Application and Validation of a New PV Performance Characterization Method

Charles M. Whitaker, Timothy U. Townsend, and Jeffrey D. Newmiller, Endecon Engineering; David L. King, William E. Boyson and Jay A. Kratochvil, Sandia National Laboratories; and David E. Collier and Donald E. Osborn, Sacramento Municipal Utility District

Presented at the 26th IEEE Photovoltaic Specialists Conference, September 29-October 3, 1997, Anaheim, California

Sandia National Laboratories

Sandia National Laboratories
Photovoltaic Systems Department
Post Office Box 5800
Albuquerque, NM 87185-0753

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Control DE-AC04-94AL85000.

September 1997

Presented at the 26th IEEE PV Specialists Conference
Sept. 1997, Anaheim, CA

APPLICATION AND VALIDATION OF A NEW PV PERFORMANCE CHARACTERIZATION METHOD

Charles M. Whitaker, Timothy U. Townsend, Jeffrey D. Newmiller, Endecon Engineering, San Ramon, CA
David L. King, William E. Boyson, and Jay A. Kratochvil, Sandia National Laboratories, Albuquerque, NM
David E. Collier, Donald E. Osborn, Sacramento Municipal Utility District, Sacramento, CA

ABSTRACT

Rating a PV system is complicated by the difficulties of obtaining performance data under the "rating" conditions, the intricate relationships between PV output and prevailing conditions, and the desire for quick results at low cost. Since 1989, PVUSA has been rating PV systems using continuous data collection and a simple regression model. Recently, Sandia National Laboratories has developed an improved IV curve–based method for characterizing PV arrays. Several systems at the PVUSA facility in Davis, CA were subjected to both methods. The results of that work are presented in this paper.

INTRODUCTION

PV system rating is often the basis for payment on new systems. Errors and delays caused by the rating procedure can cost both the buyer and seller money. Since 1989, PVUSA has been rating PV systems using continuous data collection and a simple regression model [1]. The model is used to estimate system output at PVUSA Test Conditions (PTC[1]). It is applicable to both arrays (dc output) and systems (ac output). Limitations of the model include the following:

- the necessity to collect sufficient data at and above the rating irradiance and over a range of temperatures and wind speeds
- poor model performance at low irradiance.

Recently, Sandia National Laboratories has developed an improved IV curve–based method for characterizing PV arrays [2]. The method's temperature coefficients and inclusion of irradiance dependence in the voltage terms are improvements over standard ASTM IV curve translation procedure [3]. The model additionally includes corrections for pyranometer and array solar angle-of-incidence response and PV module spectral response. The method is currently limited to PV arrays (dc only) and must be applied to each measured array segment separately (for example, when testing a 100 kW array with a 50 kW curve tracer).

1 PTC = 1000 W/m^2 global plane of array irradiance for flat-plate modules 850 W/m^2 direct normal for concentrators, 20 °C ambient temperature, 1 m/s wind speed.

PVUSA RATING METHOD

The PVUSA method is based on the simplified assumptions that array current is primarily dependent on irradiance and that array voltage is primarily dependent on array temperature, which, in turn is dependent on irradiance, ambient temperature, and wind speed. These dependencies are combined in Equation (1).

$$P = Irr*(A + B*Irr + C*Tamb + D*WS) \quad (1)$$

Where:

P	=	PV array or inverter output, kWdc or kWac
Irr	=	Plane-of-array (POA) solar irradiance, broadband measurement, W/m^2
Tamb	=	Ambient temperature, °C
WS	=	Wind speed, m/s
A, B, C, D	=	Regression coefficients

Implementation

All PVUSA systems are instrumented with comprehensive data acquisition systems including dc voltage and current; ac voltage, current, and power; plane-of-array irradiance; and module temperature. Additional weather channels are measured for the site. Systems are rated initially and periodically thereafter by evaluating several days to several weeks of data. A preliminary criterion of 10 kWh/m^2 of irradiance at or above PTC is used to establish a sufficient data set. Data below a threshold—typically either 500 or 750 W/m^2—as well as data exhibiting non-standard behavior are eliminated. A regression is performed on the remaining data to determine the coefficients in Equation (1).

