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Performance Model for Grid-Connected Photovoltaic Inverters

David L. King, Sigifredo Gonzalez, Gary M. Galbraith, and William E. Boyson

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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David L. King, Sigifredo Gonzalez,
Gary M. Galbraith, and William E. Boyson
Solar Systems Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-1033

Abstract

This document provides an empirically based performance model for grid-connected photovoltaic inverters used for system performance (energy) modeling and for continuous monitoring of inverter performance during system operation. The versatility and accuracy of the model were validated for a variety of both residential and commercial size inverters. Default parameters for the model can be obtained from manufacturers' specification sheets, and the accuracy of the model can be further refined using measurements from either well-instrumented field measurements in operational systems or using detailed measurements from a recognized testing laboratory. An initial database of inverter performance parameters was developed based on measurements conducted at Sandia National Laboratories and at laboratories supporting the solar programs of the California Energy Commission

ACKNOWLEDGMENTS

The development of our grid-connected inverter model has greatly benefited from valuable interactions with many experts in the field of photovoltaic technologies. The authors would like to acknowledge several colleagues: Chuck Whitaker (BEW Engineering), Andy Rosenthal (Southwest Technology Development Institute), Kevin Lynn (Florida Solar Energy Center), Michael Ropp (South Dakota State University), as well as several other contributors at Sandia (Jerry Ginn, Ward Bower, John Stevens, Jay Kratochvil, and Larry Moore).

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INTRODUCTION

This document provides a description and demonstrations of a versatile performance model for the power inverters used in photovoltaic (PV) systems. These inverters convert the direct current (dc) power provided by an array of PV modules to alternating current (ac) power compatible with the utility power grid. The inverter performance model can be used in conjunction with a photovoltaic array performance model [1, 2, 3] to calculate expected system performance (energy production), to verify compatibility of inverter and PV array electrical characteristics, and to continuously monitor inverter performance characteristics that may indicate the need for repair or maintenance.

A primary objective of this effort was to develop an inverter performance model applicable to all commercial inverters used in photovoltaic power systems, providing a versatile numerical algorithm that accurately relates the inverter's ac-power output to the dc-power input. The model developed requires a set of measured performance parameters (coefficients). The complexity and the accuracy of the performance model are "progressive" in the sense that the accuracy of the model can be improved in steps, as more detailed test data are available. Manufacturers' specification sheets provide initial performance parameters, field measurements during system operation provide additional parameters and accuracy, and detailed performance measurements as conducted by recognized testing laboratories [4, 5] provide further refinement of parameters used in the model. The inverter performance model presented does not provide an electrical engineering model of circuit characteristics or power conditioning algorithms used in the development of new inverter designs [6]; rather it is an empirical, or phenomenological, model that simply but accurately replicates the power delivery characteristics of the dc- to ac-inversion process.

The modeling approach used was similar to that often used in "design of experiments" analyses, where the non-linear response of a complex system or process can be modeled as the interaction of several factors, each factor typically having a linear relationship with an independent variable or variables. The understandability of the inverter performance model was improved through an algebraic construction where factors in the model have easily understood physical significance.

DESCRIPTION OF INVERTER PERFORMANCE MODEL

Manufacturers' specification sheets contain a variety of information essential to the successful application of a PV inverter, including ac voltage, ac frequency, maximum ac power and current, acceptable dc voltage range, maximum dc power and current, dc startup voltage, total harmonic distortion, power factor, and acceptable environmental extremes, as well as mechanical characteristics. However, the inverter's "power conversion performance" or efficiency is often provided as a single peak efficiency value, which can be misleading, and sometimes as a "California Energy Commission (CEC) weighted" efficiency value. Regardless, PV system engineers and analysts would benefit from more detailed performance characteristics.

Independent testing laboratories now provide more detailed inverter performance data, notably those laboratories supporting the solar power initiatives of the CEC [7]. These laboratories typically use an inverter testing methodology based on the protocol collaboratively developed by Sandia National Laboratories and BEW [8]. The objective of the CEC testing protocol is to verify inverter performance specifications, as well as to quantify performance characteristics as a function of power level and dc input voltage, the two parameters determined by laboratory evaluations to have the most significant impact on efficiency. The inverter test data documented by the CEC [4] are thorough, providing measurements at six power levels and three different dc voltage levels. Five to seven replicate measurements at each condition provide good statistical rigor. Figure 1 illustrates an example of inverter performance data documented by the CEC, providing inverter efficiency (ac-power divided by dc-power) as a function of the ac-power output of the inverter, at three different dc voltage levels. Our effort, documented in this report, shows that by presenting the CEC test data differently, additional information can be obtained that is more directly applicable in modeling PV system energy production. Later in this document, several examples will more clearly illustrate the alternative procedure for extracting more information from the CEC data.

