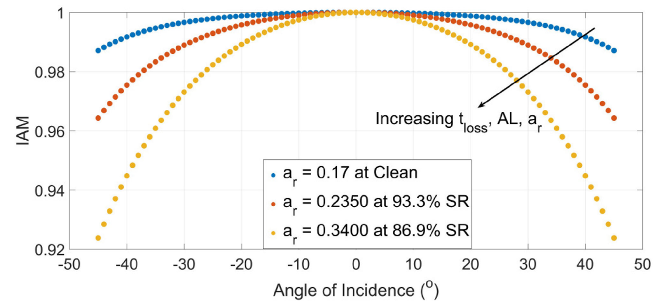

Fig. 9. IAM calculated for three module conditions, namely, clean represented by the blue curve, the SR of 93.2% represented by the red curve, and the SR of 86.9% represented by the yellow curve. The IAM was calculated from –45° to +45° at an interval of 1° based on the Sun's position on August 27, 2017. The arrow points out the increasing pattern of the AL and the AL coefficient (a_r) as a function of the SR due to soiling. The AOI in the graph represents the difference in Sun's altitude when maximum and at any time *t* on August 27, 2017.

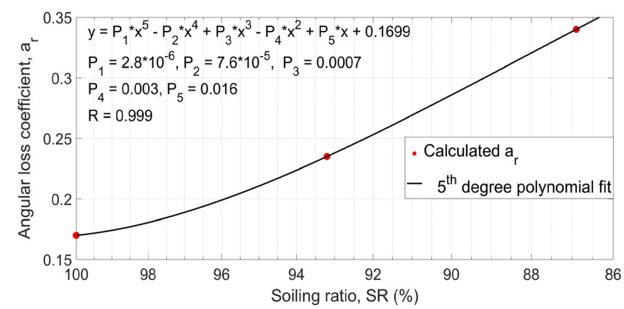

Fig. 10. Increasing trend of the AL coefficient a_r with increasing soiling loss (decreasing SR) on the module. Three different soiling conditions were SR = 100% representing clean condition, SR = 93.2%, and SR = 86.9%. The data points are fitted to fifth-order polynomial equation on MATLAB. The *R* coefficient represents the goodness of the fit. The coefficient for the clean module is 0.17, which agrees with the experiment carried out by Martín *et al.* [16].

results from both experiments confirm the presence of angular dependencs of a soiled module over a day.

C. Angular Losses on the Module

The measured short-circuit currents of the clean and soiled modules in the outdoor measurement setup were also used to determine the ALs on the PV modules. To do so, every minute Sun's altitude was calculated with respect to the module's azimuth (182°) for each day. On the solar noon of 11th of July, the solar zenith angle (SZA) was observed to be 60°, and the Sun's rays were exactly perpendicular with respect to the modules. The SZA on 27th of August was 68°; therefore, modules were already suffering from ALs even at mid of that day due to its fixed tilt. For our range of interest between 10:57 and 16:30, the light on the module was mainly due to the direct component of the solar irradiance with a little influence of shading and diffuse solar irradiance. The angular factor ($f_{\mathrm{I}\alpha}$) was calculated for three different soiling levels: clean (SR = 100%), medium soiled (SR = 93.2%), and heavy soiled (SR = 86.9%). It was then used to calculate the AL factor (a_r) at each case using (4). The graph shown in Fig. 9 represents the IAM for the three SRs.

Here, the *x*-axis represents the AOI of the Sun on the module, which is the difference between Sun's altitude at the mid of the day (when maximum) and at any time. The AL coefficient (a_r) was found to be the lowest for the cleaned module at 0.17 represented by the top-most blue curve, while it increased and reached 0.34 at an SR of 86.9%. The pattern of increasing a_r associates with the increase in ALs with decreasing SR (increasing t_{loss}). A thorough comparison of a_r at increasing soling loss (decreasing SR) has been presented in Fig. 10.

Comparing the IAM for the cleaned and soiled modules at the same AOI helps understand the detrimental effect of soiling on PV modules. The AL of a cleaned module for 30° was 0.0018, while for the soiled module, the losses increased to 0.0164, i.e., 9.12 times larger. The IAM curve for the soiled and cleaned modules was used to model the SR pattern throughout the day, as shown in the next section.

D. Soiling Ratio Modeling Based on Angular Losses

The SR over the course of the day, as described in Section III-B, will be now modeled with the help of the calculated ALs and the single midday SR value ($\mathrm{SR}_{\mathrm{midday}}$) of 86.9%. The ratio of the IAM for the soiled and cleaned modules at each AOI from Fig. 9 was multiplied by the midday SR (86.9%) value using the following empirical equation:

$$\mathrm{SR}^{\mathrm{model}} = \frac{\mathrm{IAM}_S(\theta)}{\mathrm{IAM}_C(\theta)} \times \mathrm{SR}_{\mathrm{midday}} = \mathrm{IAM}_{\mathrm{ratio}}(\theta) \times \mathrm{SR}_{\mathrm{midday}} \tag{6}$$

