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Measuring PV System Series Resistance Without Full IV Curves

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We present a method for measuring the series resistance of the PV module, string, or array that does not require measuring a full IV curve or meteorological data. Our method relies only on measurements of open circuit voltage and maximum power voltage and current, which can be readily obtained using standard PV monitoring equipment; measured short circuit current is not required. We validate the technique by adding fixed resistors to a PV circuit and demonstrating that the method can predict the added resistance. Relative prediction accuracy appears highest for smaller changes in resistance, with a systematic underestimation at larger resistances. Series resistance is shown to vary with irradiance levels with random errors below 1.5% standard deviation.

***Index Terms* —photovoltaic cells, series resistance, predictive models, condition monitoring**

I. Introduction

The series resistance (R_s) 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. [1]

A standard method for measuring series resistance is IEC 60891 [2], which requires at least three IV curves at constant spectrum and temperature but at different irradiance values. This method essentially fits a simplified single-diode model to obtain an estimate of R_s. Other methods follow the same approach but use a non-simplified single-diode model, for which it is more difficult to obtain parameters. Any method that requires full IV curves to be measured presents a number of problems for a monitoring application:

(1) Measurement of an IV curve requires shutting down and disconnecting the PV system in order to measured short circuit current, resulting in energy losses.

(2) IV curves can usually only be measured at the string level or less, due to power limitations of the measurement hardware. For large systems these measurements can take considerable time to be repeated across the array, string by string.

(3) The values estimated for the five single diode parameters can vary significantly depending on which estimation method is used [3]. This is because the solution sets of parameters can be non-unique, unless additional external constraints are imposed for the optimization.

An alternative method to estimate series resistance based on measuring the slope of the IV curve near the maximum power point has been suggested [4,5], but the technique is sensitive to variation of voltage and current around the maximum power point (MPP), which can vary significantly for different inverters.

In this paper we describe a new method to measure an "effective" R_s at a variety of system scales, including for full arrays, using only concurrent values of open circuit voltage (*Voc*) and maximum power current and voltage (*Imp* and *Vmp*, respectively). We present field validation tests as confirmation that the method reliably detects relatively small changes in effective R_s for a representative small PV system.

II. Methods

We propose a simplified empirical model that relates R_s to *Voc*, *Imp* and *Vmp* motivated by observed changes in IV curves as R_s is increased while irradiance and temperature conditions remain relatively constant. Figure 1 shows outdoor module IV curves measurd outdoors for a module with series resistance artificially increased by adding fixed resistors in series with the module. As series resistance increases, the IV curve near *Voc* becomes less steep indicating a commensurate decrease in the fill factor (FF). The blue curve to the right (with the highest FF) is the module IV curve with no added resistor. Additional IV curves to the left result from added resistors (0.22, 0.46, and 0.88 Ω). As series resistance increases, neither *Isc* nor *Voc* changes, rather, the effect is primarily seen as a change in *Vmp*.

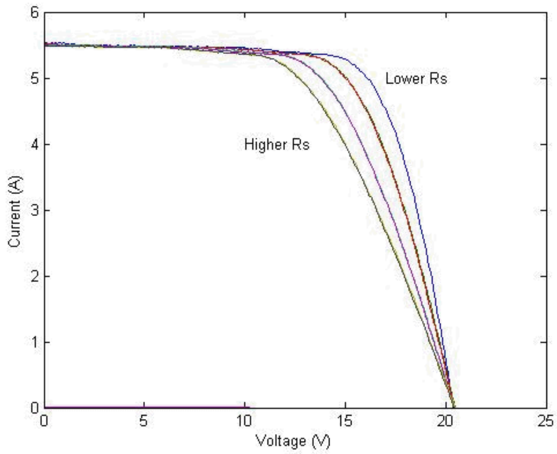

Fig. 1. Outdoor module IV curves measured with varying amounts of series resistance added to the circuit.

To simulate this IV behavior we propose the following model:

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

where $b1$, $b2$ and $b3$ 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.