SANDIA ARRAY PERFORMANCE MODEL

Photovoltaic array (module) performance for an arbitrary operating condition can be described by Equations (2-6). The variables defining the operating condition are irradiance, cell temperature, absolute air mass, and solar angle-of-incidence on the array. The equations for short-circuit current (I_{sc}), maximum-power current (I_{mp}), open-circuit

This work was performed under United States Department of Energy cooperative agreement DE-FC04-96AL89744.

voltage (V_{oc}), and maximum-power voltage (V_{mp}) provide the four primary parameters from which others (fill factor, maximum power, efficiency) can be calculated. Equations (2,4, and 5) result in linear relationships closely related to the fundamental electrical characteristics of cells in the module. Equation (6) uses a second order relationship for V_{mp} that implicitly contains the influences of factors such as module series resistance, wiring resistance, and non-ideal cell behavior at low light levels. Two additional empirical relationships, the "AM_a Function" and the "AOI-Function" are used to compensate for the influences of the solar spectrum and solar angle-of-incidence (AOI) on . short-circuit current.

$$I_{sc}(E, T_c, AM_a, AOI) = (E/E_o)\, f_1(AM_a)\, f_2(AOI)\, [I_{sco} + \alpha_{Isc} (T_c - T_o)] \quad (2)$$

$$E_e = I_{sc}(E, T_c = T_o, AM_a, AOI) / I_{sco} \quad (3)$$

$$I_{mp}(E_e, T_c) = C_1 + E_e [C_2 + \alpha_{Imp} (T_c - T_o)] \quad (4)$$

$$V_{oc}(E_e, T_c) = V_{oco} + C_3 \ln(E_e) + \beta_{Voc} (T_c - T_o) \quad (5)$$

$$V_{mp}(E_e, T_c) = V_{mpo} + C_4 \ln(E_e) + C_5 [\ln(E_e)]^2 + \beta_{Vmp} (T_c - T_o) \quad (6)$$

Where:

E = Plane-of-array (POA) solar irradiance, broadband measurement corrected for angle-of-incidence sensitivity, W/m^2

E_e = "Effective" irradiance, dimensionless

E_o = Reference POA irradiance, typically 1000 W/m^2

$f_1(AM_a)$ = Empirical function for spectral influence

$f_2(AOI)$ = Empirical function for angle-of-incidence affects

AM_a = Absolute air mass

AOI = Solar angle-of-incidence on module, degrees

I_{sco} = I_{sc} ($E = 1000\,W/m^2$, $T_c = T_o$°C, $AM_a = 1.5$, AOI = 0°)

I_{mpo} = I_{mp} (E_e=1, $T_c = T_o$°C) = $C_1 + C_2$

V_{oco} = V_{oc} (E_e=1, $T_c = T_o$ °C)

V_{mpo} = V_{mp} (E_e=1, $T_c = T_o$ °C)

T_c = Temperature of cells inside module, °C

T_o = Reference Cell temp. (for example 25 or 50)

α_{Isc} = I_{sc} temperature coefficient, A/°C

α_{Imp} = I_{mp} temperature coefficient, A/°C

β_{Voc} = V_{oc} temperature coefficient, V/°C

β_{Vmp} = V_{mp} temperature coefficient, V/°C

$C_{1\text{-}5}$ = Empirically determined coefficients

Implementation

A sample module is characterized to determine the four temperature coefficients, $f_1(AM_a)$, and $f_2(AOI)$ [4]. PV array IV curves, array temperature, irradiance and other weather parameters are recorded over a day of varying temperature and irradiance conditions. Finally, the coefficients, $C_{1\text{-}5}$, are determined through regression analysis of the field measurements.

RATING COMPARISON

In August 1997, Sandia personnel visited the PVUSA site in Davis, CA to collect IV curves on the PV systems listed in Table 1. The arrays were washed and the DAS calibrations checked approximately 1 week prior to their visit. In addition to the normal PVUSA measurements, additional back of module temperatures; direct normal, global normal, and POA irradiance; silicon reference cell; and periodic spectroradiometer measurements were made during the collection of IV curves. The additional POA measurements were made with an Eppley PSP thermopile pyranometer, a LI-COR silicon pyranometer, and a silicon cell ESTI sensor.