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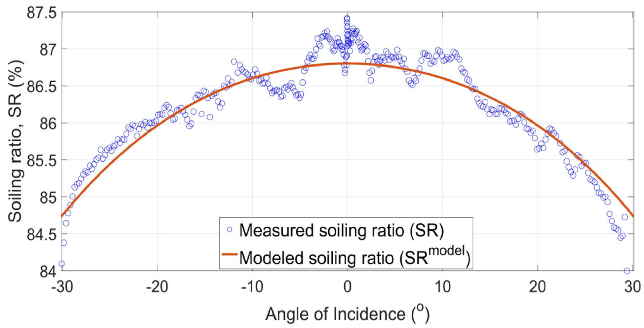

Fig. 11. Comparison of the measured SR values with the modeled values. The blue circles represent the measured SR values in Fig. 6, whereas the smooth red line represents the modeled SR values obtained from empirical equation (6). Here, the *x*-axis represents the position of the Sun on August 27, 2017. The two ends of the graph (–30° and +30°) signify morning and evening times, respectively. The AOI in the graph represents the difference in Sun's altitude when maximum and at any time *t* on August 27, 2017.

where $\mathrm{IAM}_s(\theta)$ and $\mathrm{IAM}_c(\theta)$ are the IAM of the soiled (SR = 86.9%) and the cleaned module, respectively. In (1), it can be seen that the SR is the ratio of the soiled and cleaned modules; thus, the $\mathrm{IAM}_{\mathrm{ratio}}$ in (6) has been presented as the ratio of the IAM associated with the soiled module (IAM_s) to that of the cleaned module (IAM_c). After modeling SR ($\mathrm{SR}^{\mathrm{model}}$) for each AOI for 27th of August, the red curve shown in Fig. 11 was resulted and plotted along with the measured SR values for comparison.

From a visual inspection, the modeled curve (blue) closely seems to follow the pattern of the measured curve (red). The modeled SR represented by the red curve is much smoother compared with the measured SR because the irradiance fluctuations were not considered in SR modeling. Again, for modeled values at a larger solar angle, the module ALs were also high. Both curves show the AOI dependence of a soiled module.

E. Deviation Between Measured and Modeled SRs

An error or residual calculation represents the average deviation of the modeled value compared with an actual or observed value [25]. This estimation facilitates the quantification of the difference between the experiment and the model. To measure the accuracy of the proposed model [see (6)], RMSD will be calculated for each point of the modeled and the measured SR data [26]. For the high-irradiance day, there were 334 data events representing each minute resulting in a mean squared error of 0.0458%. Thus, RMSD between the measured and the modeled dataset was then found to be ±0.21%. This means the proposed model predicted the measured with a variance of ±0.21%. The error associated with medium- and low-irradiance situations was also estimated in the same way. A comparison for each irradiance condition has been summarized in Table I.

The results indicate that for the low-irradiance condition, the degree of deviation is higher, at around ±1%. This was most likely due to a constant AOI of the diffuse irradiance from the clouds resulting in a larger amplitude of the deviation. However, during the day with an adequate amount of light, the residual errors were quite low at around ±0.2% and ±0.28%. These results suggest that the model predicts the SR very well during sufficient irradiance condition, while it is less accurate on cloudy days.

TABLE I
RMSD UNDER THREE IRRADIANCE CONDITIONS

Date	Day type	Daily Avg. Irradiance (W/m^2)	RMSD (%)
27-08-2017	High irradiance	758	±0.21
23-08-2017	Medium irradiance	559	±0.28
24-082017	Low irradiance	276	±1.04

IV. CONCLUSION

The SR from the short-circuit current method has been chosen to determine the SR over the course of a day. The SR has been found to be influenced by the AOI of the Sun. Morning and evening times corresponded to a higher degree of module ALs than around solar noon. The angular dependence of the SR of a soiled module has been found to be independent of the dust color used for the identical SR. An analytical model developed by Martin and Ruiz was followed to characterize the AL coefficient (a_r) at different SR conditions, and it was found to increase with the soiling level. The soiled and cleaned PV modules had AL coefficient (a_r) values of 0.34 and 0.17, respectively, for a high-irradiance day (average irradiance of 758 W/m^2). It has also been noticed that the presence of the dust on the module attenuated the IAM, therefore decreasing the transmittance of irradiance compared with the cleaned PV module. The proposed empirical equation based on the IAM and a single midday SR measurement was found to have accurate prediction of ±0.21% for a sunny day, whereas the deviation was higher for cloudy conditions. The SR was found to be influenced due to the presence of the clouds, thus increasing the RMSD. The cloudy conditions result in light coming from a diffuse sky, resulting in a constant AOI over the day. This results in a less good fit of the model with the measured. No significant difference in the angular dependence of SR measured for two different dust colors shows the possible validity of the proposed empirical equation for any location irrespective of the local dust. This can be further investigated in the future research studies.

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DISCLAIMER

Results presented in this work strictly concern the type of dust used and the testing condition. The results might differ based on the system's location and local environmental conditions.

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