To illustrate the model's adequacy, we first estimated a baseline R_s value for a c-Si module by fitting the single diode model [6] to a set of 2,151 outdoor IV curves measured on a two axis tracker during mostly clear conditions in Albuquerque, NM. From this analysis we estimated an R_s value of 0.3 Ω for the test module. Next we fit eq. (1) using only values of Imp, Vmp, and Voc from the measured IV curves, fixing R_s at the baseline value. To test whether this first analysis was necessary, we also tried fitting the *b* coefficients along with R_s. The advantage of this second approach is that this method does not require the full IV curve. The result of this 4-parameter fitting predicted 0.34 Ω for R_s, nearly identical to the method using the full IV curves. We used R_s = 0.34 Ω going forward with the model predictions. Figure 2 shows the comparison between measured data and model predictions for *Voc* vs. *Imp*. The goodness of fit is shown by the low residuals in Figure 3

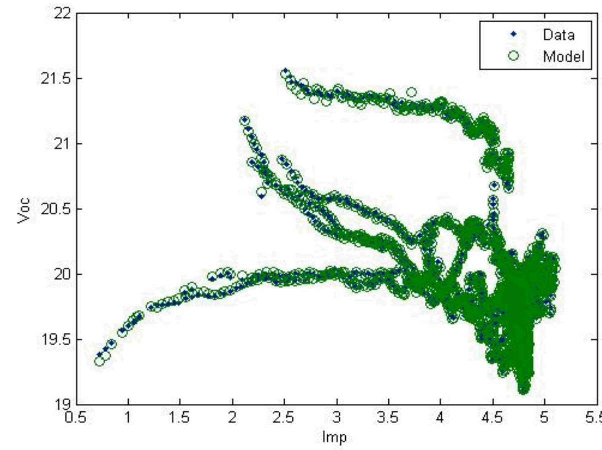

Fig. 2. Comparison of measured and predicted *Voc* and *Imp* values.

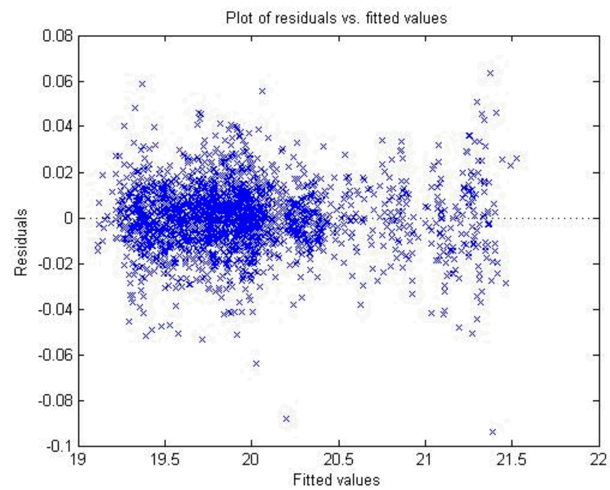

Fig. 3. *Voc* model residuals (V) (model –measured).

III. Validation

To validate this model we set up two experiments in which we added known amounts of resistance in series with a single module and with a string of modules to see how well the model could predict these changes in the series resistance. The module was placed on a two axis tracker and held normal to the sun during a clear day in December 2013 in Albuquerque, NM and two IV curves were taken with varying amounts of series resistance (Fig 1). The "True" value of the series resistance is equal to the module's R_s (assumed to be 0.34 Ω, as described earlier) plus the added resistance. We compare the "True" value of R_s with model predictions using eq. (1) with fitting parameters determined from an independent dataset as described previously. Figure 4 shows the comparison with a 1:1 line for reference. The figure suggests that the model is able to predict changes in the series resistance but has a slight tendency to underestimate R_s as it increases significantly (0.11 Ω maximum difference). These results suggest that our method may work well for detecting changes in series resistance over time.

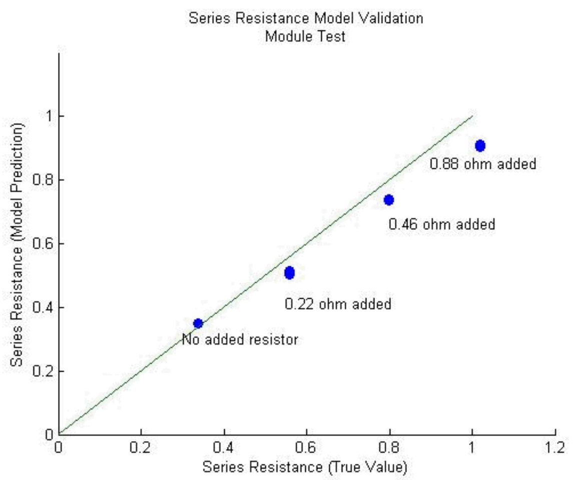

Fig 4. "True" vs. modeled series resistance for the module test.