Table 1. Systems Tested

System	Module Mfg.	Module Technology
AST-EMT2	AstroPower	Silicon-Film
SCI-EMT3	Solar Cells Inc.	Cadmium Telluride
SLX-EMT1	Solarex	Bifacial Poly-Silicon
SLX-SST1	Solarex	Polycrystalline Silicon
SOL-SST1	Solec	Single Crystal Silicon
SSI-SST1	Siemens Solar	Single Crystal Silicon

IV curves were collected over a three-day period. The 10-minute average data used for the PVUSA rating method was taken from an eight-day set centered over the IV curve days. The results are shown in Table 2.

Table 2. Rating Results

System	PVUSA Rating (kWdc)	Sandia Rating (kWdc)
AST-EMT2	15.90	17.71
SCI-EMT3	10.90	11.95
SLX-EMT1	11.90	12.92
SLX-SST1	3.33	3.46
SOL-SST1	4.31	4.40
SSI-SST1	2.32	2.47

The two methods gave different results, so which one is correct? One answer might be that the PVUSA results are correct for the system buyer and the Sandia results are correct for the system seller. Actually, they are both correct. Both methods are subject to errors associated with measurement and modeling. The uncertainty for both

methods is roughly 4-5 percent, thus, the difference between the methods for the three SST systems is within the uncertainties. Differences in approach may account for the differences in the EMT ratings as discussed below.

Maximum Power Tracking

The Sandia method provides a characterization of the PV array, while the PVUSA method characterizes the combination of the PV array and inverter. If the inverter incorporates an accurate maximum power tracking circuit, the results of the two methods should be comparable. However, if the max power tracker is inaccurate or if the array is operated at a fixed voltage, the results will diverge. Which method gives the "correct" results depends on the purpose of the rating. For a new system that the installer has verified is operating properly, the PVUSA method results are probably more appropriate. On the other hand, a model that predicts Vmp and Imp, such as the Sandia method, can be used to evaluate the max power point tracker [5].

Custom DECC/Helionetics inverters are used for all of the EMT systems. V_{mp} and I_{mp} were calculated with Equations (4) and (6) for each of the 10-minute data points used in the PVUSA regression for the SLX-EMT1 array. Fig. 1 shows the error between the actual operating voltage and current (V_{op} and I_{op}) and the estimated Vmp and Imp. The shape of the curves may be due as much to systematic model error as to systematic maximum power tracker error, though when V_{op} drops I_{op} increases, as expected. However, at high irradiance, where the models should be fairly accurate, there is a distinct offset in the operating voltage of 4-6 percent. This result suggests that the DECC maximum power tracker is not as accurate as had previously been thought and might help to explain some of the difference between the two methods.

Cell Temperature Versus Ambient Conditions

The establishment of PVUSA Test Conditions was fostered by the realization that the traditional rating based on cell temperature did not reflect what was happening outdoors and did not discourage poor thermal design. Thus, the PVUSA method directly relates system performance to ambient conditions. The relationship between ambient conditions and cell temperature is implicit. In the Sandia method, cell temperature is an explicit function therefore cell temperature at PTC must be determined. For this analysis, the data for the PVUSA method was analyzed to determine the recorded back of module temperature under PTC. All of the modules are of the common Glass-EVA-Cell-EVA-Tedlar construction, and experience shows a typically 4 °C temperature drop from the cell to the back of module. This value was added to each of the estimated PTC back of module temperatures. Several methods for better estimating cell temperature are being investigated.

Improvements to PVUSA Method

It has long been known that there are systematic errors in the PVUSA method that prevent its use over a broad range of conditions [6]. The typical fan-shaped low irradiance error is shown in Fig. 2. Previous attempts to include AM_a and AOI terms in the PVUSA regression were not successful. However, when the Sandia AM_a and AOI corrections were applied, the results were much improved below about 400 W/m^2 (also in Fig. 2). Since the impact of these corrections at high irradiance levels (low incidence angles and air mass) is small, ratings based on the "corrected" method are insignificantly different.

