Accurately Measuring PV Soiling Losses with Soiling Station Employing PV Module Power Measurements

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***Abstract* — Monitoring of PV soiling losses has become increasingly important for both operational PV power plants and pre-construction site surveys. Therefore, dedicated soiling measurement stations are being routinely deployed at many sites. Such stations typically compare the output of a "soiled" PV device with that of a "clean" device. While many stations measure only the short-circuit current of the soiled & clean devices, using the assumption that power output is proportional to short-circuit current, for accurate characterization it is often necessary to measure the actual power output in addition to the short-circuit current, especially when using crystalline silicon modules. This is essential in cases where soiling accumulates non-uniformly, such as along the edges or sides of the modules. Small amounts of non-uniform soiling may cause significant power losses that cannot be detected through measurements of short-circuit current alone. We present a case study from a pre-construction site-survey soiling station in the US Southwest region. Results presented here are an update to a previous publication about this site, with data now covering a 2-year period. The results illustrate examples of both uniform and non-uniform soiling, and demonstrate the importance of using module power measurements to get accurate results.**

***Index Terms* — photovoltaic systems, performance analysis, solar power generation, solar energy.**

I. Introduction

The effects of dust, dirt, pollen, and other contaminant accumulation on PV modules, commonly referred to as soiling, can cause significant reductions in PV power plant energy generation [1], [2]. Therefore, accurate prediction and monitoring of soiling losses has become increasingly important. As a result, dedicated soiling measurement stations are being routinely deployed at many sites, including both pre-construction site-survey locations and operational PV power plants, especially for utility-scale projects [2].

Soiling measurement stations typically employ a pair of PV reference devices, one of which is kept continuously clean and the other of which is allowed to be soiled at the natural rate [2]. The effect of soiling is then determined by comparing the output of the soiled reference device with that of the clean one. The soiled reference device is a PV module identical to those in use (or to be used) at the site, while the clean reference device may be either a reference cell or another PV module. The clean device is maintained in a clean state through either manual or automatic washing.

In the simplest method, the output of the soiled and clean reference devices is compared on the basis of the short-circuit current of each device. As a PV cell becomes soiled, the irradiance reaching the cell is reduced, and the short-circuit current of the cell is reduced proportionally. When all the cells in a module are uniformly soiled, the reduction in the module's short-circuit current is a good measure for estimating the reduction in the module's total output power.

Often, however, soiling accumulates on modules in a spatially non-uniform manner [3], [4]. One driver for this is the effect of gravity, which results in a tendency for particles to accumulate near the bottom of a PV module under the influence of small amounts of precipitation sufficient to move particles but insufficient to produce total cleaning [3]. Framed modules are typically susceptible to soiling accumulation near their edges, typically at the bottom but also possibly along the sides, due to the effects of gravity, precipitation, and wind [4].

Such spatially non-uniform soiling can have a significant effect on module power output. Due to the way in which shading affects a module's I-V curve, soiling particles accumulated in one area of a module can reduce power output by an amount much greater than expected if the same number of particles were distributed uniformly over the module, particularly for typical crystalline silicon modules [5]. In these cases the reduction in module short-circuit current due to soiling is no longer a good predictor of the reduction in module output power [5],[6][7].

Therefore, due to the possible influence of spatially non-uniform soiling, soiling measurement stations should typically measure both the short-circuit current and the power output of their soiled reference module, in order to produce the most accurate measurement [5].

In this work we present a case study from a pre-construction site-survey soiling station in the US Southwest region, as an update to a previous publication on this site [8] with data now covering a 2-year period. The results show examples of the effects of both uniform and non-uniform soiling with greater clarity than in the initial work, and demonstrate the importance of using module power measurements to get accurate soiling assessment.

II. Data Collection

The data collection station was installed in an undeveloped area with potential for future solar projects, and has been online since August of 2014. The station includes typical meteorological instruments as well as a dedicated soiling measurement system. The soiling measurement system is

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implemented using two identical 295 W framed polycrystalline-silicon PV modules, one of which is designated the clean reference and the other of which is designated the soiled reference. The clean reference is manually cleaned 2-3 times per week, and at each cleaning both modules are photographed. The modules are installed co-planar on a fixed rack, with a tilt angle of 5°, chosen to represent the average position of a potential single-axis tracker. Fig. 1 shows photographs of the two reference modules under various conditions which will be described below. The I-V curves of both modules are measured once per minute by a control unit (Atonometrics RDE300 series), which also fits the curves and calculates I-V parameters. The results are logged and periodically uploaded via a cell modem for analysis.

