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Array Performance Characterization and Modeling Method for Real-Time System Performance Analysis

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ABSTRACT

The goal of this project is to provide applied research in direct collaboration with module and inverter manufacturers and system integrators, focusing on procedures for field characterization and long-term monitoring of array and inverter performance and reliability. This paper illustrates the use of a simplified array performance model that provides an unprecedented level of detail in evaluating inverter performance, plus the accuracy of system monitoring procedures and system performance indices used by industry can be improved.

1. Objectives

The ability to accurately predict (design) and then monitor the energy production from PV systems is of primary importance for verifying initial performance and for monitoring long-term performance (reliability). With many systems now being installed, a variety of system performance metrics (indices) have evolved.[1,2] Every system performance index being considered requires an accurate determination of the power and/or energy available from the associated PV array. Specific objectives of our effort include the following:

- Develop array testing, data analysis, and performance modeling procedures that are accurate and practically implemented for c-Si, thin-film, and concentrator PV,
- Assist industry in developing improved performance indices and monitoring techniques for PV systems,
- Apply testing/modeling methods providing integrators and manufacturers detailed inverter and array performance data for current technology systems,
- Evaluate the field aging characteristics of arrays and inverters that affect performance, reliability, and safety.

2. Technical Approach

The photovoltaic array performance model and outdoor testing procedures developed at Sandia have been extensively validated at the module and array level in cooperation with NREL, PVUSA, and NIST,[3] and the model has been incorporated in PV system design software.[4] The model has been used to study the sensitivity of annual energy production to the most influential factors; solar availability, array temperature, solar spectral variation, and solar angle-of-incidence effects.[5] Recently the performance model has been dramatically simplified for the purposes of continuous array performance monitoring and array power ratings conducted in the field. The key to the simplification was a "matched" reference cell (irradiance sensor) as described by Ossenbrink in 1992.[6] The reference cell is "matched" in the sense that its spectral response, optical characteristics, and thermal behavior closely mimic those of the PV array being evaluated, and it is carefully mounted in the same plane as the array. The simplified testing and modeling procedure is being applied to eight new configurable PV systems at Sandia. One of the reference cells (irradiance sensors) used for the Sandia arrays is shown in Fig.1.

Fig. 1. 'Matched' reference cell for array characterization.

3. Results and Accomplishments

The following discussion describes the simplified model, its associated measurements, and specific applications.

3.1 Simplified Array Performance Model

By using a matched reference cell to directly measure the effective solar irradiance, E_e, and thermocouples to measure back surface module temperature, T_m, the Sandia array performance model[4] simplifies to the following:

$$I_{sc} = M_p \cdot I_{sco} \cdot E_e \cdot \{1 + \alpha_{Isc} \cdot (T_c - T_o)\} \quad (1)$$

$$I_{mp} = M_p \cdot [I_{mpo} \cdot \{C_0 \cdot E_e + C_1 \cdot E_e^2\} \cdot \{1 + \alpha_{Imp} \cdot (T_c - T_o)\}] \quad (2)$$

$$V_{oc} = M_s \cdot [V_{oco} + N_s \cdot \delta(T_c) \cdot \ln(E_e) + \beta_{Voc} \cdot (T_c - T_o)] \quad (3)$$

$$V_{mp} = M_s \cdot [V_{mpo} + C_2 \cdot N_s \cdot \delta(T_c) \cdot \ln(E_e) + C_3 \cdot N_s \cdot \{\delta(T_c) \cdot \ln(E_e)\}^2 + \beta_{Vmp} \cdot (T_c - T_o)] \quad (4)$$

$$P_{mp} = I_{mp} \cdot V_{mp} \quad (5)$$

where:

$$\delta(T_c) = n \cdot k \cdot (T_c + 273.15) / q \quad \text{, cell 'thermal voltage'} \quad (6)$$

$$T_c = T_m + E_e \cdot \Delta T \quad \text{, cell temperature (ºC)} \quad (7)$$

E_e = Plane-of-array equivalent irradiance (suns)
ΔT = Temperature difference between cell and back surface
N_s = Number of cells in series in each module
M_s = Number of series-connected modules in string
M_p = Number of module-strings in parallel

3.2 Array Performance Characterization (Rating)

For each of the eight new arrays at Sandia, a DayStar DS-100 curve tracer was used to record a series of I-V curves from early morning until evening with a matched reference cell as the irradiance sensor. The measured data were analyzed to obtain the parameters I_{sco}, I_{mpo}, V_{oco}, and V_{mpo} at Standard Reporting Conditions (1000 W/m^2, AM1.5, T_o=25ºC), as well as the coefficients C_0, C_1, C_2, C_3, and n.

Only the temperature coefficients (α_{Isc}, α_{Imp}, β_{Voc}, β_{Vmp}) needed to be determined from prior module testing. Table 1 summarizes the array configurations, power ratings, and associated inverters for each system. Fig. 2 illustrates test results for one array. All eight arrays will be re-characterized annually to maintain model accuracy and to provide rarely available array degradation rates.

Table 1. Configurations and ratings of new Sandia systems.

