In-Situ Module-Level I-V Tracers for Novel PV Monitoring

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***Abstract* — The current state of PV module monitoring is in need of improvements to better detect, diagnose, and locate abnormal module conditions. Detection of common abnormalities is difficult with current methods. The value of optimal system operation is a quantifiable benefit, and cost-effective monitoring systems will continue to evolve for this reason. Sandia National Laboratories performed a practicality and monitoring investigation on a testbed of 15 in-situ module-level I-V curve tracers. Shading and series resistance tests were performed and examples of using I-V curve interpretation and the Loss Factors Model parameters for detection of each is presented.**

***Index Terms* — data analysis, detection algorithms, performance analysis, photovoltaic cells, photovoltaic systems.**

I. Introduction

The current state of photovoltaic (PV) system performance monitoring is lacking the granularity necessary to detect, pinpoint, and characterize the range of possible PV system faults. Comparative and performance metric monitoring practices have many implementation challenges and monitoring limitations [1]. Module-level monitoring ideas offer advantages over current methods.

Sandia National Laboratories (SNL) is participating in a project with Stratasense LLC to investigate the benefits of automatic, module-level current-voltage (I-V) curve tracers for system monitoring. Module I-V curves offer significant detection advantages over other monitoring methods [2]. The in-situ design adds ease to the implementation of the tracers into operational PV arrays.

II. In-Situ Module-Level I-V Tracers and Testbed

The Stratasense module level I-V tracers are designed to regularly perform in-situ I-V traces at the module-level for modules connected in series to an inverter. These traces are taken regardless of load type, allowing nearly uninterrupted power production. When multiple units are connected to modules in a string, each module is disconnected and swept individually, which allows the current and voltage to the inverter to remain within the maximum power-point tracking operating window. Each trace causes a module bypass lasting less than two seconds.

Fig. 1 shows the in-situ design of the system and string interconnection logic. An integrated 'disconnect' switch to isolate the module under test allows for a sweep in the power quadrant. Simultaneously, a bypass diode allows current to continue to flow through the string during the I-V sweep to allow for near continuous power production. The I-V tracers utilize low power wireless technology for data transmission to a single site-wide gateway. There are also analog inputs in the gateway that accept – pyranometer, reference cell, and thermocouple temperature measurements to be added to the dataset.

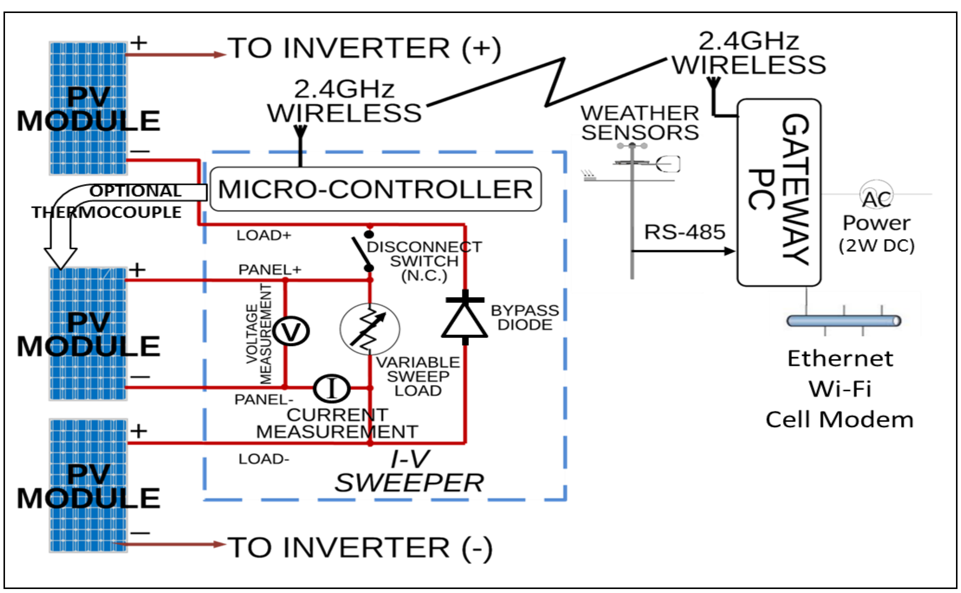

Fig. 1. Connection diagram of Stratasense in-situ I-V curve tracers and gateway.