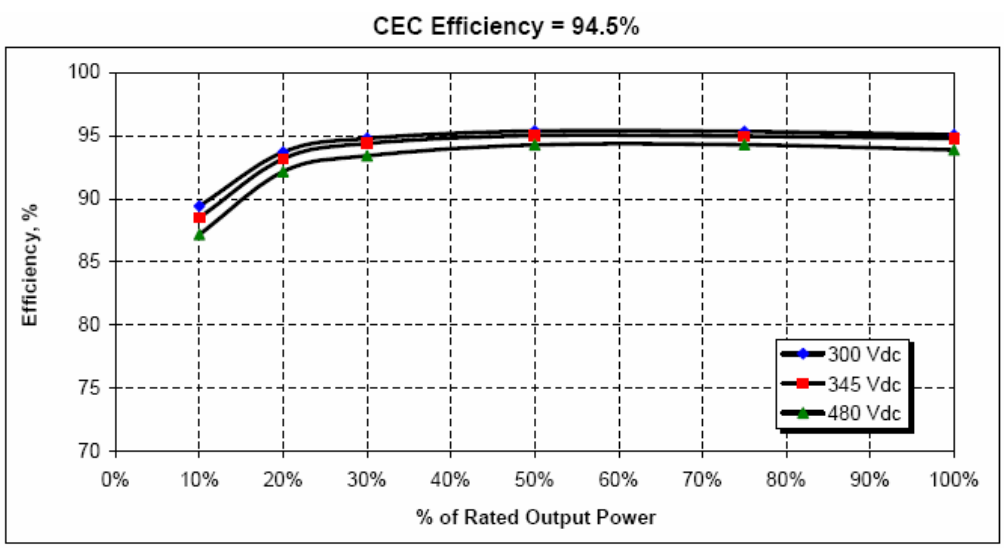

Figure 1. Inverter performance measurements conducted by a nationally recognized testing laboratory and documented by the CEC.

The initial concept for the new inverter performance model provided in this document resulted from analysis of system performance data recorded in Sandia's PV System Optimization Laboratory [2]. Fully instrumented PV systems provided the opportunity to analyze performance of both the PV array and the inverter based on daylong energy production for many days with a wide variety of operating (environmental) conditions. These "field" data provided hundreds of measurements at different power levels, from startup to levels exceeding the inverter's peak power rating, but the range for dc voltage was relatively limited and not easily controlled compared to the CEC laboratory testing approach. The advantages of the "field testing" approach for acquiring inverter performance data are that recorded data are completely representative of actual system operating conditions, and free from possible electronic interactions that might occur between an inverter and test equipment (power supplies) in the laboratory. Figure 2 illustrates a "field test" example with thousands of measurements recorded over a 13-day period.

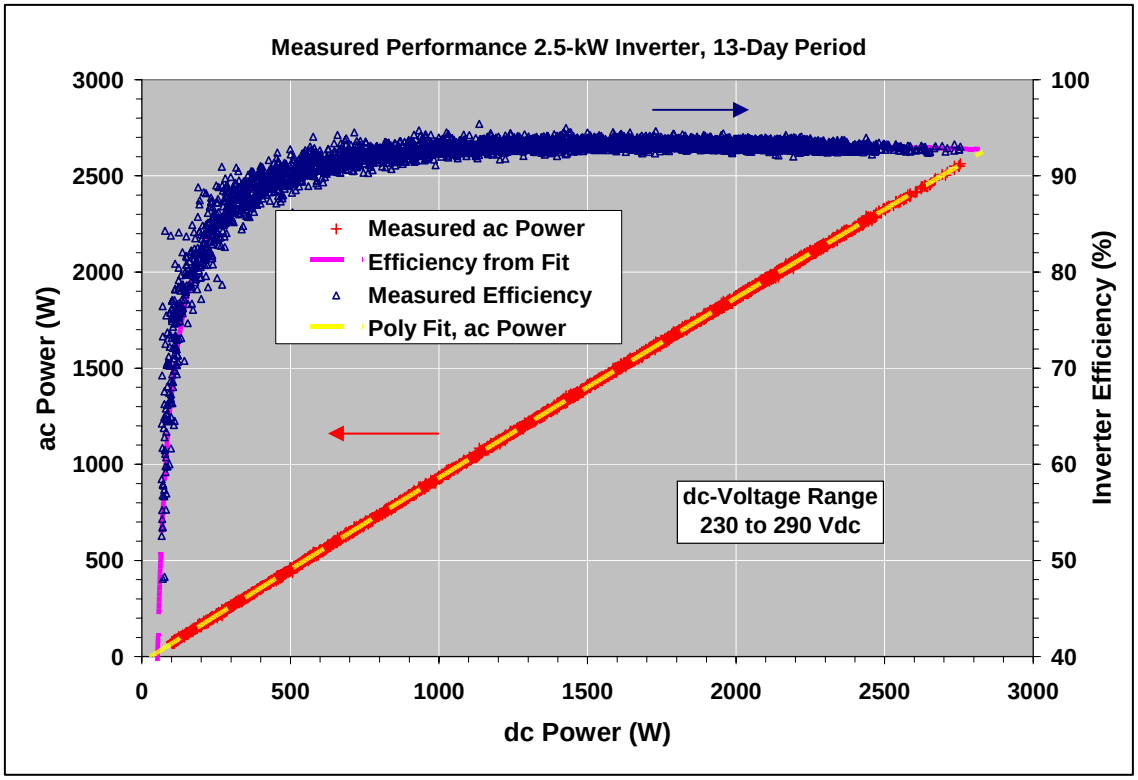

Figure 2. "Field test" results for a 2.5-kW Solectria PVI2500 inverter recorded during system operation at Sandia, showing both inverter efficiency and relationship between ac-power and dc-power over an extended 13-day test period, including both clear and cloudy days.

