May 2003 • NREL/CP-520-33531

Conference Paper

Long-Term Performance of the SERF PV Systems

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Presented at the National Center for Photovoltaics and Solar Program Review Meeting
Denver, Colorado
March 24-26, 2003

NREL

National Renewable Energy Laboratory

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Golden, Colorado 80401-3393

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Contract No. DE-AC36-99-GO10337

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Long-term Performance of the SERF PV Systems

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ABSTRACT

This paper provides the changes in performance ratings of two photovoltaic (PV) systems located on the roof of the Solar Energy Research Facility (SERF) building at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. For the period of May 1994 to April 2002, the performance rating of the two PV systems decreased at the rate of 1% per year. Most of the changes in performance rating are attributed to changes in the performance of the PV arrays. But about a fifth of the observed changes were from the inverter not tracking the peak-power as effectively as the PV arrays aged.

1. Background

As part of the construction of the Solar Energy Research Facility building at the National Renewable Energy Laboratory in Golden, Colorado, two grid-connected photovoltaic systems were installed on the roof to provide power to the building and the utility grid. Corresponding to their location on the building, the systems are identified as SERFEAST and SERFWEST. The SERFEAST PV array is shown in Fig. 1.

Figure 1. SERFEAST array on the roof of the building.

Each PV array consists of 140 Siemens Solar Industries model M55 PV modules. The PV arrays are electrically connected as five source-circuits, with each source-circuit having a positive and negative monopole of 14 series-connected PV modules. Each PV array is connected to an 8 kW Omnion Series 2200 inverter for conversion from d.c. to a.c. power. The PV arrays are tilted from the horizontal at an angle of 45° and are aligned with the azimuth of the building that is oriented 22° east of south. The longitude and latitude of the SERF is W105.2° and N39.7°, and the elevation is 1782 meters.

The SERF PV systems began operation in March 1994, and the data acquisition of performance parameters began in May 1994 using Campbell Scientific data loggers. Data are recorded as 15-minute averages and include d.c. and a.c. voltage, current, and power; ambient and PV module back-surface temperature; and plane-of-array (POA) irradiance.

These data were used to calculate PV system ratings from May 1994 to April 2002 to determine the extent of system degradation over the 8-year period.

2. Data Screening

For calculating PV system ratings, data were selected to meet meteorological criteria and to avoid data recorded when the inverters were malfunctioning or off-line for repairs.

Meteorological criteria for data selection were a 15-minute average POA irradiance greater than 800 W/m^2 and an angle-of-incidence of direct-beam radiation to the PV array of less than 30 degrees. This ensures that the cloud presence was small and that the pyranometer measurement of irradiance was performed within a range of incident angles where the cosine response of the pyranometer is not detrimental to measurement accuracy.

A region of acceptable PV array operating voltages as a function of PV array temperature was identified using data recorded during normal system operation. This resulted in the "boxed" area shown in Fig. 2. Data within the "boxed" area were judged acceptable for use for data analysis, whereas data in the remaining area were judged unacceptable because they were measured under malfunctioning or system-off (open-circuit) conditions.

Normal operation for these systems does not necessarily mean peak-power tracking, although that was the original intent. The inverters were specially ordered to achieve a peak-power tracking range of 200 to 280 volts. However, as delivered, the inverters do not operate below about 220 volts. Consequently, for elevated PV array temperatures, the inverters do not peak-power track because the PV arrays are operated at 220 volts and the PV array voltage for maximum power (V_{mp}) is considerably less.

The diagonal lines in Fig. 2 represent PV array V_{mp} values as a function of PV array temperature for 1994 and 2002. They were determined from PV module and array current-voltage (I-V) curve measurements. Values of V_{mp} for 2002 are about 10 volts less than they were in 1994; consequently, for elevated PV array temperatures in 2002, the inverter operates the PV array further from its peak-power point than in 1994. As an example, the power penalty for not peak-power tracking at a PV array temperature of

50°C in 1994 is 2%, but increases to 7% in 2002. Losses in system performance from 1994 to 2002 are attributed to both changes in the PV array performance and increased peak-power tracking losses as the PV array voltages decreased. These effects are discussed in the next sections.