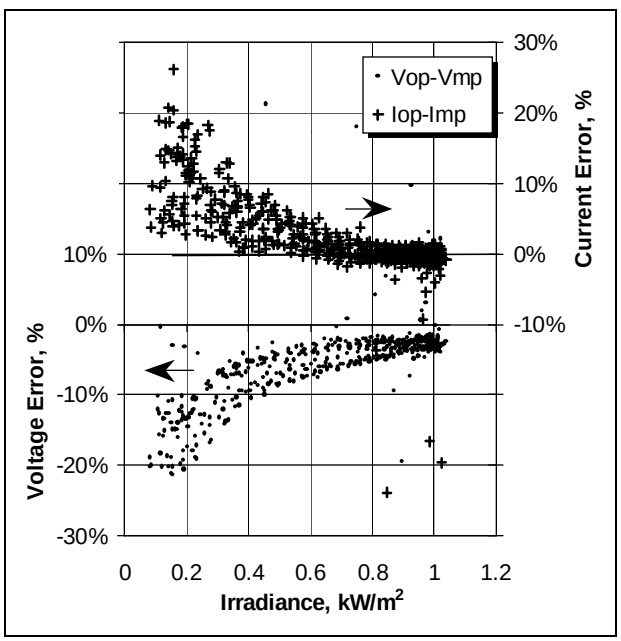

Fig. 1 SLX-EMT1 Maximum Power Tracking Error

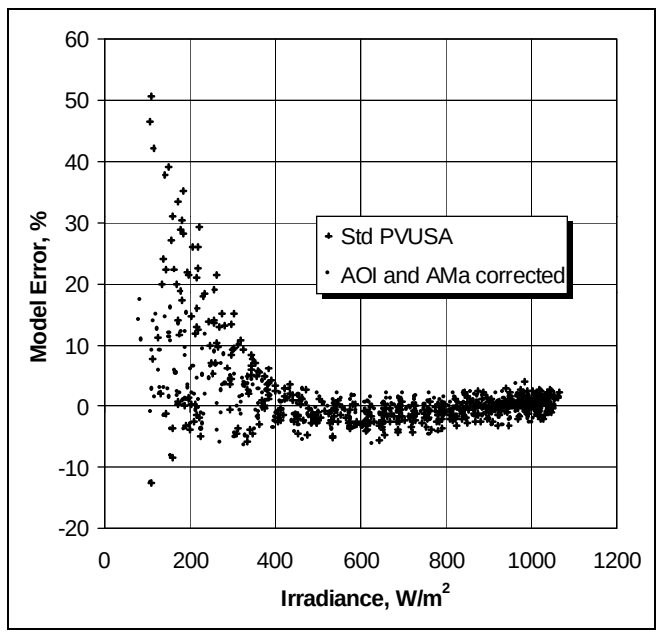

Fig. 2. PVUSA Model Error, SLX-EMT1

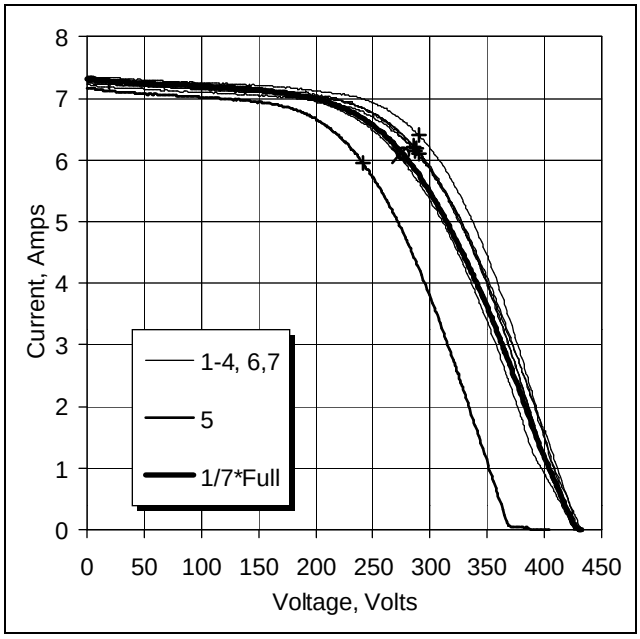

Fig. 3. SLX-EMT1 Source Circuit and Array IV Curves

Circuit Mismatch

All of the data presented above was measured on complete arrays. This is not always possible especially with large arrays. With the Sandia procedure, when the array has to be broken up into smaller segments, the segment results must be added to obtain a full array rating. When array segments are operated together in series or parallel, they do not necessarily operate at their respective maximum power points. Rather than adding the individual maximum power point values, it is necessary to add the complete IV curves and determine the composite maximum power point.