The characteristic perhaps most evident in Figure 2 is the well-behaved nature of the relationship between measured ac-power and dc-power, over the full range of dc-input power for both rapidly changing cloudy conditions as well as clear sky conditions. The relationship between ac and dc power appears to be nearly linear. However, the power consumed by the inverter itself (self-consumption) as well as the electrical characteristics of inverter circuitry at different voltage and power levels result in differing degrees of non-linearity in the relationship between ac-power and

dc-power. The measured inverter efficiency values (ac-power divided by dc-power), also shown in Figure 2, amplify the non-linearity inherent in the relationship between ac- and dc-power. Frequently in modeling PV system energy production, inverter efficiency is assumed to be a constant value, which is the same as assuming that inverter efficiency is linear over its operating range, which is clearly not the case. The scatter in the efficiency measurements resulted from a combination of variation in dc input voltage, inherent inverter behavior, rapidly varying solar irradiance, and measurement error. Again, the objective of our effort was to accurately model the relationship between ac-power and dc-power for all inverter types, over their full operating voltage and power range.

Stability and repeatability of inverter performance characteristics are a prerequisite both for reliable PV system performance, as well as for determining parameters used in the performance model. Similarly, the stability and repeatability of performance characteristics for PV arrays are a prerequisite for high-reliability PV systems. Therefore, when conducted in the laboratory, the inverter testing protocol must be accurate, repeatable, and not introduce electrical instabilities that are not representative of actual operation in a PV system. Additional discussion of instabilities introduced by test equipment are provided later in this report for specific inverter test results that are used to validate our inverter performance model.

It should be noted that the inverter's maximum-power-point-tracking (MPPT) effectiveness was not explicitly included in our performance model for several reasons. First, the MPPT effectiveness of most inverters manufactured today is quite high, providing 98 to nearly 100% of the energy available from the PV array. Second, MPPT effectiveness is very difficult to measure because it requires simultaneous measurements of dc-power into the inverter and the maximum power point (P_{mp}) of the PV array. In most cases, the inverter is rapidly varying its operating voltage over a reasonably large range while "searching" for the array P_{mp}. To complicate the situation, the only way to measure the array P_{mp} accurately is to disconnect the inverter from the array and measure a current-voltage (I-V) curve, thus interrupting the MPPT process. Another procedure used to monitor an inverter's MPPT characteristics involves using an accurate performance model for the PV array so that the measured dc-power into the inverter can be continuously compared to a predicted P_{mp} for the PV array [2]. Using the array performance model to continuously predict P_{mp} based on solar irradiance and array temperature measurements provides an effective way to observe the inverter's MPPT characteristics, particularly during rapid variations in solar irradiance (clouds) where the MPPT algorithm must be versatile in order to "lock on" to a rapidly changing P_{mp}. However, due to the uncertainty in the PV array performance model (± 2% at best), the approach is not accurate enough to quantify MPPT effectiveness for high-performance inverters where the MPPT effectiveness is 98% or better. Therefore, instead of attempting to incorporate an inverter's MPPT effectiveness in our model explicitly, the slight system energy loss related to MPPT can be better addressed as a simple multiplicative "derate factor" in system performance modeling.

Neither the inverter (heat sink) operating temperature nor the ambient temperature were explicitly included in our performance model, for two reasons. Current inverters that are laboratory tested and listed as eligible for CEC recognized applications in California are tested at different ambient temperatures (25 and 40 ºC), and their efficiencies typically do not have a strong temperature dependence, as evidenced in test results presented later in this document. In

actual applications, inverters are mounted in a wide variety of locations and orientations (in garages, on external walls, in the sun, in the shade) and as a result, it is impractical to attempt to model inverter operating temperature as a function of environmental conditions. Therefore, if laboratory tests verify that inverter performance is stable at its maximum specified ambient temperature, and if the inverter is mounted according to the manufacturer's specifications, then it is not necessary to include inverter temperature in the performance model.

Basic Equations

Figure 3 graphically illustrates our inverter performance model, with performance characteristics exaggerated in order to illustrate the physical significance of the parameters used in the model. The basic equations describing the model and the definition of all parameters follow.