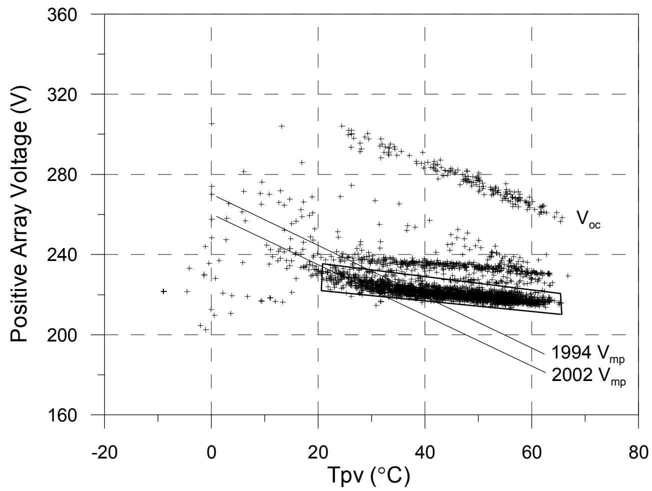

Figure 2. Positive array voltage as a function of module temperature. "Boxed" area is acceptable region for data screening. Data shown meet meteorological criteria.

3. PV Rating Methodologies

Two methods were used to assign monthly power ratings for the SERFEAST and SERFWEST PV arrays: (1) the PVUSA rating method [1], and (2) the power equation.

The PVUSA method uses a regression model and system performance and meteorological data to calculate power at PVUSA Test Conditions (PTC), where PTC are defined as 1000 W/m^2 POA irradiance, 20^{o}C ambient temperature, and 1 m/s wind speed. Unlike the power equation method, the PVUSA method does not require measurement of the PV array temperature. This may be an advantage if PV array temperature measurement is difficult, such as for large PV systems.

One-month blocks of the 15-minute average data meeting the screening criteria in Section 2 were used to determine the four PVUSA regression coefficients. Because the SERF data acquisition system does not include wind speed, wind speed data were obtained from the nearby Reference Meteorological and Irradiance Station (RMIS) weather station.

For each month, the four coefficients were determined and then used to calculate PV array power at PTC using the PVUSA equation:

$$P_{PTC} = I_o \cdot (a + b \cdot I_o + c \cdot T_{amb} + d \cdot W) , \qquad (1)$$

where:

P_{PTC} = d.c. power for PTC, W
I_o = irradiance for PTC, 1000 W/m^2
T_{amb} = ambient temperature for PTC, 20^{o}C
W = wind speed for PTC, 1 m/s
a,b,c,d = regression coefficients derived from data

Monthly PV array rating were also determined using the power equation to normalize performance to rating conditions of a POA irradiance of 1000 W/m^2 and a PV array temperature of 25°C using the following equation:

$$P_{RC} = (P \cdot I_o / I) \div [1 + \gamma \cdot (T - T_o)] , \qquad (2)$$

where:

P_{RC} = d.c. power for rated conditions, W
P = measured d.c. power, W
I_o = irradiance for rated conditions, 1000 W/m^2
I = measured POA irradiance, W/m^2
γ = temperature power correction factor, -0.005°C^{-1} [2]
T_o = PV array temperature for rated conditions, 25°C
T = measured PV array temperature, °C

The PV array temperature was determined as the average back-surface temperature measurement of three PV modules in the PV array. Power for rated conditions was determined for all 15-minute data meeting the screening criteria, and then the 15-minute rated power values were averaged by month to yield a power rating for each month of the period.

4. Results

Figures 3 and 4 present the calculated monthly ratings for the SERFEAST and SERFWEST PV systems. Gaps in the data reflect periods of time when the inverters were not operating properly or were being repaired, or failure of the data acquisition system.

As shown in Table 1, both methodologies provided similar performance degradation rates for both PV systems, on the order of 1% per year. This change in performance is consistent with that seen for other PV systems using crystalline silicon modules [3]. Power ratings using the PVUSA methodology were lower because its reference conditions of irradiance, temperature, and wind speed