We repeated the same experiment with a string of five modules to see how the model performed under these conditions. As before, we collected IV curves on a string of 12 c-SI modules connected in series and fit b coefficients and R_s to this data. Results of the string test are shown in Figure 5. The model shows an even better match for most of the cases and a similar underestimate bias for the highest value of R_s (1 Ω maximum difference).

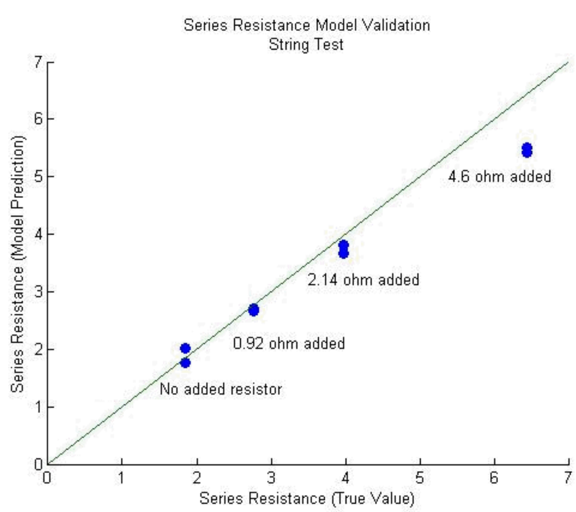

Fig 5. "True" vs. modeled series resistance for the string test.

To test the method using continuous monitoring data we collected additional IV curves over several days on a string of 12 c-Si modules in series on a two axis tracker. We purposely chose not to filter any of the IV curves for variable irradiance conditions or measurement artifacts so that the method would be tested using data representative of field conditions. Figure 9 shows the measured irradiance during one day of the test.

Figure 6 shows the estimated R_s values for each IV curve during a day with no resistor added to the circuit. The figure clearly shows a nonlinear relationship between R_s and plane-of-array (POA) irradiance, with R_s increasing as irradiance is reduced. This behavior appears to be characteristic of many c-Si modules. The R_s value at 1,000 W/m^2 is approximately 9.77 Ω.

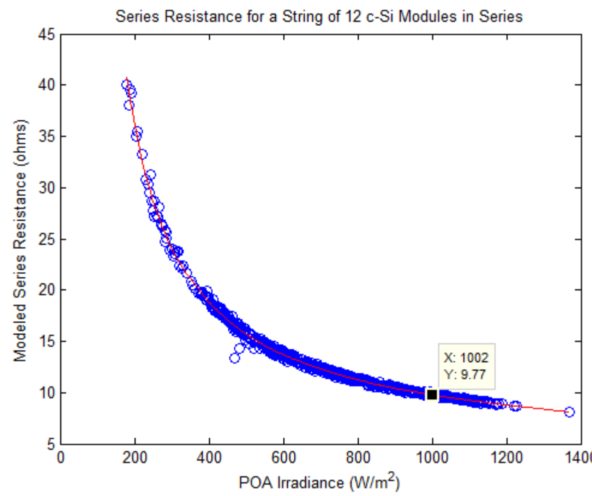

Fig 6. Series resistance as a function of plane of array irradiance for a string of 12 c-Si modules mounted on a 2-axis tracker in Albuquerque, NM.

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.

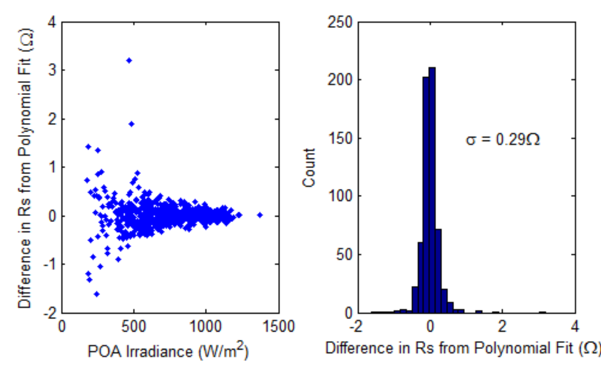

Fig 7. Precision of R_s calculated as the difference between estimated R_s and the fitted polynomial (9th order) shown in Fig 6.

After this baseline measurement, we added three different fixed resistors (3.2Ω, 4.7Ω and 10Ω) in series in the circuit on each of three days and collected IV curves every minute.