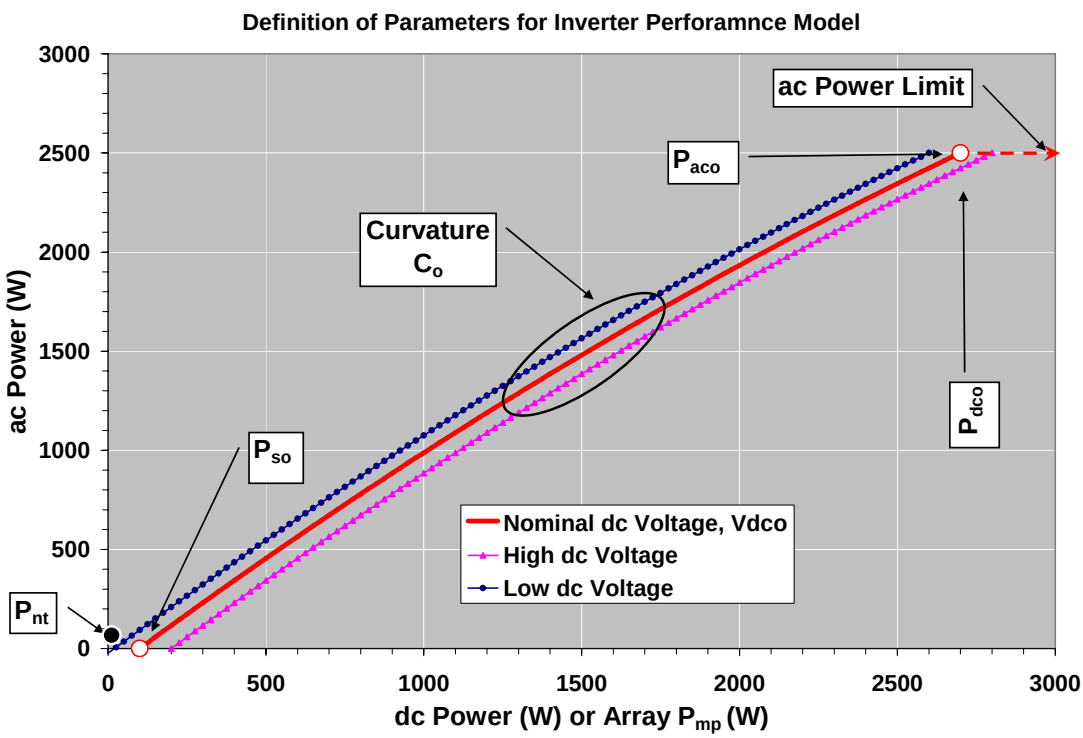

Figure 3. Illustration of the inverter performance model and the factors describing the relationship of ac-power output to both dc-power and dc-voltage input.

The following equations define the model used to relate the inverter's ac-power output to both the dc-power and the dc-voltage, which were used as the independent variables. The parameters with the "o" subscript are constant values that define a reference or nominal operating condition.

$$P_{ac} = \{(P_{aco} / (A - B)) - C \cdot (A - B)\} \cdot (P_{dc} - B) + C \cdot (P_{dc} - B)^2 \qquad (1)$$

where:

$$A = P_{dco} \cdot \{1 + C_1 \cdot (V_{dc} - V_{dco})\} \quad (2)$$

$$B = P_{so} \cdot \{1 + C_2 \cdot (V_{dc} - V_{dco})\} \quad (3)$$

$$C = C_o \cdot \{1 + C_3 \cdot (V_{dc} - V_{dco})\} \quad (4)$$

Performance Parameter Definitions

P_{ac} = ac-power output from inverter based on input power and voltage, (W)
P_{dc} = dc-power input to inverter, typically assumed to be equal to the PV array maximum power, (W)
V_d = dc-voltage input, typically assumed to be equal to the PV array maximum power voltage, (V)
P_{aco} = maximum ac-power "rating" for inverter at reference or nominal operating condition, assumed to be an upper limit value, (W)
P_{dco} = dc-power level at which the ac-power rating is achieved at the reference operating condition, (W)
V_{dco} = dc-voltage level at which the ac-power rating is achieved at the reference operating condition, (V)
P_{so} = dc-power required to start the inversion process, or self-consumption by inverter, strongly influences inverter efficiency at low power levels, (W)
P_{nt} = ac-power consumed by inverter at night (night tare) to maintain circuitry required to sense PV array voltage, (W)
C_o = parameter defining the curvature (parabolic) of the relationship between ac-power and dc-power at the reference operating condition, default value of zero gives a linear relationship, (1/W)
C_1 = empirical coefficient allowing P_{dco} to vary linearly with dc-voltage input, default value is zero, (1/V)
C_2 = empirical coefficient allowing P_{so} to vary linearly with dc-voltage input, default value is zero, (1/V)
C_3 = empirical coefficient allowing C_o to vary linearly with dc-voltage input, default value is zero, (1/V)

DETERMINATION OF INVERTER PERFORMANCE PARAMETERS

The accuracy and versatility of the inverter performance model depends on the data available for determining the performance parameters used in the model. We structure our model to make it possible to add parameters successively, improving accuracy, as more detailed test data are available. Initial (default) parameters can be obtained from manufacturer specification sheets. If available, daylong ac-power and dc-power measurements from operating systems provide additional parameters and improved accuracy. Finally, detailed laboratory measurements, like those conducted by nationally recognized testing laboratories for the CEC [4], can be used to obtain all performance parameters currently included in the model. During the validation of our performance model, an initial database of inverter parameters was generated and is given in the appendix of this document. Using the methods described in this document, field measurements or tabulated performance data provided by recognized laboratories provide the means for adding parameters for new inverters to the database.