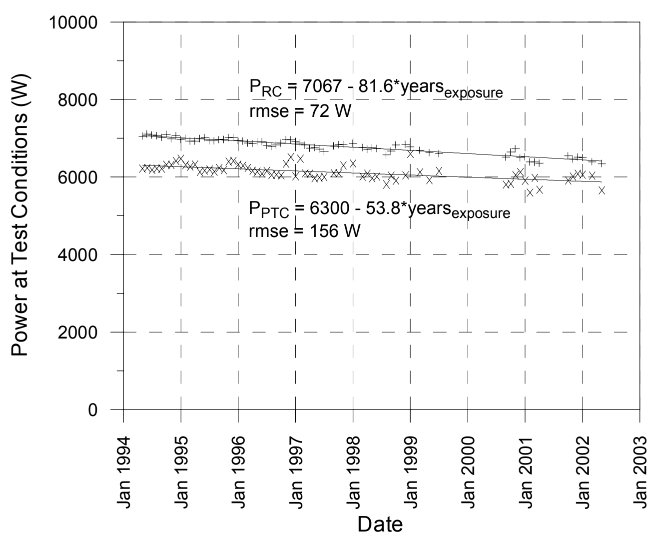

Figure 3. Calculated power ratings for the SERFEAST PV system for 1994-2002. (rmse is root-mean-square error.)

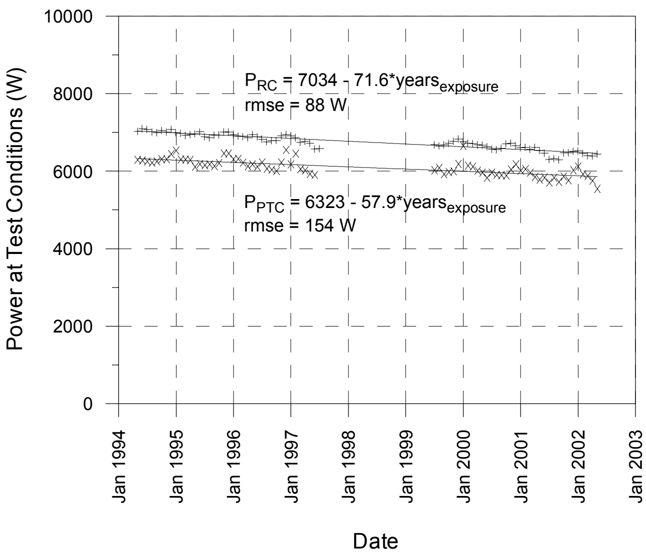

Figure 4. Calculated power ratings for the SERFWEST PV system for 1994-2002.

Table 1. Decrease in PV System Ratings from 1994 to 2002

Method	SERFEAST		SERFWEST	
	(%)	(%/yr)	(%)	(%/yr)
PVUSA	6.8	0.9	7.3	0.9
Power Eqn.	9.2	1.2	8.1	1.0

correspond to PV array temperatures typically 20°C to 25°C greater than the PV array reference temperature that was used with the power equation method.

Compared to the PVUSA method, the power equation method's monthly rating values exhibited less scatter and were closer to the linear regression line. Statistically, this is represented by the root-mean-square error (rmse) for the power equation method being only half as great as that for the PVUSA method. Better results using the PVUSA method might have been obtained by eliminating winter months with ambient temperatures significantly different than PTC.

The inability of the inverters to peak-power track the PV arrays at elevated PV array temperatures, and how this condition became more prevalent as the I-V characteristics of the PV arrays changed with time, did not seriously affect the analysis outcome. In Fig. 3 and Fig. 4, this condition might be exhibited as an increase in the differences between summer and winter ratings with the passage of time. To quantify the effect of inverter operation on the PV system degradation rate, the power equation analysis was repeated using only data when the PV array temperature was between 30°C and 35°C. For this range of temperatures, corresponding primarily to winter months, the inverters operate at or near the peak-power point of the PV arrays (see Fig. 2). This analysis lowered the degradation rate by about a fifth, which is considered the contribution of the inverter not peak-power tracking at elevated temperatures on the overall degradation rate.

5. Summary

For the period of May 1994 to April 2002, monthly performance ratings were calculated for the two PV systems located on the roof of the SERF building. A linear regression of the monthly ratings showed the performance of the two systems to be decreasing at a nominal rate of 1% per year. Most of the changes in performance rating are attributed to changes in the performance of the PV arrays. But about a fifth of the observed changes were from the inverter not peak-power tracking as effectively as the PV arrays aged and their V_{mp} decreased.

6. Acknowledgement

The authors would like to acknowledge Bill Sekulic for performing the post-test calibrations and I-V curve measurements.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2003	Conference Paper

4. TITLE AND SUBTITLE
Long-Term Performance of the SERF PV Systems

5. FUNDING NUMBERS
PVP3.7101

6. AUTHOR(S)
B. Marion and J. Adelstein

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-520-33531

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

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14. SUBJECT TERMS
photovoltaic systems; SERF; performance rating; PV array; inverter; peak-power tracking

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL