Validation of In-Situ I-V Measurement Unit for PV System Monitoring Applications

Audrey Marquis[1], Michael Gostein[1], and Bruce H. King[2]

[1]Atonometrics, Inc., Austin, TX, USA; [2]Sandia National Laboratories, Albuquerque, NM, USA

***Abstract*—Electrical output measurement of PV reference modules in an array is used for a variety of applications in PV system monitoring, including measurements of irradiance and soiling as well as detection of degradation and faults. Using currently available measurement equipment, reference modules are typically standalone modules installed alongside the array, which results in extra costs for system engineering and racking. New products will allow measuring I-V curves on power-producing PV modules in-situ within a PV array, simplifying implementation. However, for in-situ use it is critical that the I-V measurement unit does not disturb inverter operation or reduce energy output. In this work we developed a test protocol to quantify impacts of the I-V unit on inverter energy output and evaluated a new in-situ I-V measurement product in multiple arrays. In initial results, we found no adverse impact of the I-V unit on inverter operation, with minimal power loss approximately as expected from the series resistance and duty rate of the I-V measurement.**

Keywords—photovoltaic systems, monitoring, I-V curves

I. Introduction

Various applications in PV system monitoring use current-voltage (I-V) measurement on PV reference modules – modules identical to those of the PV array but designated for measurement and characterization purposes – to extract system performance data. Examples include determining matched irradiance by measuring short-circuit current of a calibrated reference module [1]; determining soiling loss by comparing short-circuit current or maximum-power output of clean and dirty reference module pairs [2]; identifying faults by classification of reference module I-V curves [3]; measuring module degradation rates; and determining effective total irradiance for bifacial systems from a reference module within an array [4].

However, due to the capabilities of currently used I-V curve tracer products, PV reference modules must typically be installed standalone – at the array but not within it. Reference modules are therefore typically installed on extension arms above or to the side of a row of modules or on separate racking. Alternatively, standalone reference modules sometimes occupy a standard module position with neighboring modules wired around them. These standalone configurations result in significant extra costs for engineering and racking.

It would be advantageous to have I-V tracers that could be deployed in-situ within an array on power-producing modules, simplifying deployment and lowering overall costs. This has been explored by a number of groups [5][6]. Here we report on a new product for in-situ I-V measurement developed by Atonometrics, the RDE300i, and on our study to validate the RDE300i product for in-situ application.

For in-situ application it is critical to know that the I-V unit will not disturb inverter function and that any energy loss will be negligible. We have begun a test program at Sandia National Laboratories to evaluate the RDE300i and quantify any impact on inverter function and energy harvest.

II. Experiment

A. I-V System

The RDE300i, shown in the top panel of Fig. 1, is designed to be installed between a selected module and the rest of the array, for in-situ operation. The module is connected to the

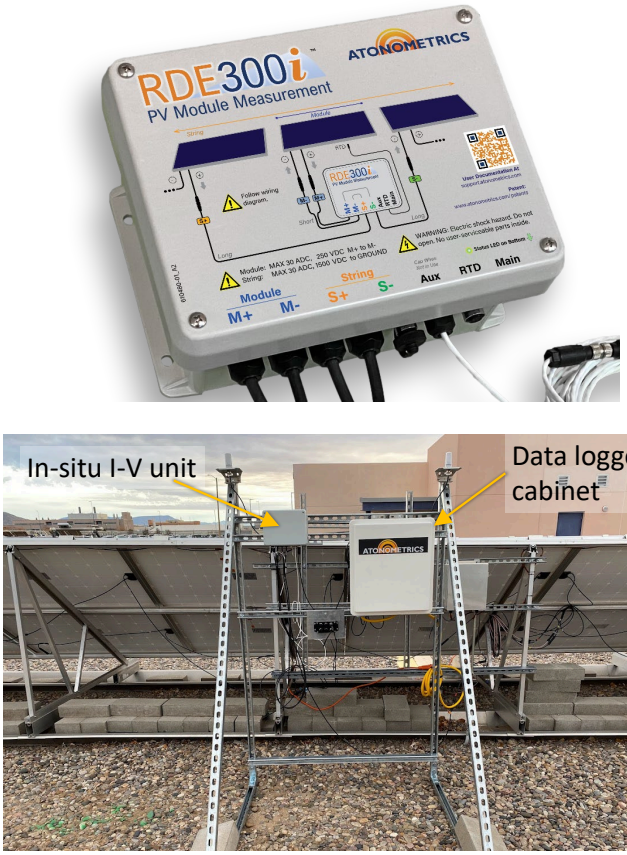


Fig. 1. Top: RDE300i PV module in-situ I-V tracer. Bottom: RDE300i I-V tracer on a test stand at Sandia National Laboratories wired into a PV string.