From the results, we calculate two soiling ratio (SR) metrics. The first, the soiling ratio Isc index, is defined as:

$$SR^{Isc} = \frac{I_{sc}^{soiled}}{I_0^{soiled} \cdot \left(1 + \alpha \cdot (T^{soiled} - T_0)\right) \cdot (G/G_0)} \qquad (1)$$

where I_{sc}^{soiled} is the measured short-circuit current of the soiled reference module, I_0^{soiled} is the module's short-circuit current at a reference condition (e.g. STC), α is the module's temperature coefficient of short-circuit current, T^{soiled} is the measured module temperature, T_0 is the module temperature at the reference condition (e.g. 25° C at STC), G is the measured plane-of-array irradiance determined from the clean module short-circuit current, and G_0 is the irradiance at the reference condition (e.g. 1000 W/m^2 at STC). The denominator in this equation is the "expected" short-circuit current in the absence of soiling and the numerator is the actual measured short-circuit current.

The second metric, the soiling ratio Pmax index, is defined similarly as:

$$SR^{Pmax} = \frac{P_{max}^{soiled}}{P_0^{soiled} \cdot \left(1 + \gamma \cdot (T^{soiled} - T_0)\right) \cdot (G/G_0)} \qquad (2)$$

where P_{max}^{soiled} is the measured maximum power of the soiled module, P_0^{soiled} is the module maximum power at the reference condition, γ is the temperature coefficient of maximum power, and the other terms are as in eq. (1). In eq. (2), the denominator is the "expected" maximum power in the absence of soiling and the numerator is the actual measured maximum power.

In the absence of soiling, both SR^{Isc} and SR^{Pmax} should be unity.

We integrate the once-per-minute readings of the two metrics to calculate daily average values for each, denoted $<SR^{Isc}>$ and $<SR^{Pmax}>$. Following the method described in [2], these daily values are calculated as the irradiance-weighted averages of those measurements which are performed within ±2 hours of solar noon on each day.

(a) 02/22/2016, uniform soiling:



(b) 02/29/2016, non-uniform soiling:



(c) 05/06/2016, bottom right still soiled:



(d) 05/13/2016, both modules clean:



Fig. 1. Photographs of the clean (left) and soiled (right) reference module pair on different dates, corresponding to the lettered annotations in Fig. 2, illustrating various conditions.

III. Results and Discussion

Fig. 2 shows the $<SR^{Isc}>$ and $<SR^{Pmax}>$ daily average soiling ratio metrics over a 24-month period, together with the measured daily rainfall. Initially the soiled reference module is clean and both soiling metrics are close to unity. However as soiling accumulates the metrics fall indicating lower output of the soiled module compared to the clean one. During many periods the Isc-based metric well represents the actual power loss measured by the Pmax-based metric. However during other periods the two metrics diverge, for example in early 2015 (as previously reported [8]) and then more dramatically in mid-2016.

A close examination of the mid-2016 period is instructive. On Feb. 22, 2016, as shown in Fig. 1 (a), the soiling is fairly uniform and the $<SR^{Isc}>$ and $<SR^{Pmax}>$ values, as shown in Fig. 2 at point (a), are about equal. Following a very slight rain

