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MEASURING PV SYSTEM SERIES RESISTANCE WITHOUT FULL IV CURVES

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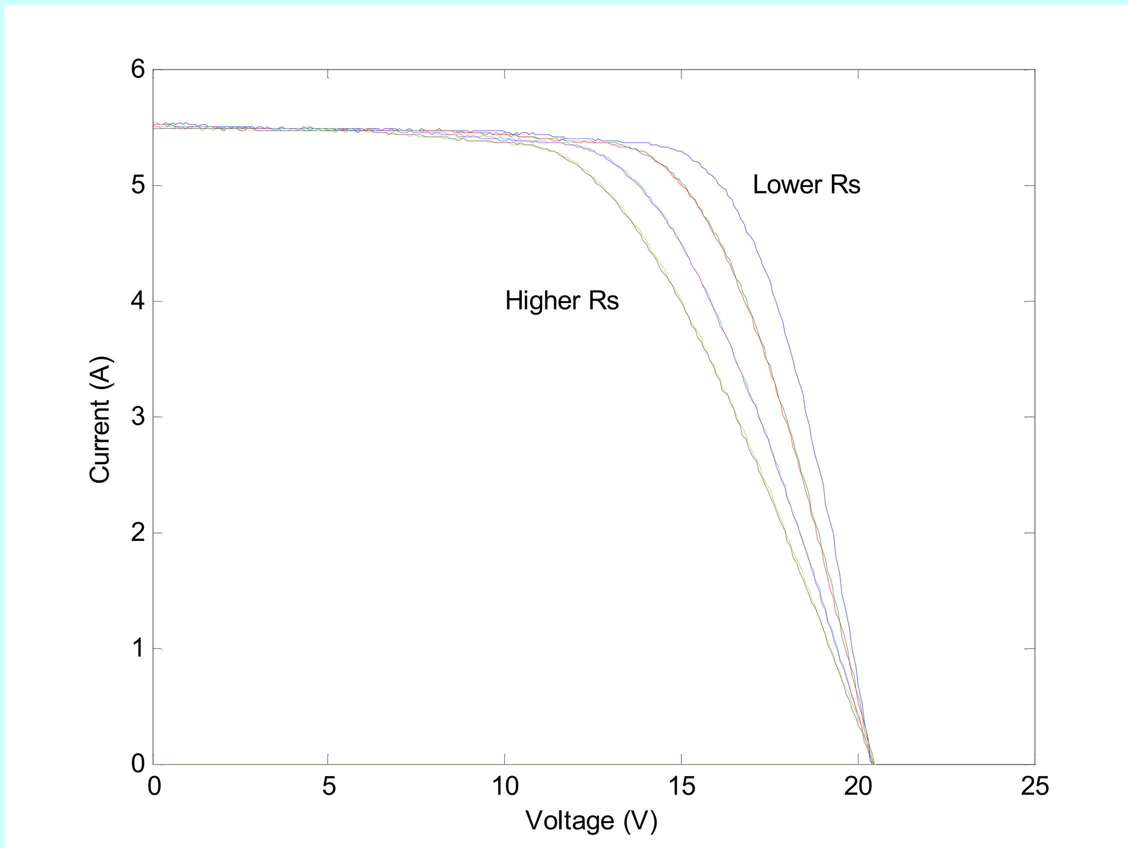
Increasing series resistance can indicate degradation and reliability problems in a PV system

Background

The series resistance (Rs) of a photovoltaic system (i.e., cell, module, or array) represents the sum of the resistances contributed by all of the series-connected cell layers, contacts, and wiring between both ends of the system's circuit. Because the value of series resistance is affected by changes in resistance for any of these component and subcomponent parts of the PV system, monitoring series resistance over time provides valuable information about the system's electrical health. Increases in series resistance have been linked to corrosion inside modules and connectors, UV degradation of silicon, and other material degradation processes that contribute to overall degradation of PV system performance.



As series resistance increases, the fill factor decreases.

Predict Rs from Voc, Vmp, and Imp

To simulate this IV behavior we propose the following model:

$$Voc = Rs * Imp + b1 * ln(Imp) + b2 * Vmp + b3. \quad \text{(Eq. 1)}$$

where *b*1, *b*2 and *b*3 are empirical constants to be determined. Once the b coefficients and an initial value of R_s are determined, the method can be applied to monitored data by solving eq. (1) for R_s.