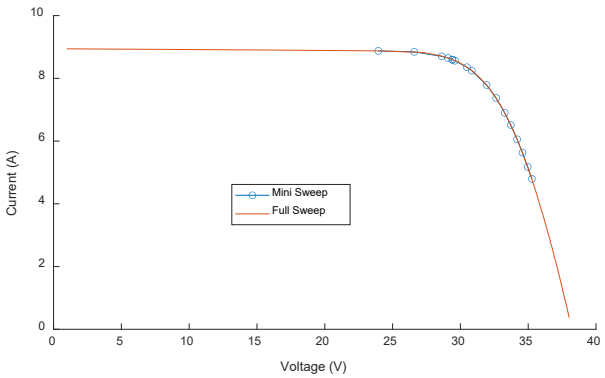


Fig. 2. Example of I-V curves showing two operation modes.

RDE300i which is then connected to the neighboring modules on the PV string. I-V sweeps are performed at periodic intervals. The RDE300i supports two I-V sweep modes, illustrated by Fig. 2. In one mode the RDE300i momentarily disconnects the module from the string, performs a full I-V sweep, and reconnects the module. While the module is disconnected, string current goes around the module via an integrated bypass circuit. In another mode, the RDE300i does not disconnect the module but performs a mini-sweep, as illustrated in Fig. 2, to measure the module's maximum power point without disconnection. The mini-sweep mode permits more frequent measurements while minimizing power loss. In between I-V sweeps the RDE300i directly connects the module to the string for pass-through operation. RDE300i can measure I-V sweeps up to 30 A, 250 V, and 1500 W.

The bottom panel of Fig. 1 shows a prototype RDE300i I-V unit wired in-situ a string of crystalline silicon PV modules in a test array at Sandia National Laboratories. For this study the I-V unit is mounted on a test stand that may be easily moved to different arrays that use different modules and inverters. However, in typical installations the RDE300i unit would likely be mounted underneath the module racking.

For these experiments we are using a data logger, mounted in the cabinet shown to the right of the I-V unit in Fig. 1, to capture the I-V curves and the fit results. We measure a full I-V sweep every 1 minute and a mini-sweep every 10 seconds. From the full I-V sweeps the I-V unit automatically determines short-circuit current (Isc), open-circuit voltage (Voc), maximum power (Pmax), and voltage and current of the maximum power point (Vmp and Imp). From the mini sweeps it determines Imp, Vmp, and Pmax. In addition, in between the I-V sweeps the unit records the output voltage and current (Vout and Iout), which are the voltage and current operating point of the module governed by the inverter's maximum power point tracking of the entire string. Fig. 3 depicts an example of data outputs of the RDE300i over a ten-day period.

B. PV Arrays

We have begun a test campaign at the Sandia National Laboratories Photovoltaic Systems Evaluation Laboratory (PSEL) in Albuquerque, New Mexico, which has numerous test arrays and inverter systems. For the testing performed so far, we selected three arrays representing different module and inverter types. Two of the arrays use crystalline silicon Suniva 270 W modules and one uses crystalline silicon LG 400 W modules. Inverters included models from Power One and SMA. Strings selected for testing have output power up to 4.8 kW. As the study proceeds, we plan to test with additional module types, including monofacial and bifacial silicon as well as CdTe thin film modules, and additional inverters from multiple manufacturers.