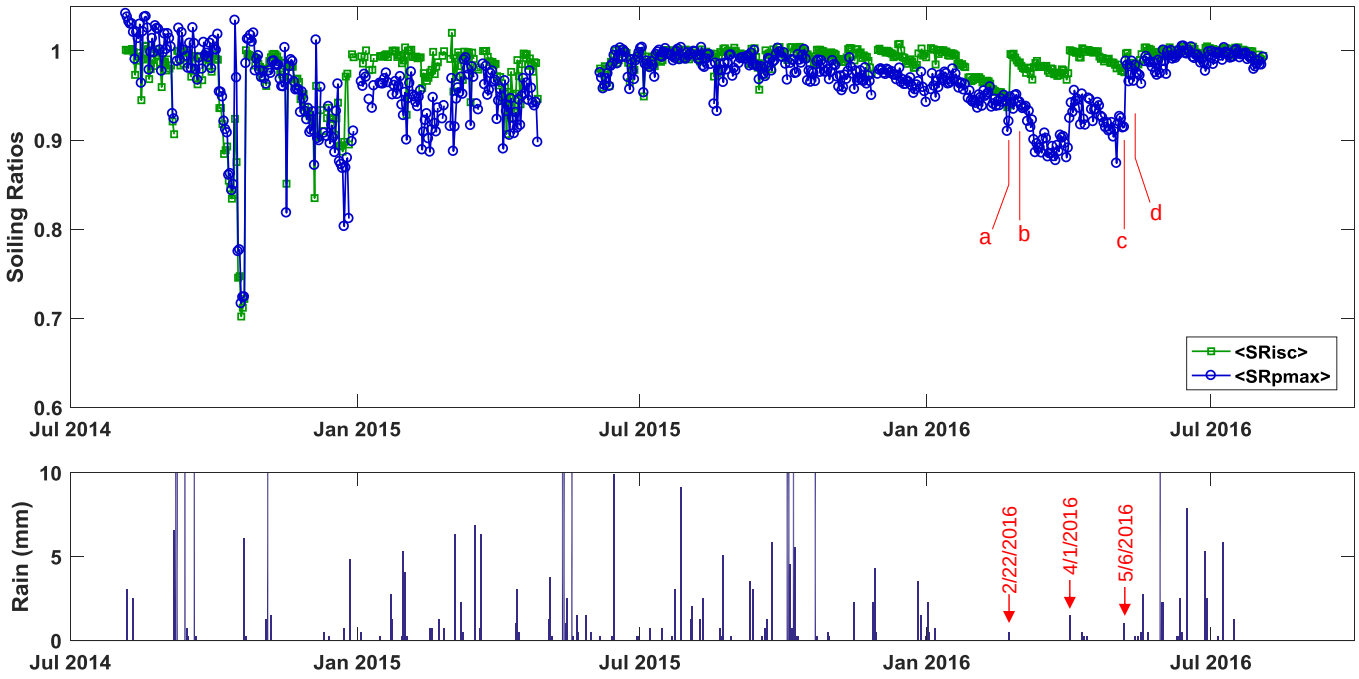


Fig. 2. Measured daily average values of the SR^{Isc} and SR^{Pmax} metrics (top) along with daily rainfall (bottom, y-axis limited to 10 mm) over a 24-month period. The four lettered arrows (a, b, c, d) indicate the days shown in the module photographs in Fig. 1.

(0.5 mm) late in the day on Feb. 22 the $<SR^{Isc}>$ value recovers to unity, while the $<SR^{Pmax}>$ is hardly affected. From the photo in Fig. 1 (b) taken on Feb. 29 we see that the rain has only cleaned the top and left portions of the soiled module, allowing the short-circuit current to recover but with power still suppressed, as shown by point (b) in Fig. 2. A similar event occurs following the 1.5 mm rain on Apr. 1, 2016, which causes a complete recovery of the $<SR^{Isc}>$ but only a partial recovery of $<SR^{Pmax}>$. The photo in Fig. 1 (c) taken early on May 6, 2016 shows that soiling has accumulated in the corner of the module, and Fig. 2 (c) shows that this causes the $<SR^{Pmax}>$ to be suppressed to 0.90 (a 10% loss of power) while $<SR^{Isc}>$ is still 0.97 (only a 3% loss). Finally, the 1.0 mm rain late in the day of May 6 completely cleans the module, as shown in Fig. 1 (d), causing both $<SR^{Isc}>$ and $<SR^{Pmax}>$ to recover as shown in Fig. 2 at point (d).

For the entire 24-month period, the average loss in current (1 - $<SR^{Isc}>$) was only 1.9% while the average loss in power (1 - $<SR^{Pmax}>$) was 3.7%.

These results demonstrate several important points. First, it is important to measure the actual module power in order to determine the true soiling loss, which can be significantly higher than the loss in short-circuit current. In addition, we see that small rain events of approximately 1 mm can easily result in redistributing dust on PV modules into a non-uniform pattern, which results in disproportionate power loss [5].

The results in this example illustrate the benefits of incorporating module power measurements into soiling measurement stations in order to detect non-uniform as well as uniform soiling events, providing for an accurate overall measurement of soiling-related power losses.

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