Manufacturer Specification Sheets

The terminology used and the performance parameters available from manufacturers' specification sheets vary greatly. However, it is usually possible to determine reasonable estimates for the three parameters needed to provide a simple linear model for inverter performance (P_{aco}, P_{dco}, P_{so}), with no dependence on dc-voltage input. The rated ac-power (P_{aco}) is usually specified, as is the peak and/or CEC weighted efficiency. Dividing P_{aco} by the efficiency value provides a value for the associated dc-power level (P_{dco}). The dc-power required to start the inversion process (P_{so}) may not be given in the specification, and should not be confused with the nighttime ac-power consumption (P_{nt}). Lacking a specification, a reasonable estimate for P_{so} is 1% of the inverter's rated power. Field and laboratory test data have indicated that the startup or self-consumption power, as used in our model, is typically larger than the power level sometimes referred to as "standby" power or "consumption during operation."

Field Performance Measurements

When accurate daylong measurements of both dc-power input and true ac-power (not volt-amps, VA) from the inverter are available, then additional performance parameters can be determined, providing improved accuracy for the inverter performance model relative to the simple linear model. Figure 4 illustrates field measurements of true ac-power, dc-power, and inverter efficiency over a 13-day period including both clear and cloudy weather conditions. The data values recorded were near instantaneous measurements, as opposed to average values determined over a time interval. The associated dc-voltage was also recorded during the field measurements. A parabolic fit (2nd order polynomial) to the measured ac-power versus dc-power provided parameters (P_{dco}, P_{so}, C_o) used in the performance model. P_{aco} was assumed equal to the manufacturer's peak ac-power rating. The quadratic formula was used to solve for both the x-intercept (P_{so}) when $P_{ac} = 0$ and for P_{dco} when $P_{ac} = P_{aco}$ (2500 W in this case). A chart of measured dc-voltage versus measured dc-power over the 13-day period was used to obtain an estimate for the V_{dco} associated with the peak power condition at P_{dco}, P_{aco}. Good day-to-day repeatability in performance characteristics has been observed for a variety of inverters during field testing at Sandia; therefore, it is likely that measurements recorded over a single day would provide inverter performance parameters that are representative of expected behavior.

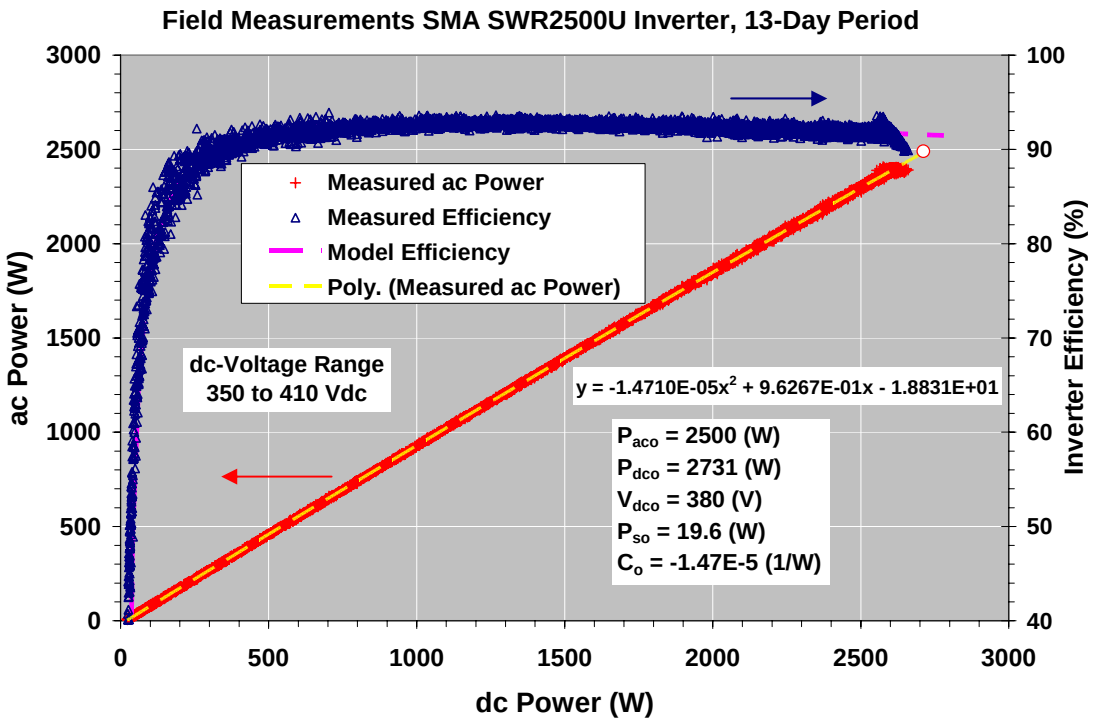

Figure 4. "Field test" results for a SMA SWR-2500U inverter recorded during system operation at Sandia, showing both inverter efficiency and relationship between ac-power and dc-power over a 13-day test period, including both clear and cloudy days. Chart shows over 4,000 measurements.

