Design and Operation of a Waterless PV Soiling Monitoring Station

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Abstract — ASU-PRL has developed an autonomous, waterless, and wireless soiling monitoring station for photovoltaic (PV) plants. This soiling monitoring station is a 4th generation design, featuring: two split-cell coupons as sensors coplanar to the PV arrays (two soiled half-cells and two covered clean half-cells), utilizing remote web-monitoring, and capable of providing data for up to 13 different useful ratios. This design employs built-in heat sinks which eliminates the need for temperature correction of the monitored short-circuit current. This paper presents the design and operation of a waterless PV soiling monitoring station and how it differs from currently available soiling monitoring stations on the market as well as a data set obtained from different PV plants located in diverse climates to quantify the operation and methodology.

Index Terms — soiling loss factor, rain coefficient, Isc, Pmax, sensor ratios, PV, monitoring

I. INTRODUCTION

Currently, soiling monitoring stations are used in the industry to determine the photovoltaic (PV) module cleaning frequency, calculate the annual O&M costs and predict energy production gain due to cleaning. The two measurement approaches used in the industry to quantify soiling loss are short-circuit current (Isc) and maximum power (Pmax), and the merits and demerits of these two methods are presented in Fig. 1. The Isc method is simply measuring the Isc of the soiled cell/module against the clean cell/module and finding the ratio. The Isc method, in all practicality, does not require temperature correction. The Pmax method is the same, except it requires an I-V measurement to obtain the module’s power and must be temperature corrected.

The Isc method requires only a data acquisition system (DAS) whereas the Pmax method requires both a DAS and an I-V curve tracer. If all cells in a single module, all modules in a string or all strings in a plant are uniformly soiled both Isc and Pmax would provide identical soiling loss values. However, if the soiling uniformity varies from one module to another or from one string to another in a plant, either method by itself, would be giving misleading soiling loss values representative of the entire plant.

To address this limitation, a coupled approach measuring both cell-Isc and string-Imax or string-Pmax is presented in (1) which still eliminates the need for temperature correction. The cell-Isc data can be obtained from the soiling station and the individual string Imax or Pmax can be obtained from the individual inverters in the plant which continuously record these values. By coupling these two data sets, the soiling loss factor (SLF) of any string (e.g., string i) can be obtained as shown in (1) by multiplying the SLF measured from the soiling station with the individual string-mismatch factor. The string-mismatch factor is determined by dividing Imax (or Pmax) of any string of interest by Imax (or Pmax) of the best string (least soiled or least non-uniform soiling) in the entire plant.

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\text{SLF}_{\text{string } i} = \text{SLF}_{\text{cell-Isc}} \times \left( \frac{I_{\text{max-string } i}}{I_{\text{max-string best}}} \right)
\]

Fig. 1 Merits and demerits of Isc and Pmax methods
existing organizations.

measurement method is yet to be demonstrated by the particles (multilayer soiling) can be quantified by this relying on an LED to measure reflected light from the soiled module. Dust IQ by Kipp and Zonen [3], is another commercially available soiling monitoring technology. Instead of the reference module using water to compare next to a soiled module. Dust IQ by Kipp and Zonen [3], is another commercially available soiling monitoring technology. Instead of a clean vs. soiled cell/module comparison, this device measures the transmission loss of the module glass directly, relying on an LED to measure reflected light from the soiled surface. Whether soiling loss caused by the stacked soil particles (multilayer soiling) can be quantified by this measurement method is yet to be demonstrated by the independent organizations.

Every soiling monitoring station primarily determines the SLF or the soiling loss which is simply (1-SLF). ASU-PRL’s waterless and autonomous soiling monitoring stations are capable of providing up to 13 useful ratios, including four SLF ratios as explained in the next section. This paper presents the evolution of soiling monitoring stations leading up to this current 4th generation waterless design, the operation and differences compared to other technologies, and the data collected and analyzed from four different sites in diverse climates.

II. METHODOLOGY

So far, ASU-PRL has developed four different types of outdoor soiling loss monitoring stations. The 1st generation soiling monitoring station produced at ASU-PRL in 2010 consisted of 18 mini frameless PV modules mounted at nine tilt angles on an open rack structure. The mini-modules were shunted using precision resistors and divided into two groups; nine left to soil naturally at nine tilt angles, and the other nine with corresponding nine tilt angles were manually cleaned daily (except the weekends and holidays). The SLF was calculated using the monitored Isc data of soiled and cleaned mini-modules containing series connected mini-cells (1 cm x 5 cm). This station design was focused primarily on the effects of tilt-angle, more information regarding this can be found in work by Cano [4].