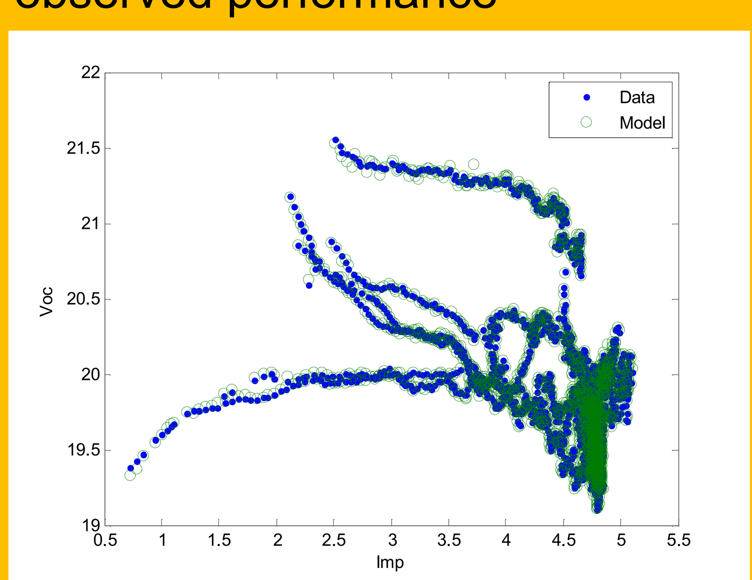
Model Verification 1

The model was verified by collecting outdoor measurements of Voc, Vmp, and Imp for both a single c-Si PV module (and a string of such modules). These data were used to fit equation 1 with a set of b-coefficients and an initial Rs value.

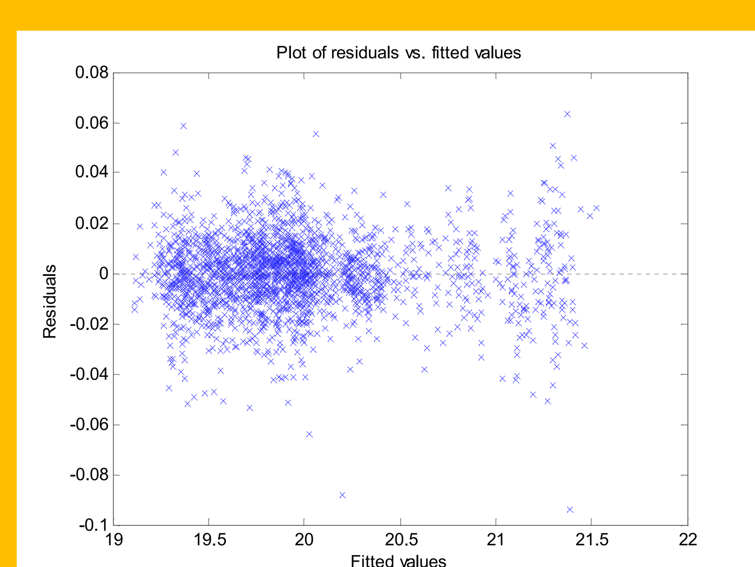
Initial Rs was calculated two ways:
1. Fitting a single diode model to a set of full IV curves
2. Fitting Rs at same time as b-coefficients were fit.

Both methods resulted in very similar estimates of initial Rs!

Running the model using estimated Rs and b-coefficients and comparing to the raw measurements demonstrated that the this mathematical formulation can accurately represent observed performance



Comparison of measured and predicted *Voc* and *Imp* values.



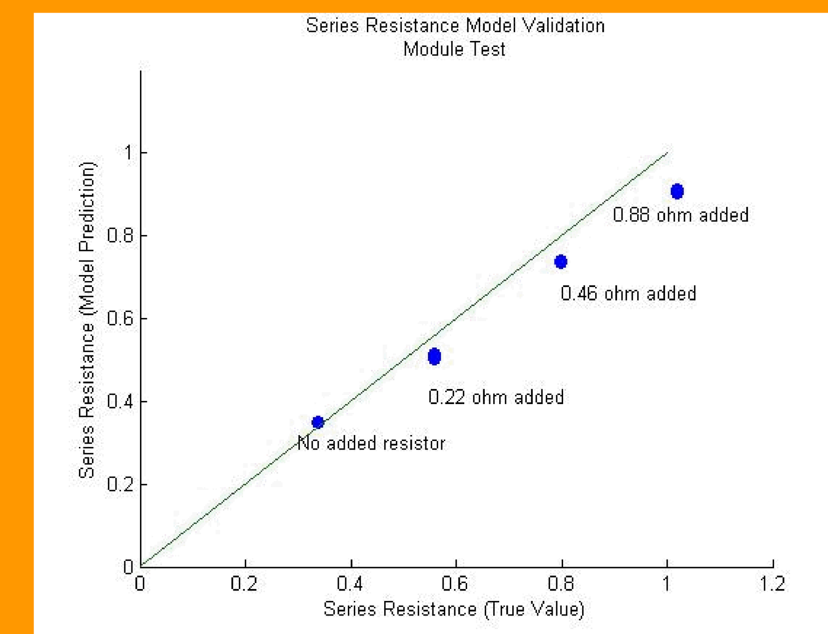
Voc model residuals (V) (model –measured).