The error in the inverter performance model for field measurements was evaluated by calculating the percentage difference between the modeled and measured efficiency and plotting this difference as a function of the measured dc-power. Figure 5 shows the calculated error in the inverter efficiency model for the inverter data shown in Figure 4. Note that the error was well distributed about zero, and that for the majority of the power range the error was within ± 1%. Thus, an inverter with a modeled efficiency of 92% would have an uncertainty of about ± 0.9%. The larger error at the peak power level occurred when the inverter was operating at its peak dc-power limit. The large error (scatter) at low power levels occurred as inverter efficiency rapidly dropped and was due to both measurement error and limitations in the model. The accuracy obtained using "field" measurements can be improved using laboratory measurements and a slightly more complex model, as will be discussed next. Nonetheless, the inverter model, with performance coefficients derived from field measurements during PV system operation, provides a very straightforward method for modeling inverter performance, and it provides a good method for monitoring inverter behavior as the system ages.

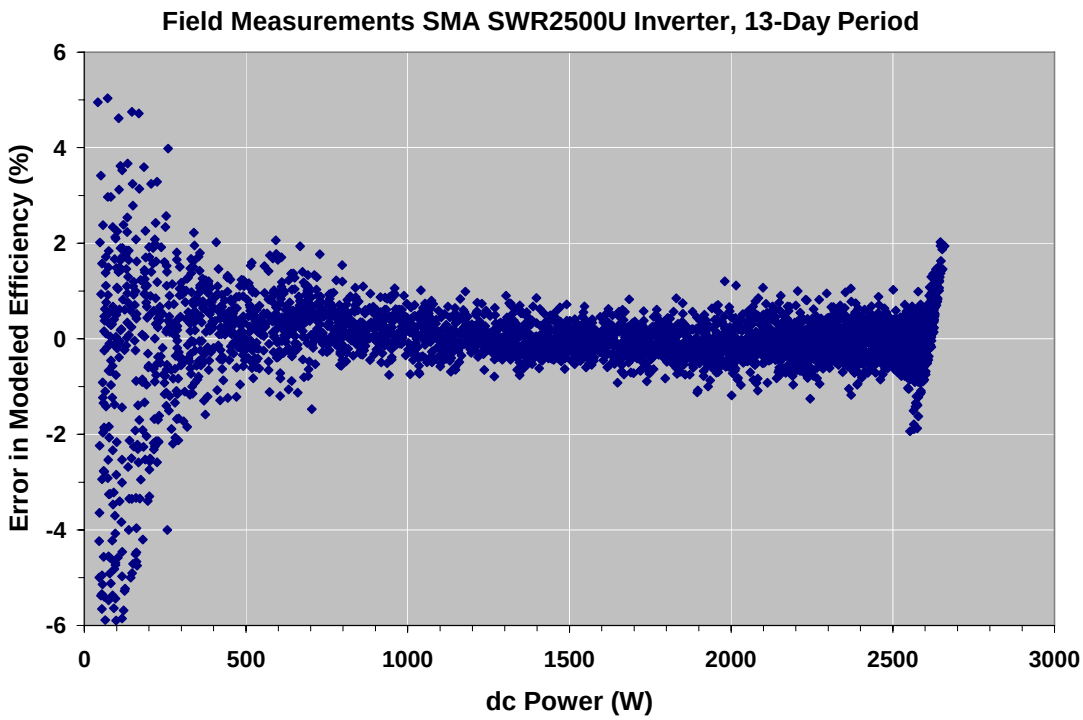

Figure 5. Calculated errors between modeled inverter efficiency and measured efficiency based on field test data over a 13-day period for the SMA SWR-2500U inverter in an operating system.

Laboratory Performance Measurements

The example shown in Figure 6 illustrates laboratory measurements available on the CEC website "List of Eligible Inverters" [4]. In this case, the inverter had a reasonably large operational range for dc-voltage input; as a result, the inverter efficiency varied noticeably, being higher at low dc-voltage input.

The CEC test protocol provides inverter performance (efficiency) measurements at six different power levels (10%, 20%, 30%, 50%, 75%, and 100% of ac-power rating) and three different input voltage levels (V_{min}, V_{nom}, V_{max}). The mid-range dc voltage, V_{nom}, defined by the CEC protocol (selected by the manufacturer at any point between Vmin+0.25*(Vmax-Vmin) and Vmin+0.75*(Vmax-Vmin)), was used as the reference voltage, V_{dco}, in the inverter performance model. The CEC measurement procedure provides five to seven replicated measurements at each test condition, providing good statistical rigor. The primary limitation of the CEC procedure was that measurements were performed for a single inverter of each type; the inverter may or may not be representative of the "typical" inverter off the production line.

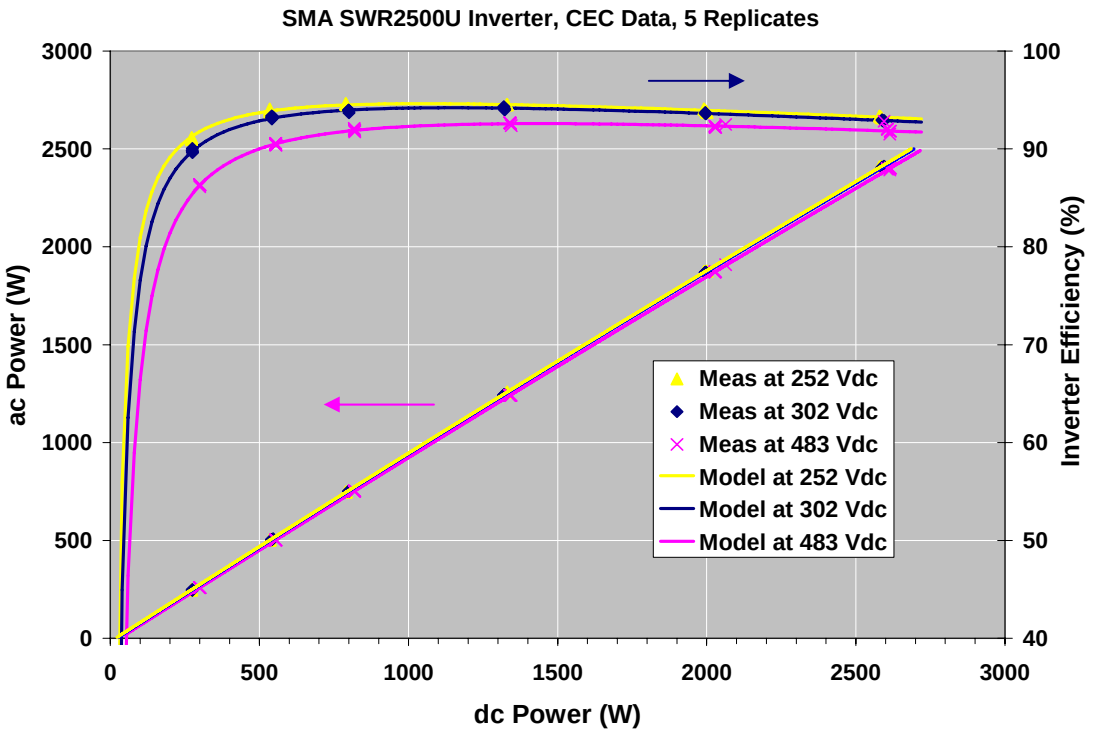

Figure 6. Inverter performance measurements conducted by nationally recognized testing laboratory for the CEC at six power levels and three dc-voltage levels. After parameter determination, the Sandia inverter performance model provided the solid lines through the measured values.

All the performance parameters required in the more complex inverter model, defined in Equations 1 through 4, can be determined using the CEC test data. The procedure for determining performance parameters from the tabulated CEC data is the same as previously discussed for the case using field measurements. The distinction is that data at each of the three dc-voltage levels were treated separately, allowing three of the parameters (P_{dco}, P_{so}, C_o) to be expressed as a linear function of the dc-voltage, V_{dc}, as indicated in Equations 2 through 4. Three separate parabolic fits were used, one for each set of ac-power versus dc-power measurements recorded at a near constant dc-voltage level. During analysis, the tabulated CEC test data were first combined using all replicate measurements, and then sorted by ascending dc voltage to combine measurements for each of the three common dc-voltage levels. The mid-voltage data, V_{nom}, provided the "reference" operating condition.

In order to determine the coefficients C_1, C_2, and C_3, the values for P_{dco}, P_{so}, and C_o determined from the three separate parabolic fits were used to calculate the dc-voltage dependence for each factor. For instance, Figure 7 shows the linear fit used to determine the coefficient C_2, as well as the value for P_{so} at the V_{nom} reference voltage. The data for this inverter, as well as several others investigated, suggested that the dc-power required to start the inversion process was somewhat lower at the low dc-voltage level, consistent with achieving higher inverter efficiency at low dc-voltage levels. The same analytical procedure (linear fit) was used to determine C_1, P_{dco}, and C_3, C_o at the V_{nom} reference voltage.

