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Quantifying Uncertainty in PV Performance Delta Measurements

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ABSTRACT

We propose fundamental improvements to the quantification of measurement uncertainty in the performance deltas that are key to photovoltaic (PV) module degradation studies and reliability modeling. A performance delta is the change in the value of a performance parameter (e.g., Isc or Pmp) that can occur over various timescales. These deltas are often determined from current-voltage (I-V) curves measured at standard test conditions (STC) using a solar simulator. Measured changes in a performance parameter must be properly interpreted within the change's uncertainty. Achieving the lowest possible uncertainties requires additional careful quantification of the correlations between individual measurements, which are typically both significant and time dependent.

PROBLEM STATEMENT

The measurement uncertainty computation for the PERFORMANCE DELTA between two replicate measurements differs significantly from a single measurement (Isc or Pmp).

Consider short-circuit current:

$$\Delta I_{SC_0} = I_{SC_0,2} - I_{SC_0,1}.$$

The variance of this delta is given by

$$\sigma^2_{\Delta I_{SC_0}} = \underbrace{\sigma^2_{I_{SC_0,2}} + \sigma^2_{I_{SC_0,1}}}_{\text{Sum-of-squares portion}} - 2\,\sigma_{I_{SC_0,2}}\,\sigma_{I_{SC_0,1}}\underbrace{\rho(I_{SC_0,2}, I_{SC_0,1})}_{\substack{>0 \text{ and } <1\text{, with} \\ \text{correlation strength} \\ \text{decreasing over time}}}$$

$$< \sigma^2_{I_{SC_0,2}} + \sigma^2_{I_{SC_0,1}}. \text{ (E.g., 0.5\% vs. 3.5\%!)}$$

Elucidating the measurement correlation over various timescales is challenging:

- *Solar simulator and instrument drift*
- *Instrument and reference re-calibrations*
- *Changes in test device, including degradation (e.g., spectral correction M)*

Measurement Function for Isc

Consider the spectral and irradiance-level correction to get Isc0 (ASTM E948 or E1036).

Symbol Legend:

- *RD= Reference Device*
- *MD= Monitor Device*
- *TC= Transfer Calibration (RD to MD)*
- *I= Current [A]*
- *S= Spatial Non-Uniformity Corr. Factor*
- *M= Spectral Correction Factor*
- *R_{Isc}= Current-Shunt Resistance [Ω]*
- *μ_{TC}= Average of MD to RD Ratio in TC*
- *V_{Isc}= True Current-Shunt Voltage [V]*

The correction in terms of nominal values is

$$\hat{I}_{SC_0} = \hat{S}\,\frac{\hat{I}_{SC_0,RD}\,\hat{R}_{I_{SC},RD}\,V_{I_{SC}}}{\hat{M}\,\hat{R}_{I_{SC}}\,V_{I_{SC},MD}}\,\hat{\mu}_{TC}. \quad (1)$$

The correction in terms of uncertain values (given as random variables, or RVs) is

$$\tilde{I}_{SC_0} = \tilde{S}\,\frac{\tilde{I}_{SC_0,RD}\,\tilde{R}_{I_{SC},RD}\,V_{I_{SC}}}{\tilde{M}\,\tilde{R}_{I_{SC}}\,V_{I_{SC},MD}}\,\tilde{\mu}_{TC}. \quad (2)$$

Dividing (2) by (1), cancelling common factors, solving for the RV I_{SC0}, and rewriting in terms of nominal-normalized RVs gives

$$\tilde{I}_{SC_0} = S\,\frac{I_{SC_0,RD}\,R_{I_{SC},RD}}{M\,R_{I_{SC}}}\,\mu_{TC}\,\tilde{\hat{I}}_{SC_0}. \quad (3)$$

The true current-shunt voltages are never actually measured at short-circuit (I=Isc at V=0), and they fully cancel out in the ratio.

However, the nominal Isc0 is uncertain due to the I-V curve regression that determines its value (esp. noisy irradiance monitoring).

KEY QUESTION:

Which components of (3) are CORRELATED between two Isc measurements used to compute a performance delta?