The granularity of the I-V curve points varies with irradiance and I_{sc} and traces consisting of several hundred points were regularly collected. The rated sweep accuracy of ±1% is based on known component accuracies and comparison to other calibrated meters. The tracers are 9.8” x 6.3” x 3.9” and weigh approximately 2.5 lbs. Depending on proximity, trace frequency, and trace resolution, the gateway is capable of managing 100+ tracers and has a maximum range of 3000ft (line of sight).

The I-V tracers use rechargeable NiMH AA batteries to run sweeps when no module power is available. The batteries charge during periods of sufficient sunlight. In the case of battery failure, the unit is simply bypassed with the bypass diode shown in Fig. 1. The gateway requires 2 W DC, which could allow it to function in remote locations without AC power.

SNL has developed a testbed consisting of 15 I-V tracers connected in a string of 16 fixed latitude-tilt modules connected to a grid-tied inverter. The modules are 145 W (I_{mp} = 6.3 A, V_{mp} = 23 V, I_{SC} = 7.12 A, V_{OC} = 29 V. The inverter is rated at 3000 W with a maximum power-point (MPP) voltage range of 230-500 V. Fig. 2 is a photo taken from behind the testbed showing the interconnected I-V tracers attached near the modules. Fig. 3 shows the gateway unit. The units are constructed with fully weatherized enclosures, NEMA 4 and 3R rated, respectively [3].

Fig. 2. Photograph of back side of testbed showing I-V tracers connected to string of 16 fixed-tilt modules.

Fig. 3. Gateway unit.

There are many configurable settings and flexibility that come with the gateway PC (Raspberry PI-based system). The system is highly configurable allowing the user to define the time interval between sweeps. Time can be established through a network connection (NTP) or independently with a real-time clock within the gateway. One configuration option worth noting is the ability to sweep synchronously across all panels while not connected to an inverter. This allows for better comparison between panel technologies reducing the data convulsion from varying environmental effects.

III. Field Testing and Data Analysis

Fig. 4 shows a set of 12 I-V curves taken during one interval (approximately 2-minute span between first and last I-V curve) on 01/19/2015 at approximately 12:12 PM MST, just a few minutes before local solar noon.

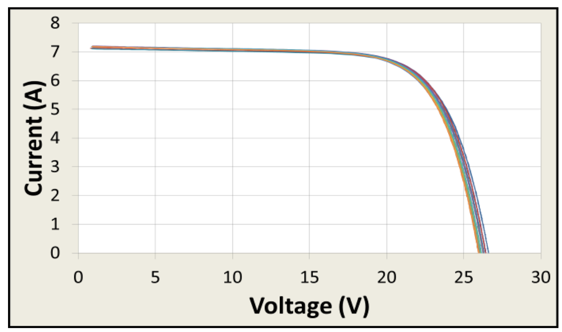

Fig. 4. I-V curves from 12 Stratasense tracers in the testbed.

The I-V curves in Fig. 4 show a fair amount of uniformity, and the conditions were ideal enough to allow operation near optimal MPP levels for the modules. There is little sign of mismatch in current. The variability in voltage is probably due to different operating temperatures of the modules due to their different positions in the array (i.e. [4]).

By inspecting measured I-V curve deviations, either against predicted curves from performance models [5] or curves from neighboring modules, detection of a wide range of possible performance problems can be achieved. To test the capabilities of the Stratasense I-V tracers, SNL performed several tests using the 15 tracer testbed. These tests were designed to collect module-scale I-V curves and investigate the ability to identify specific problems within an array that might be “invisible” with only system-level monitoring. The tests consisted of applying partial shading to selected modules (using three different approaches) and adding series resistance to a module to simulate degradation.

A. Partial Shading Effects

Partial shading of selected modules was done by applying opaque squares of paper on the module surface, by applying mud to the array, and by placing a pole in front of the array to cast a shadow that moved across a portion of the array during the day.