The 2nd generation soiling monitoring station from 2014 consists of 10 split monocrystalline silicon cells manufactured into coupons identical to commercial PV modules containing: PV glass, encapsulant, cell, encapsulant and backsheet. Each PV cell is split exactly in half to form two sensors capable of independent measurements. Each half-cell sensor is equipped with a separate junction box containing two precision current shunts, (0.020 ohm each with TCR of ± 20 ppm/°C) between the positive and negative terminals of the cell. Short circuit current (Isc) of each half-cell is determined by measuring the voltage drop across the current shunt. The right-half cell of each coupon is cleaned manually twice per week and the left-half cell is left to soil naturally. The design and set-up of this station is given in more detail in a previous publication [5]. This station design was also focused more on the effects of tilt-angle as the 1st generation station but the data obtained in the 2nd generation station is expected to be more accurate during bird dropping incidents, due to the larger sized cells and no series connection of the cells.

The 3rd generation soiling monitoring station erected in 2015 coplanar to the test array (single tilt angle or 1-axis tracker), retained the two split-cell coupons which are mounted on a 91.44 cm (36 in) long aluminum plate shown in Fig. 2. The white-painted back mounted aluminum plate is used as a heat sink to help dissipate heat from the sensors and thus, stabilize the cell temperatures close to ambient temperature. Again one split-cell module is left to collect soil naturally, while the other split-cell receives an automatic water spray wash every morning to remain clean. This is possible by using a timer, marine pump, 55-gallon (208 liter) drum of distilled water and hose assembly, as well as a small DAS to record Isc of the half-cells. The details of this design were not published but were communicated via internal reports with Salt River Project (SRP).

Through this evolution, the 4th generation soiling monitoring station built in 2016, was designed to combine the strengths of the same split-cell sensors as in the 3rd generation station but has eliminated the need for water. Pictured in Fig. 3, the upgraded design utilizes an actuator operated glass shutter which opens each day approximate to solar noon for two minutes (or less as needed) to capture Isc readings on the two clean half-cells. This design also integrates a DAS which

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SLF_{\text{string } i} = SLF_{\text{cell } \text{Isc}} \times \frac{I_{\text{max } \text{string } i}}{I_{\text{max } \text{string } \text{best}}} \quad (1)
\]
transmits data via cellular networks, enabling monitoring multiple stations from virtually anywhere world-wide. The PLC and circuitry, actuator, and DAS battery are all powered/charged by a 12V battery charged via the 30W solar module affixed to the front of the tripod assembly.

Fig. 3. ASU-PRL’s 4th generation soiling monitoring station (left: glass shutter opened showing the split sensor, right: glass shutter closed)

A graphical representation of the open-shutter readings at noon is given in Fig. 4. Temperature correction is not needed, as the sensors are all practically the same value due to the white painted aluminum heat sink material used in this design. From this operational depiction it is clear to see the (SLF) ratio determination.

Fig. 4. Soiling monitoring station (SLF) determination

This 4th generation waterless soiling station design allows up to 13 useful ratios to be obtained for monitoring of different aspects. Given in Fig. 5, the four ratios 3-6 (S1/C1, S2/C1, S1/C2, S2/C2) contribute to SLF determination, thus, giving a much more statistically redundant end value for the daily SLF. The daily SLF is the average of the four SLF values recorded while the glass shutter is in the open position for 2 minutes at noon.

Fig. 5. The thirteen ratio capabilities and their usefulness

Ratios 1, 2, and 7 are able to provide information on whether a sensor is malfunctioning. A deviation of these three measured ratios from 1 ± 0.01 would indicate a problem and the average SLF should not be trusted. Ratios 8-11 are useful to determine the effectiveness of an anti-soiling (AS) coating if the glass shutter has an (AS) coating on the surface. In ratios 12 and 13, the (a) denotes after shutter is closed and the (b) denotes before shutter is open. These two ratios are unique in their ability to provide information regarding the nature of the soil adhesion whether it is loose or cemented. This could be a useful parameter when considering whether to use a wet or dry cleaning approach for the PV site where the station is installed. A matrix and visual of the ratios corresponding to the clean/soiled sensors is given in Fig. 6.