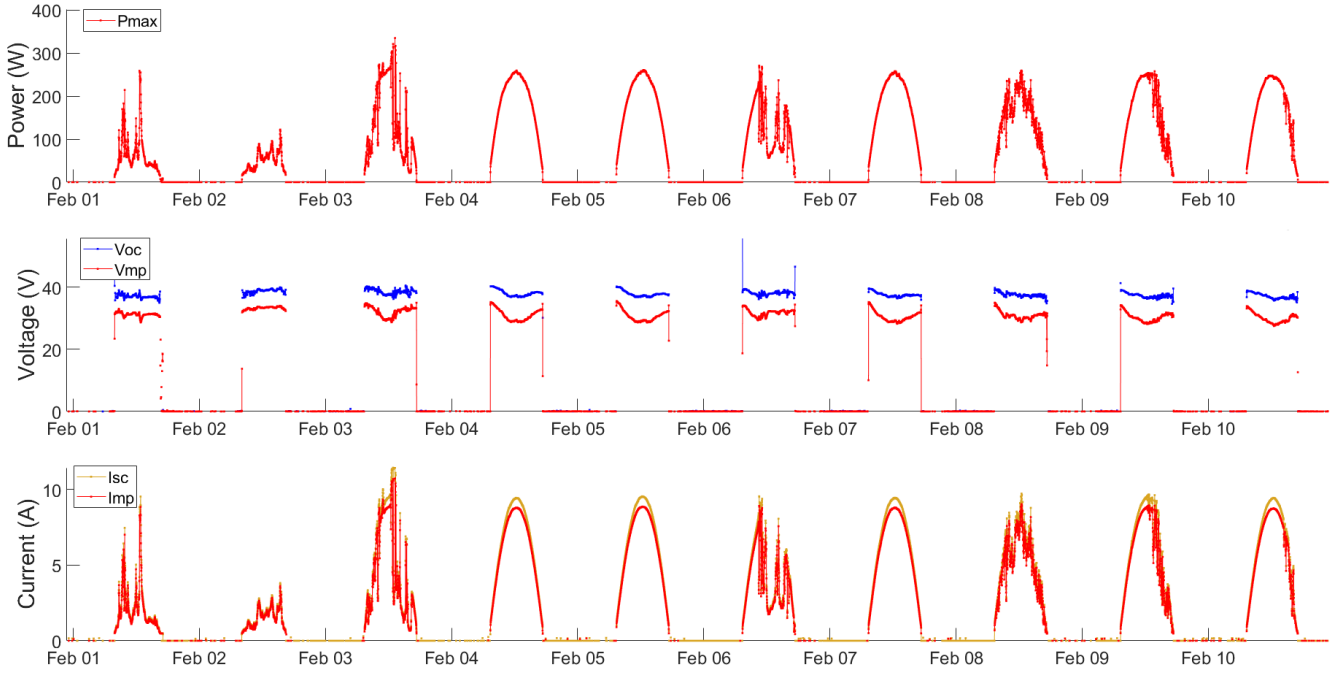


Fig. 3. Example data outputs from RDE300i in-situ I-V tracer, showing measurements of module power, voltage, and current parameters.

Table 1: Summary of functionality and energy harvest test results

System	Hours of Collected Data	Minutes of Inverter Fault	Performance Index	Expected Power Losses	Observed Power Losses
System 1	916	0	0.9984 ± 0.0017	1.8 W	1.02 W
System 2	648	0	0.9983 ± 0.0017	1.5 W	1.23 W
System 3	570	0	0.9963 ± 0.0009	3.4 W	4.99 W

C. *Functionality Test*

The first part of our test protocol is a functionality test to identify and quantify fault events and determine if the I-V sweeps performed by the RDE300i unit adversely affect inverter operation, for example causing the inverter to register a fault or temporarily disengage from maximum power point tracking.

To perform this test, we insert the RDE300i into one of the PV array test systems and record the module's maximum power, measured by the RDE300i unit, together with the array DC power output, measured by a separate array-level monitoring system, once per minute for 2-4 weeks. We then correlate the two data sets and look for outliers. Any points in which the array is not producing power, as determined by the array monitoring system, but the module itself has power-producing capability, as determined by the P_{max} measured by the RDE300i, would indicate that the inverter is not operating, even though it should be. These points could indicate a momentary inverter fault condition caused by an adverse inverter response to the I-V sweep.

D. *Energy Harvest Test*

The second part of our test protocol, the energy harvest test, is designed to quantify the power loss from the array introduced by the insertion of the RDE300i in-situ I-V measurement unit. A small amount of power loss will occur due to added series resistance of the measurement device and cables as well as from the lost operation time of the module during I-V sweeps. However, these losses should be negligible. Of greater concern is whether the periodic I-V operation subtly disrupts optimal maximum power point tracking and therefore results in lower power output. The energy harvest test is designed to put an upper limit on any such energy loss.

To perform this test, we use two identical strings, one with the RDE300i and one without, each with its own inverter channel. The DC output of each string is measured by an array-level monitoring system at the inverter inputs. We then compare the DC energy input to the two inverters over 2-4 weeks. Since the two strings and inverters may have different efficiencies, we compare the strings both before and after insertion of the RDE300i. From these data we calculate a performance index

$$PI = \frac{(\sum P_2 \ / \ \sum P_1)_{after}}{(\sum P_2 \ / \ \sum P_1)_{before}} \qquad (1)$$

where subscripts 1 and 2 refer to the two strings used in the test, P_1 and P_2 are the 1-minute average power outputs of each string, summations are taken over all minutes in the test, and "before" and "after" refer to data acquired before and after putting the RDE300i into string 2. The objective is for the performance index to be close to 1.00; to the extent that it is less than 1.00, the difference equals an energy loss factor.