Using only Voc, Imp, and Vmp values from the IV curves and eq. (1) we again estimated the R_s value as described earlier. Figure 8 shows the resulting R_s values colored by the amount of additional resistance added. Clearly, for the vast majority of these data, the added resistance is easy to detect. The few outlier points are likely due to transient irradiance conditions that affected the IV curves and thus measurements of Voc, Imp, and Vmp.

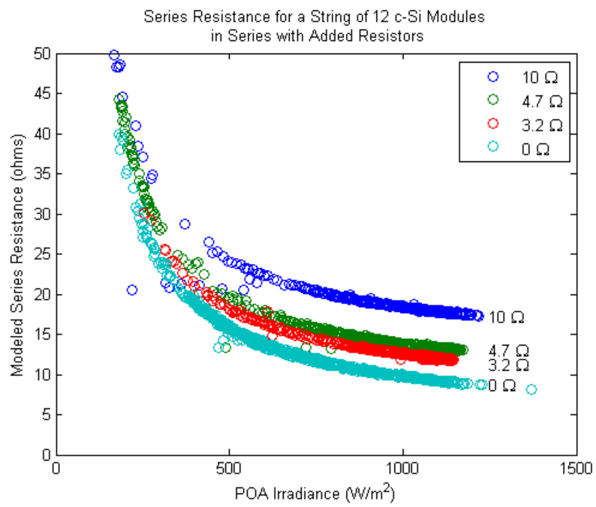

Fig 8. Estimated series resistance as a function of plane of array irradiance for a string of 12 c-Si modules mounted on a 2-axis tracker in Albuquerque, NM with varying values of added resistance.

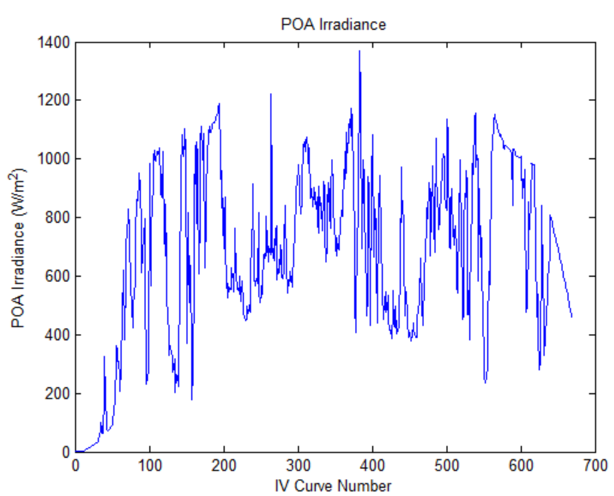

Fig. 9. Irradiance profile for the day shown in Fig. 6.

IV. DISCUSSION

We have proposed and validated a method for easily measuring changes in the series resistance of a module, string, or array using only commonly available monitoring data and without needing to manually disconnect any part of the array. Because the changes in series resistance are likely to occur slowly, it is probably only necessary to measure it on a daily, weekly, or even monthly interval, but we have demonstrated that changes can easily be discerned from continuous monitoring data. In order to make measurements infrequently, more work is needed to quantify the effect of irradiance and other environmental conditions (e.g., temperature) on estimated R_s. It may be possible to measure a different irradiance levels and later transform to a common level, but this has not been demonstrated.

Most inverters measure and report values of *Imp* and *Vmp* as a matter of course, because inverters need these values as inputs to their maximum power point tracking (MPPT) controllers. The *Voc* measurement can be made quite easily on inverters that support communication based controls (e.g., MODBUS) by sending a signal to the inverter to deliver zero power (for a fraction of a second), which brings the array to *Voc*, and then immediately signaling the inverter to return to MPPT. Many inverters can remain connected to the grid during this excursion. .

V. CONCLUSIONS

We present a method for measuring changes in the series resistance of the PV module, string, or array. Our method does not require measuring an IV curve or disconnecting any part of the system. Instead it relies on remotely made measurements of open circuit voltage and maximum power voltage and current that can be obtained using standard PV monitoring equipment. We validate the technique by adding fixed resistors to a PV circuit and demonstrating that the method can predict the added resistance. Relative prediction accuracy appears highest for smaller changes in resistance, with a systematic underestimation bias at larger resistances.

VI. ACKNOWLEDGEMENTS

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