The SLX-EMT1 array consists of 14 parallel source circuits of 24 series modules. Six modules in one source circuit were shaded to simulate an array problem. IV curves were measured on pairs of source circuits in addition to full array, to evaluate the mismatch problem. Fig. 3 shows the eight IV curves (seven source circuit pairs and one full array) taken near solar noon when conditions were relatively stable. The current for the full array curve was divided by 7 to match the source circuits. The maximum power point for each curve is marked with an "+".

Table 3. Circuit Mismatch Evaluation

Circuit	I_{sc} (A)	I_{mp} (A)	V_{oc} (V)	V_{mp} (V)	P_{mp} (kW)
1	7.11	6.04	463.6	312.0	1.88
2	7.10	6.14	464.6	327.1	2.01
3	7.08	6.01	468.3	328.3	1.97
4	7.09	6.17	469.7	333.2	2.05
5	*6.95*	*5.88*	*439.7*	*277.7*	*1.63*
6	6.99	6.00	463.9	327.3	1.96
7	7.03	6.06	465.5	326.0	1.98
Sum of Individual Circuits					13.49
Full Array	49.59	41.82	469.2	317.2	13.26

Since the circuits are connected together in parallel, the currents at each voltage point add. If the maximum power points all occurred at roughly the same voltage, then the array maximum power would be very close to the sum of the individual circuit maximum powers. Fig. 3 shows a ±3 percent variation between V_{mp} of the normal circuits (1-4, 6, 7) and problem circuit #5 V_{mp} is about 16 percent lower than the average of the others in this 8-year-old array.

Model coefficients, $C_{1\text{-}5}$, were determined for each of the individual circuits. Table 3 shows the Sandia-based PTC ratings for each circuit and the entire array. The error associated with simply adding the individual circuit maximum powers is +1.7 percent, which could be attributed as much to model and measurement errors as to mismatch.

Though this error is small, a method for translating and adding entire IV curves is being developed.

CONCLUSION

As performed for this analysis, both methods were fairly labor intensive in terms of data collection and data analysis. However, both can be greatly simplified by reducing the number of parameters measured to a minimum. Data collection can be automated for both methods, but with large arrays, the curve tracer must be manually connected to each array segment. The regression for the PVUSA approach is significantly simpler than for the Sandia method. However, there is a fair amount of manual data screening with both methods, which accounts for most of the effort. Databases have been developed for both methods to simplify the analysis task, but neither has been developed to the "commercial product" stage.

The methods described in this paper provide acceptable ratings if the differences—maximum power tracker versus IV curve tracer, ambient versus cell temperature, etc.—are properly accounted for. Improvements for both methods are currently under development to help address these differences.

ACKNOWLEDGEMENTS

The authors thank the Dan Whitney and Don Osborn of the Sacramento Municipal Utility District and Nancy Jenkins of the California Energy Commission for their support and guidance on this project.

[1] R.N. Dows, et al, “PVUSA Procurement, Acceptance, and Rating Practices for Photovoltaic Power Plants,” Pacific Gas and Electric Co R&D Report # 95-30910000.1, Sept. 1995.

[2] D. L. King, “Photovoltaic Module and Array Performance Characterization Methods for All System Operating Conditions,” NREL/SNL Program Review, AIP Press, 1996, pp.347-368.

[3] ASTM E 1036, “Standard Methods for Testing Electrical Performance of Nonconcentrator Terrestrial PV Modules and Arrays Using Reference Cells.”

[4] D. L. King, et al., “Measuring Solar Spectral and Angle-Of-Incidence Effects on Photovoltaic Modules and Solar Irradiance Sensors,” this conference

[5] M. Jantsch, et al., “Measurement of PV Maximum Power Point Tracking Performance,” *14th EC PVSEC*, 1997.

[6] “1989-1990 PVUSA Project Report,“ PVUSA, 1991.