III. Results

Table 1 summarizes results of both the functionality and energy harvest tests on the three systems tested to date.

Using the functionality test protocol described above, we found zero instances of inverter fault on any of the three systems while in operation with RDE300i. During this testing the RDE300i unit was performing mini-sweeps once every 10 seconds and full sweeps once every 60 seconds. These sweeps did not cause any of the tested inverters to detect a fault condition and shut down even temporarily.

Performance indices evaluated for all three systems using eq. (1) are shown in Table 1. For this analysis, data were filtered to exclude days with low insolation when performance of the strings could change due to non-linearities. To determine an uncertainty for each performance index resulting from random fluctuations in irradiance, temperature, and other conditions, we evaluated the performance index with eq. (1) using subsets of the full data for each system, where each subset comprises a single day from the "before" period paired with a single day from the "after" period, and then calculated the standard deviation σ of the results for all subsets of day-pairs. This allowed us to estimate the uncertainty of the result using the complete data set as $\sigma/\sqrt{N}$ where N is the number of day pairs in the full data set.

As shown in Table 1, performance indices for all three systems were very close to 1.00, indicating minimal energy loss.

As discussed above, some minimal level of power loss is expected even if inverter max power point tracking is unaffected. The series resistance of the RDE300i unit and its associated PV cables is approximately 60 milliohms. In addition, due to full I-V sweeps conducted once per minute, the PV module connected to RDE300i is off-line up to 0.8% of the time. Using these two factors we estimated the expected average power loss in each system test due to series resistance and measurement time alone. We can then compare this with observed power losses calculated using the performance index results.

Table 1 shows the expected and actual observed average power loss due to RDE300i for each of the three systems tested. The observed losses are very close to the expected ones. This indicates no detectible adverse effect of RDE300i on the inverter

maximum power point tracking, and certainly no fault conditions that resulted in gross power loss.

IV. Conclusions

We have developed a protocol for validating I-V tracing equipment for in-situ use within PV arrays to enable efficient use of PV reference modules for system monitoring applications. Our protocol was designed to identify any fault conditions caused by I-V sweeps and to quantify any power losses due to adverse impact on inverter maximum power point tracking. In our evaluation of the RDE300i product on three systems, comprising different inverter types, we observed no adverse impact on the I-V unit on inverter operation, with only minimal power losses as expected from the insertion of the I-V unit. This suggests that the I-V unit is well suited for PV power plant deployment. Our study is ongoing; we continue to test additional module and inverter types.

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References

[1] J. Polo, W. G. Fernandez-Neira, and M. C. Alonso-García, "On the use of reference modules as irradiance sensor for monitoring and modelling rooftop PV systems," *Renew. Energy*, vol. 106, pp. 186–191, Jun. 2017, doi: 10.1016/J.RENENE.2017.01.026.

[2] M. Gostein, J. R. Caron, and B. Littmann, "Measuring soiling losses at utility-scale PV power plants," in *2014 IEEE 40th Photovoltaic Specialist Conference, PVSC 2014*, 2014, pp. 885–890, doi: 10.1109/PVSC.2014.6925056.

[3] C. B. Jones *et al.*, "Automatic fault classification of photovoltaic strings based on an in situ IV characterization system and a Gaussian process algorithm," in *2017 IEEE 44th Photovoltaic Specialist Conference, PVSC 2017*, 2017, pp. 1264–1267, doi: 10.1109/PVSC.2017.8366372.

[4] M. Gostein *et al.*, "Measuring Irradiance for Bifacial PV Systems," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 896–903, Jun. 2021, doi: 10.1109/PVSC43889.2021.9518601.

[5] J. E. Quiroz, J. S. Stein, C. K. Carmignani, and K. Gillispie, "In-situ module-level I–V tracers for novel PV monitoring," *2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015*, Dec. 2015, doi: 10.1109/PVSC.2015.7355608.

[6] J. I. Morales-Aragonés *et al.*, "Low-Cost Electronics for Online I-V Tracing at Photovoltaic Module Level: Development of Two Strategies and Comparison between Them," *Electron. 2021, Vol. 10, Page 671*, vol. 10, no. 6, p. 671, Mar. 2021, doi: 10.3390/ELECTRONICS10060671.