For the opaque tests, squares of paper were applied to several module surfaces as shown in Fig. 5. The effect on the I-V curve for the module is shown in Fig. 6 along with two normal I-V curves taken shortly before and after the shade was applied. The measurements were made in the late morning and the increasing I_{sc} values show the irradiance was increasing during the test sequence (opaque paper applied between the two bounding I-V curves). The MPP of the shaded I-V curve exhibits a reduced V_{mp} and the indentation characteristic of mismatch losses. The MPP points highlighted were chosen from measured data points and no interpolation between points was considered.

Fig. 5. Opaque partial shade applied to module surface.

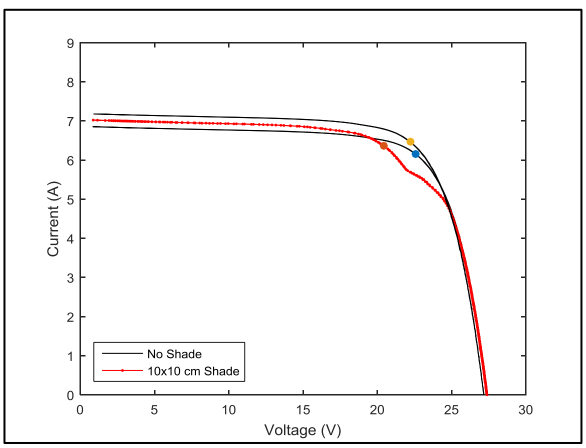

Fig. 6. I-V curves showing effect of 10x10 cm opaque partial shading on a single module in the array testbed. Max power points are shown on curves.

Fig. 7 shows the same type of results shown in Fig. 6, except for a 5x5 cm opaque piece of paper. At this scale, the shade slightly decreases the I_{mp}, with less effect on the voltage. There is still a slightly visible mismatch loss indentation.

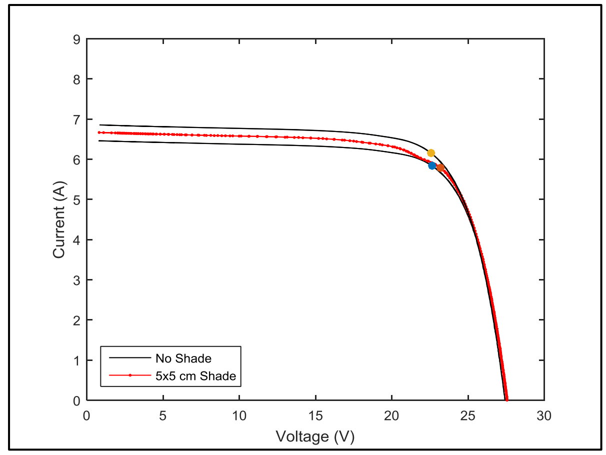

Fig. 7. I-V curves showing effect of 5x5 cm opaque partial shading on a single module in the array testbed. Max power points are shown on curves.

The next set of plots show the effect of dirt on a module. Fig. 8 shows the dirt applied to a module and Fig. 9 shows the effect on the I-V curves. As expected, the dirt mainly affects the current (I_{sc} and I_{mp}) and the non-uniformity causes mismatch between the cells in the module.

Fig. 8. Module shown with applied dirt for soiling example.

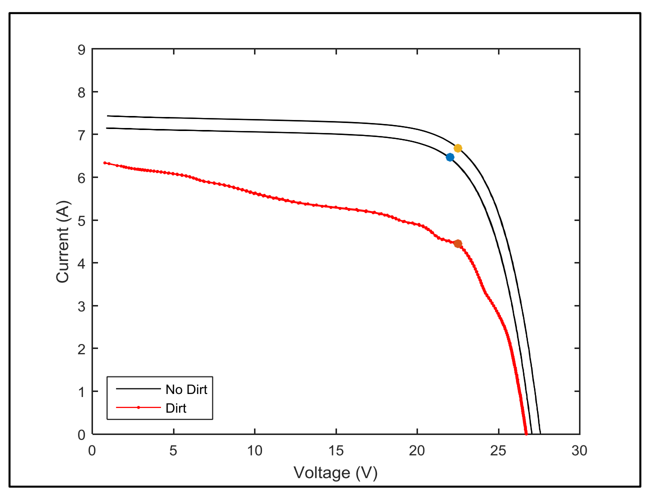

Fig. 9. I-V curves showing effect of applied dirt in Fig 8. Black lines show curves before and after dirt was applied for reference.