Verification Results

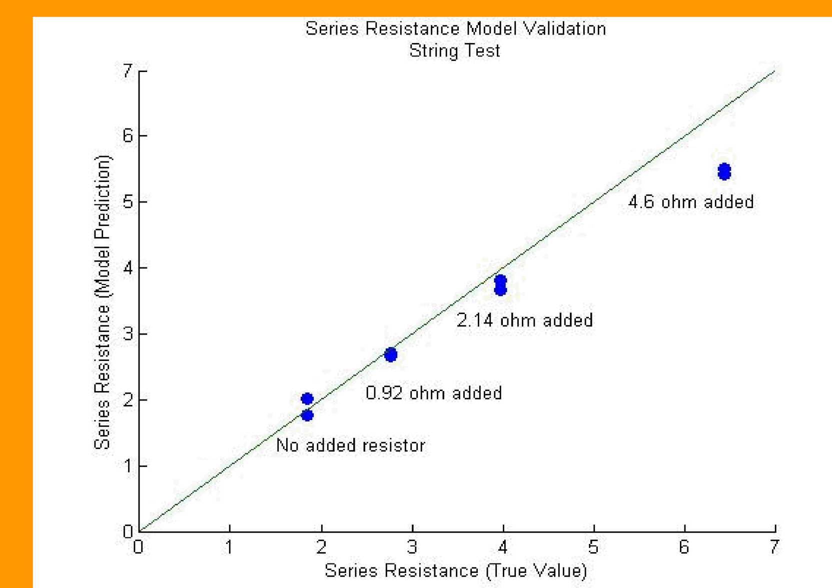
Next we measured how well this model form could detect changes in the series resistance of a module and string of modules. We systematically added fixed amounts of resistance to PV circuits and measured Voc, Vmp, and Imp outdoors on a 2-axis tracker facing the sun in Albuquerque, NM on a clear day.

We then used equation 1 and the previously calculated b-coefficients to calculate the total series resistance in the circuit with each of the added resistances.

The figures to the right compare predicted Rs to "True" Rs (based on the amount of resistance added for each measurement. Irradiance remained constant during the test period.



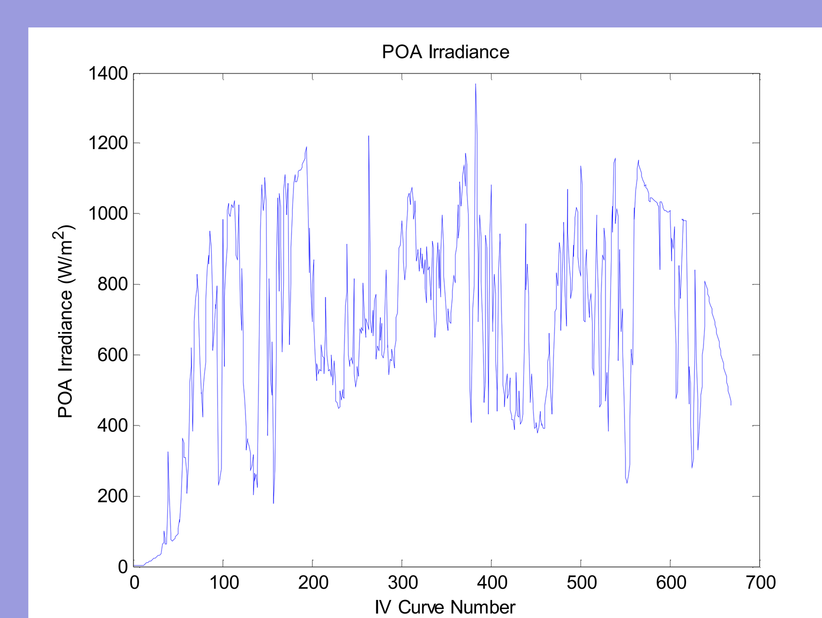
"True" vs. modeled series resistance for the module test.