Component Uncertainties: Systematic vs. Random and Associated Correlations

Shortest Timescale Measurements

Same test device with a stable solar simulator (SS), a calibrated data acquisition system (DAS) and reference device (RD), and the same transfer calibration (TC):

$$\tilde{I}_{SC_0} = \underbrace{S\,\frac{I_{SC_0,RD}\,R_{I_{SC},RD}}{M\,R_{I_{SC}}}\,\mu_{TC}}_{\substack{\text{Unchanging, perfectly correlated} \\ \text{systematic components} \\ \text{(repeatability w/same test} \\ \text{device, simulator setup, and TC)}}}\;\underbrace{\tilde{\hat{I}}_{SC_0}}_{\substack{\text{Random} \\ \text{component} \\ \text{from} \\ \text{MD noise} \\ \text{in each} \\ \text{I-V curve}}}.$$

Medium Timescale Measurements

A degraded test device with a stable SS, DAS, and RD, but a different TC:

$$\tilde{I}_{SC_0} = \underbrace{\frac{S}{M}}_{\substack{\text{Systematic} \\ \text{AND} \\ \text{random} \\ \text{effects!}}}\;\underbrace{\frac{I_{SC_0,RD}\,R_{I_{SC},RD}}{R_{I_{SC}}}}_{\substack{\text{Unchanging, perfectly correlated} \\ \text{systematic components} \\ \text{(reproducibility w/same} \\ \text{simulator setup)}}}\;\underbrace{\mu_{TC}\,\tilde{\hat{I}}_{SC_0}}_{\substack{\text{Random} \\ \text{components} \\ \text{(reproducibility} \\ \text{w/different TC for} \\ \text{each I-V curve)}}}.$$

The current limiting cell (affecting S) and/or M may change with test device degradation. M's re-measurement decreases correlation between M values for $I_{SC0,1}$ and $I_{SC0,2}$.

Longest Timescale Measurements

A degraded test device with a drifted (or even different) SS, a re-calibrated DAS and RD, and a different TC:

$$\tilde{I}_{SC_0} = \underbrace{S\,\frac{I_{SC_0,RD}\,R_{I_{SC},RD}}{M\,R_{I_{SC}}}}_{\substack{\text{Systematic AND random} \\ \text{effects that are} \\ \text{difficult to decompose!}}}\;\underbrace{\mu_{TC}\,\tilde{\hat{I}}_{SC_0}}_{\substack{\text{Random} \\ \text{components}}}.$$

Properly quantifying the correlations becomes quite challenging!

However, ignoring certain correlations may give a conservative uncertainty estimate.

Computational Approaches

Consider the RELATIVE change in Isc:

$$\frac{\Delta\tilde{I}_{SC_0}}{\tilde{I}_{SC_0,1}} = \frac{\tilde{I}_{SC_0,2} - \tilde{I}_{SC_0,1}}{\tilde{I}_{SC_0,1}} = \frac{\tilde{I}_{SC_0,2}}{\tilde{I}_{SC_0,1}} - 1.$$

Shortest Timescale Measurements

$$\frac{\Delta\tilde{I}_{SC_0}}{\tilde{I}_{SC_0,1}} = \frac{S\,\dfrac{I_{SC_0,RD}\,R_{I_{SC},RD}}{M\,R_{I_{SC}}}\,\mu_{TC}\,\tilde{\hat{I}}_{SC_0,2}}{S\,\dfrac{I_{SC_0,RD}\,R_{I_{SC},RD}}{M\,R_{I_{SC}}}\,\mu_{TC}\,\tilde{\hat{I}}_{SC_0,1}} - 1$$

$$= \tilde{\hat{I}}_{SC_0,2} \Big/ \tilde{\hat{I}}_{SC_0,1} - 1,$$

where most of the uncertain factors have cancelled out and the only uncertainty is due to the nominal values from the regressions (two independent random effects).

Medium Timescale Measurements

$$\frac{\Delta\tilde{I}_{SC_0}}{\tilde{I}_{SC_0,1}} = \frac{S_2\,\dfrac{I_{SC_0,RD}\,R_{I_{SC},RD}}{M_2\,R_{I_{SC}}}\,\mu_{TC,2}\,\tilde{\hat{I}}_{SC_0,2}}{S_1\,\dfrac{I_{SC_0,RD}\,R_{I_{SC},RD}}{M_1\,R_{I_{SC}}}\,\mu_{TC,1}\,\tilde{\hat{I}}_{SC_0,1}} - 1$$

$$= \frac{S_2\,M_1\,\mu_{TC,2}\,\tilde{\hat{I}}_{SC_0,2}}{S_1\,M_2\,\mu_{TC,1}\,\tilde{\hat{I}}_{SC_0,1}} - 1,$$

where fewer uncertain factors cancel. To evaluate with the smallest uncertainty using linearization (or Monte Carlo), one must establish the correlations between (or joint distributions of) S_1 and S_2 and M_1 and M_2.

Conclusion

Understanding measurement correlations on various timescales is key to quantifying the lowest possible uncertainties in PV performance deltas, enabling more proper interpretation of degradation measurements.

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