Fig. 6. Visual of the clean/soiled sensors and corresponding ratios
III. RESULTS AND DISCUSSION
Currently there are four waterless soiling monitoring stations deployed in different climatic zones of the South West region of the United States as shown in Fig. 7.

- Station 1 is located at a solar PV plant in Arizona (AZ1) – set to 5°S tilt.
- Station 2 is located at a solar PV plant in California (CA1) – on a single-axis tracker.
- Station 3 is located at ASU in Arizona (AZ2) – set to 33°S tilt.
- Station 4 is located at a solar PV plant in Texas (TX1) – set to 20°S tilt.

Data is collected wirelessly from all 4 stations and filtered with the following limits:

1. Irradiance must be higher than 600 W/m²
   - C1 ≥ 0.6
   - C2 ≥ 0.6

2. Significant anomalies must be removed – such as bird droppings
   - C1/C2 ≥ 0.996 and C1/C2 ≤ 1.004
   - S1/S2 ≥ 0.996 and S1/S2 ≤ 1.004

Fig. 7. Site map of ASU-PRL’s deployed soiling stations

The data is then compared with site-specific rainfall (mm per day), cleaning or other events for validation as given in Fig. 8. Each time the sensors are cleaned due to heavy rain, the ongoing ratio becomes 1 and matches the initial ratio in the time-series plot.

Figs. 9, 10 and 11 are the SLF plots for the other three sites where the soiling monitoring stations are collecting data on an on-going basis.
To quantify the cleaning efficacy of the rain on the soiled modules, determination of a rain coefficient is necessary. The calculation to determine the rain coefficient or rain gain (in %/mm) is given in (2), where $SLF_{ar} = SLF$ after rain and $SLF_{br} = SLF$ before rain.

$$\text{Rain coeff (}\%\text{/mm)} = \frac{((SLF_{ar} - SLF_{br}) / SLF_{br}) \times 100}{\text{Rainfall}} \quad (2)$$

After determining the rain coefficient and applying it for each set of site-specific data, the following Figs. 12, 13, 14 and 15 show the effectiveness of rain cleaning. To qualify as a rain event, the measured amount of rain must be greater than 1 mm over a day. All these plots indicate that the modules with thin soil layers tend to become dirtier (negative rain gain or coefficient) irrespective of the location of the plant if the rain fall is less than 2 mm/day.
For the California plant, the observed rain gain or rain coefficient shown in Fig. 12 can be explained as follows:

- If the rain fall is less than 8 mm/day and the SLF is about 0.97 (thin soil layer), the maximum rain coefficient is only 0.2%/mm as the SLF does not reach 1 after the rain fall. This low rain gain is potentially due to the chemical bonding of the first few soil layers on the glass surface (hard to remove cemented soil due to the presence of higher humidity).

- If the rain fall is about 16 mm/day and the SLF is 0.86 or higher (thick soil layer), the true rain coefficient potential is not known but it should be higher than 1%/mm as the SLF becomes 1 after the rain fall. This high rain gain is potentially due to the effective removal of both chemically bonded layers (hard to remove cemented soil) and non-chemically bonded stacked layers (easy to remove loose soil) over the chemically bonded layers.

Similar explanations can be given to the other rain coefficient plots shown in Figs. 13, 14 and 15. The rain gain or coefficient may vary from one location to the other depending on the nature of the soil adhesion (loose or cemented) which is heavily dictated by the local soil composition and humidity level.

IV. CONCLUSION

In this paper, the evolution of soiling monitoring stations developed at ASU-PRL has been presented, with a focus on the current 4th generation waterless web-monitored station. The operation and capabilities of this waterless soiling station have been demonstrated with actual site data collected and analyzed at four different locations. Having multiple sensors in the station design to provide data redundancy has proven to reduce the data loss. The rain coefficient determination is able to provide insight whether the amount of rainfall is helpful in cleaning a module versus actually increasing the dirtiness if too little rain is present. This was found to be the case with rainfall below 2 mm at high SLF values. At lower SLF values (thick soil layer), the positive gain due to the rain is high at about 1%/mm. At higher SLF values (thin soil layer), the positive gain due to the rain is low and is typically less than 0.2%/mm.

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