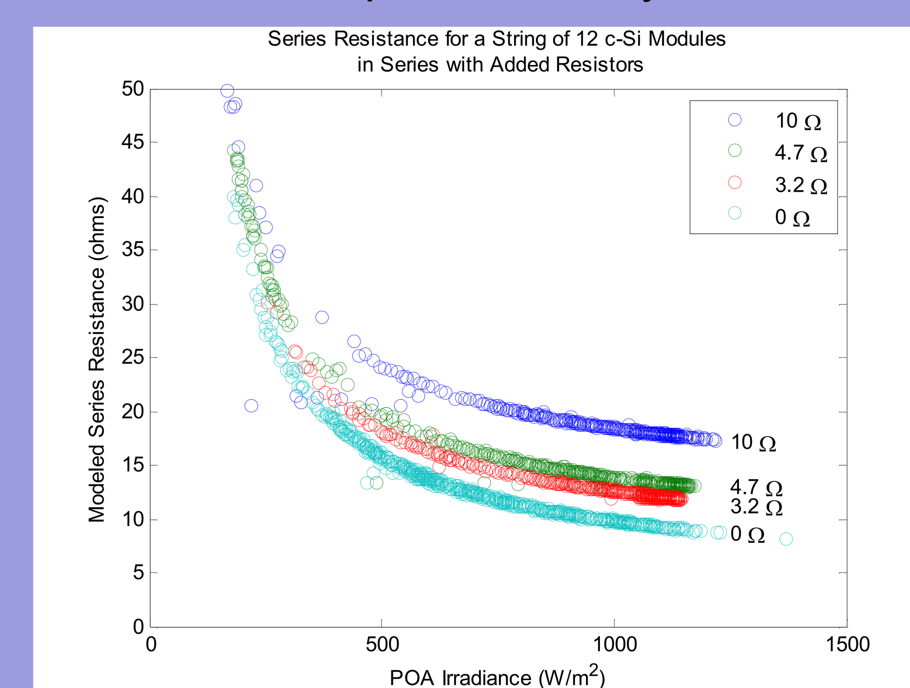
"True" vs. modeled series resistance for the string test.

Validation Under Normal Operating Conditions

After verifying that the equation appears to work we performed a validation under normal operating conditions (variable irradiance and temperature). We set up a string of c-Si modules on a 2-axis tracker and measured Voc, Vmp, and Imp every minute for four days. Each day we changed the amount of added resistance to the circuit (0-10Ω). The figure below shows that Rs changes with irradiance and that the prediction method provides very consistent results despite dynamic and variable irradiance.



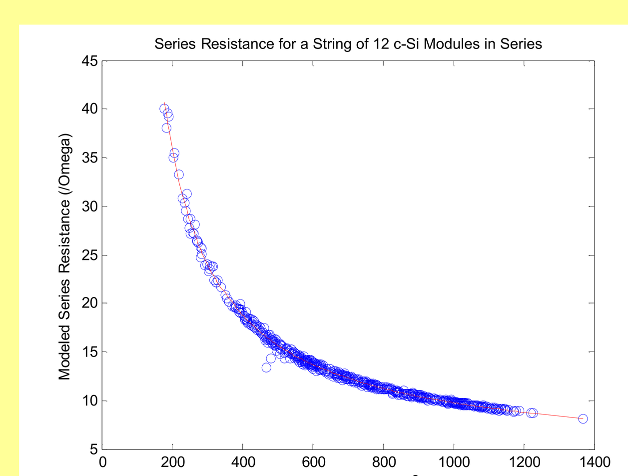
Irradiance profile for the day with no added resistance

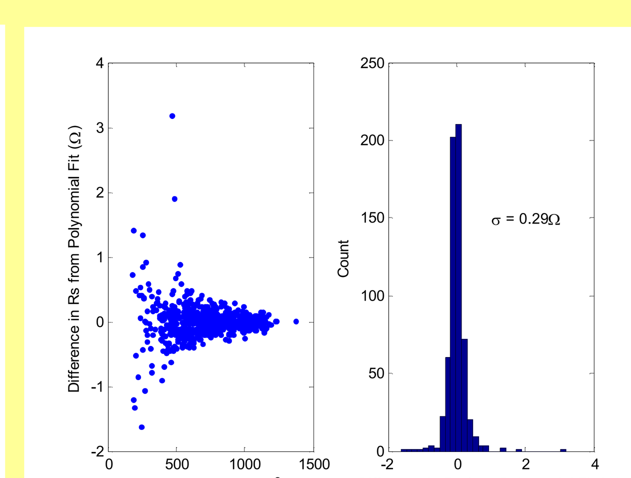


Predicted Rs values vs. Irradiance for each of the days

Uncertainty Quantification

Because the predicted Rs changes with irradiance, it was necessary to estimate the precision of the method for predicting Rs in the field. The red line in Figure 6 is a fitted polynomial (9th order) used to empirically detrend the data in order to estimate the model's precision. Figure 7 shows that the precision of this estimate is quite high (standard deviation = 0.29 Ω or ~1.5% of the value at 1,000 W/m^2) as calculated from the variation in the detrended signal. This result suggests that changes in R_s of approximately 3% could be detected in a monitored system.





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