The next set of plots show the effect of pole shade on a module. Fig. 10 shows the test setup with a standard mop handle (~1 inch diameter). Fig. 11 shows four I-V curves taken over a 60 minute period (every 20 minutes) on a module with shade from a vertical pole. Fig. 12 shows normal I-V curves from a nearby module unaffected by the pole shade. Note that scan times can differ up to two minutes between modules and irradiance was varying during this day due to passing clouds. This caused the large variations in I_{sc} values between curves.

Fig. 10. Picture of the pole shading test setup.

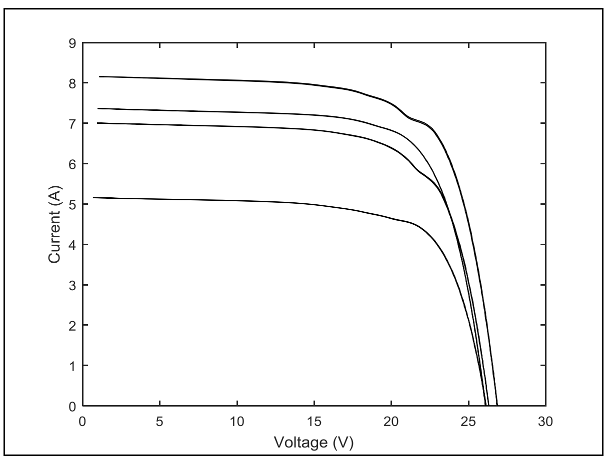

Fig. 11. Effect of pole shade on a single module. Shade causes mismatch indentation on the curve and possibly decreases fill factor.

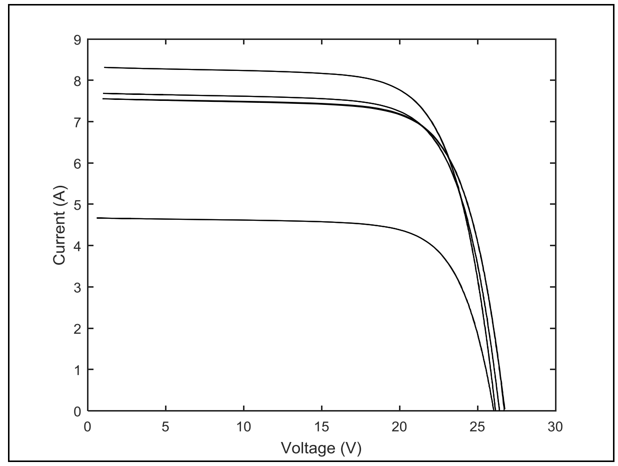

Fig. 12. Normal unshaded module I-V curves at similar times.

B. Increased Series Resistance Effects

An additional series resistance was applied to a single module for testing. The resistance applied (5 ohms) was too high to be representative of realistic degradation for a single module. However, the test did demonstrate the effect of such high resistances on I-V curves for a single module and the ability of the Stratasense to measure an "extreme" I-V curve.

Fig. 13 shows four I-V curves with the added resistance during the morning as the irradiance level was increasing from about 70 – 600 W/m^2. As expected, the series resistance has a big effect on the slope of the I-V curve at V_{oc} and this effect extends to I_{sc} by the time irradiance is >600 W/m^2. In comparison, Fig. 14 shows four I-V curves from a module without added resistance.

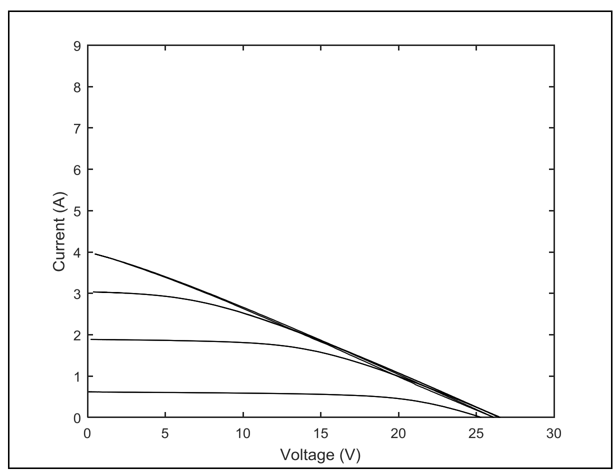

Fig. 13. Four I-V curves taken on a module with 5 ohm series resistance added.