Modules	Type	Ms	Mp	Spec (W)	Meas (W) ±3%	Inverters
BP380	mc-Si	16	2	2560	2470	PVI2500
HIP175	HIT-Si	8	2	2800	2798	SWR2500U
SQ80	c-Si	28	3	6720	6290	TBD
BP380	mc-Si	22	4	7040	6660	IG3000 PVP2800
SPR90	c-Si	-	-	7200	TBD	SPR3200
PW750	mc-Si	22	4	6600	5975	TBD
HIP190	HIT-Si	7	6	7980	7720	TBD
AP75	c-si	20	4	6000	5470	SWR2500U GT 3.0

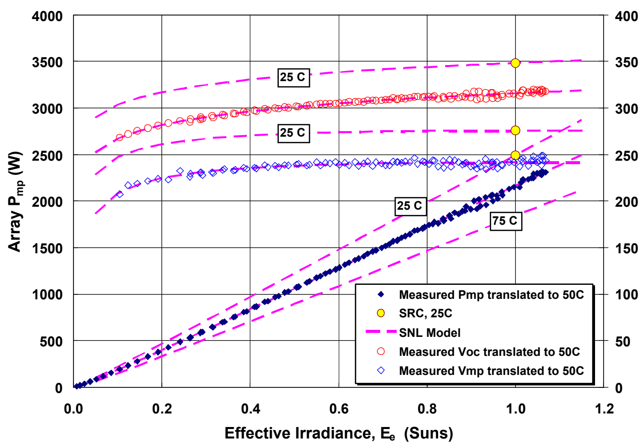

Fig. 2. Measured data and resulting performance model for the array of 32 BP Solar BP380 mc-Si modules.

3.3 System and Inverter Performance Analysis

The technical staff at Sandia has for many years emphasized the evaluation of PV system performance, as well as the development and improvement of balance-of-system components. The inverter testing laboratory at Sandia now provides detailed baseline inverter characterizations used for long-term system research at Sandia, as well as at FSEC and SWTDI.[7] In addition, our fully instrumented systems, in conjunction with the accurate array performance model, provide for the first time a research capability for quantifying the performance of both the array and the inverter during continuous operation. Inverter efficiency, power factor, array utilization (MPPT effectiveness), as well as start-up, shut-down, power limiting, thermal 'foldback,' and ground fault detection characteristics can be evaluated for the full range of outdoor operating conditions. In addition, optimum array/inverter combinations and characteristics are being identified that will improve performance, reliability, and cost of the next generation of factory assembled PV systems.[8] Fig. 3 and 4 illustrate test/modeling results for one array-inverter combination for a clear day and a cloudy day of operation.

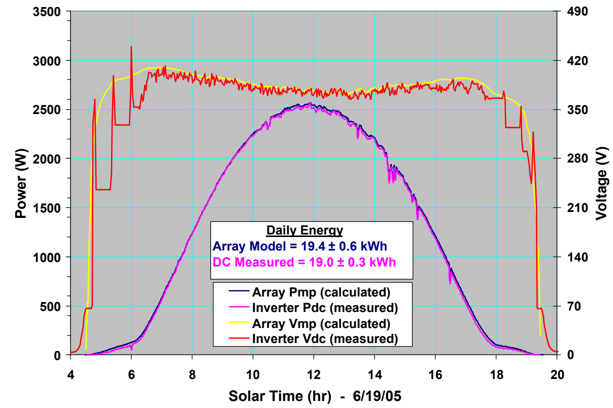

Fig. 3. Array and inverter power and voltage, clear day.

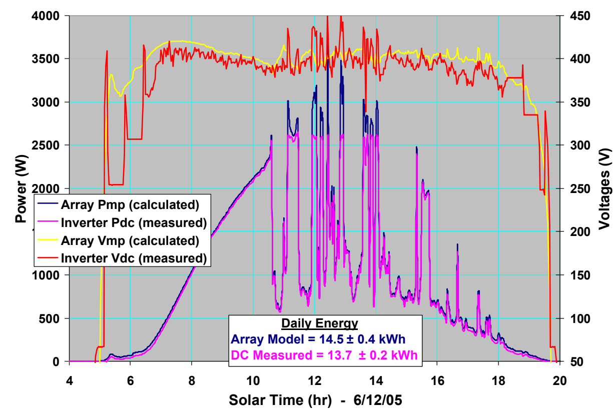

Fig. 4. Array and inverter power and voltage, cloudy day.

4. Conclusions

New and existing laboratory capabilities and expertise at Sandia are being applied in cooperation with industry to fully understand the real-time and long-term energy production characteristics of grid-connected PV systems.

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REFERENCES

[1] C. Whitaker, et al., "Performance Report for First Twelve Months of Exposure and Operation for the Comprehensive Large PV System Comparison," CEC Contract 500-00-036, August 2005.
[2] B. Marion, et al., "Performance Parameters for Grid-Connected PV Systems," *31st IEEE PVSC*, Lake Buena Vista, (2005).
[3] D. King, W. Boyson, J. Kratochvil, "Photovoltaic Array Performance Model," Sandia Report, SAND2004-3535.
[4] "PV-DesignPro User's Manual," Maui Solar Software Corporation, http://www.mauisolarsoftware.com.
[5] D. King, W. Boyson, J. Kratochvil, "Analysis of Factors Influencing the Annual Energy Production of PV Systems," *29th IEEE PVSC*, New Orleans, (2002).
[6] H. Ossenbrink, K. Munzer, "ESTIsensor – New Reference Cell for Monitoring PV Plant Performance," *11th E.C. PVSEC*, (1992).
[7] J. Ginn and S. Gonzalez, "Inverter Baseline Characterization Methods/Results for Field Aging Program," this meeting.

[8] M. Quintana, et al., “Development of New System Manufacturing, Integration, Deployment Concepts,” ibid.