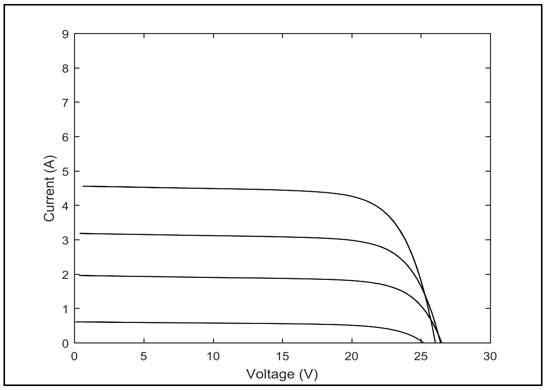

Fig. 14. Four I-V curves taken on a module with no added series resistance at approximately the same time as those in Fig 13.

IV. Application of the Loss Factors Model (LFM)

In order to utilize the continuous stream of I-V curves delivered by the Stratasense units for monitoring the health of a PV array it is necessary to apply a method to normalize the measured I-V curves for variable environmental conditions, such as irradiance and temperature, so that unexpected changes such as degradation and/or component failures can be detected.

The Loss Factors Model (LFM) [5-8] was developed especially for interpretation and monitoring of continuous module I-V curves. The model is based on a set of six normalized parameters or factors that describe each I-V curve independent of plane-of-array irradiance (G_i). Other more sophisticated versions also include corrections for temperature [5-8]. By monitoring changes in these factors over time it is possible to detect very fine changes to the performance of the module. Given a measured I-V curve (prefix = "m") and a reference I-V curve at STC (prefix = "r"), the following six normalized LFM factors (prefix = "n") are defined. mVr and mIr are coordinates of the intersection point of lines tangent to the ends of the measured I-V curve as shown in Fig 1 of [5].

$$nI_{SC} \equiv \frac{mI_{SC}}{rI_{SC}} \div G_i \quad (1)$$

$$nR_{SC} \equiv \frac{mI_r}{mI_{SC}} \quad (2)$$

$$nI_{mp} \equiv \frac{mI_{mp}}{mI_r} \times \frac{rI_{SC}}{rI_{mp}} \quad (3)$$

$$nV_{mp} \equiv \frac{mV_{mp}}{mV_r} \div \frac{rV_{OC}}{rV_{mp}} \quad (4)$$

$$nR_{OC} \equiv \frac{mV_r}{mV_{OC}} \quad (5)$$

$$nV_{OC} \equiv \frac{mV_{OC}}{rV_{OC}} \quad (6)$$

To demonstrate the utility of the LFM normalization, LFM factors vs. time for three I-V curves were calculated for a module with a 10x10 cm shade applied (Fig. 15) and a module with a 5x5 cm shade applied (Fig. 16). The shade is applied in the middle variables of each figure. In each case, the changes to the relative position of the MPP (V_{mp}, I_{mp}) are easily seen when compared with Figures 6 and 7, respectively. Only nVmp and nImp are affected. That the two factors changed in opposite directions between the two tests is a reflection of where the MPP ended up relative to the indentation caused by the shading.

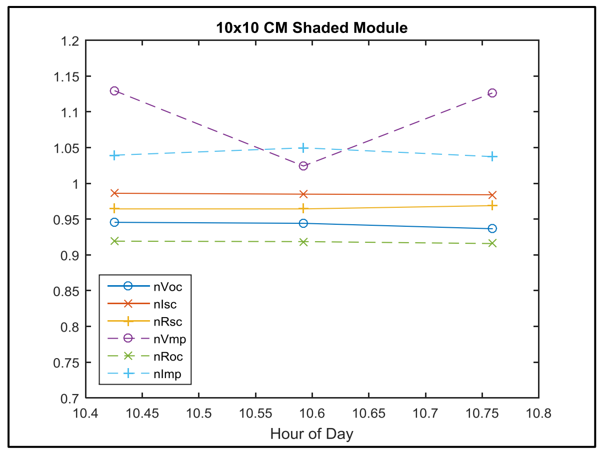

Fig. 15. LFM factors for three I-V curves measured on a module where 10x10 cm shade was applied to the middle I-V curve (points in center of x-axis).

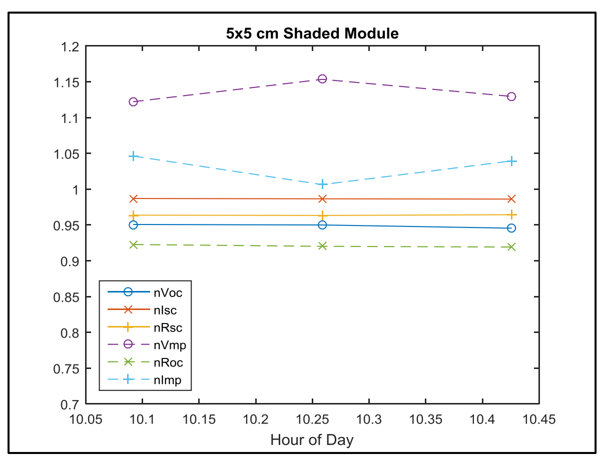

Fig. 16. LFM factors for three I-V curves measured on a module where 5x5 cm shade was applied to the middle I-V curve (points in center of x-axis).

Fig. 17 shows the change in LFM parameters for the case where dirt was applied to the modules surface (Figures 8 and 9). In this case there are reductions in nIsc, nRsc (increase in the negative slope at Isc), and nImp. Changes to the other LFM parameters would indicate systematic changes to other aspects of the I-V curves (e.g., series resistance and Voc, etc.). The advantage of using the LFM normalized parameters for monitoring is that they effectively identify shape changes of the I-V curves while accounting for irradiance (and temperature with more sophisticated applications of the model) effects. This method is therefore effective for monitoring the effects of degradation, soiling, and other operational problems.

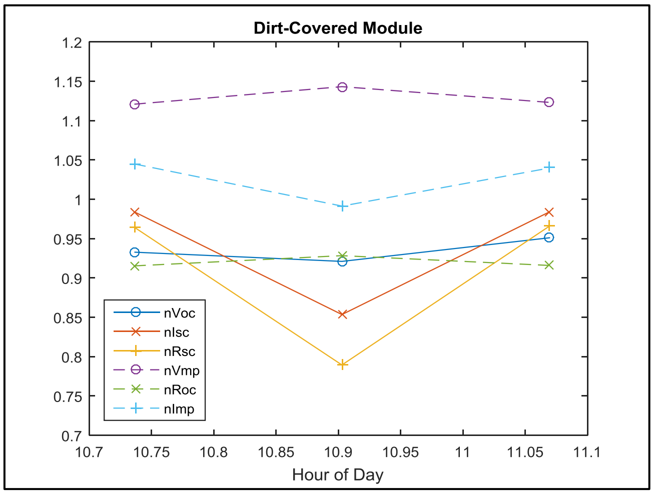

Fig. 17. LFM factors for three I-V curves measured on a module where dirt was applied to the middle I-V curve (points in center of x-axis).

V. Conclusions

The benefits of I-V curves to the detection of system faults are well documented. This product design offers many benefits in terms of ease of implementation and valuable data acquisition. SNL conducted controlled tests to demonstrate the ability of these in-situ module-level tracers to provide the I-V data necessary to diagnose and locate the cause of several common PV module issues.

String level I-V tracers could provide less sensitive diagnostic advantages of having I-V curves demonstrated in this paper, but they would not be able to provide indication of the specific modules under abnormal conditions that module-level traces can. Knowing exactly what module is experiencing a condition that requires correction in a string, which can potentially consist of 20+ modules, could reduce maintenance time required to locate issues.

Future challenges of this type of monitoring technology include economic feasibility at the consumer level, proven reliability, consistent data collection, accuracy of measurement, and computational interfaces to support the large data management and interpretation. Aside from the consumer feasibility, the in-situ module- level I-V tracers can have many research applications as a low cost automated solution for continuous I-V curves.

Acknowledgement

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