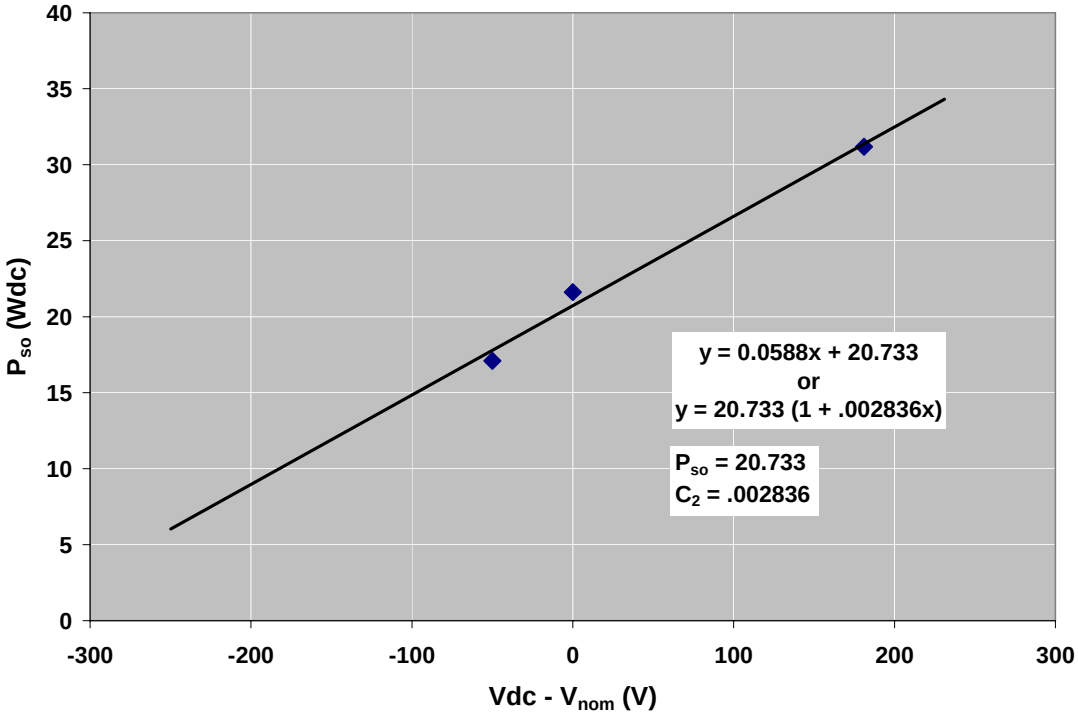

Figure 7. Linear regression (trend line) used to determine C_2 coefficient and value for P_{so} at the V_{nom} reference voltage for SMA SWR2500U inverter.

The added complexity in the inverter performance model, resulting from including voltage dependence for three factors, significantly reduced the error associated with the modeled inverter efficiency. Figure 8 shows that the calculated error between the modeled and the measured inverter efficiency was reduced to less than ± 0.2% when all parameters were included in the model. This result was encouraging because the inverter model is actually rather simple, and it is straightforward to determine the required performance parameters. Additional analysis was conducted to verify that the model worked equally well for inverters from a variety of manufacturers.

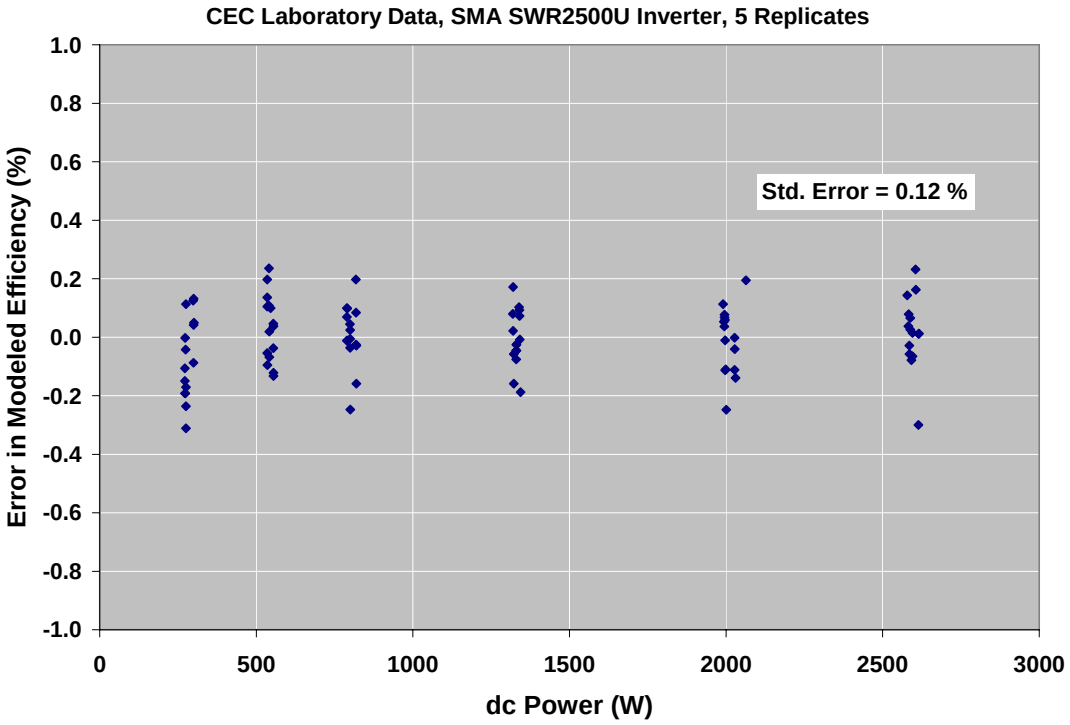

Figure 8. Calculated errors between modeled inverter efficiency and measured efficiency based on CEC laboratory test data for the SMA SWR-2500U inverter at six power levels and three dc-voltage levels.

VALIDATION OF INVERTER PERFORMANCE MODEL

The data quality and the large variety of inverter types included in the tabulated CEC test results provided an ideal opportunity for validating our inverter performance model. The CEC website includes measured performance data for inverters from many different manufacturers, as well as for both low (~2.5-kW) and high capacity (~225-kW) inverters. Analysis and determination of performance parameters for a variety of inverters with subsequent analysis of modeling errors was used to validate our performance model.

Typical Laboratory Test Results

Figures 9 and 10 show CEC measured performance for two common residential-scale inverters, along with the Sandia performance model shown as solid lines through the measured data points. The performance parameters determined for these two inverters are provided in the inverter database in the appendix of this document. The performance model was very effective in fitting measured data for both these inverters with a standard error in measured versus modeled efficiency of about 0.1%. The model was equally effective for the commercial-scale 225-kW inverter shown in Figure 11.

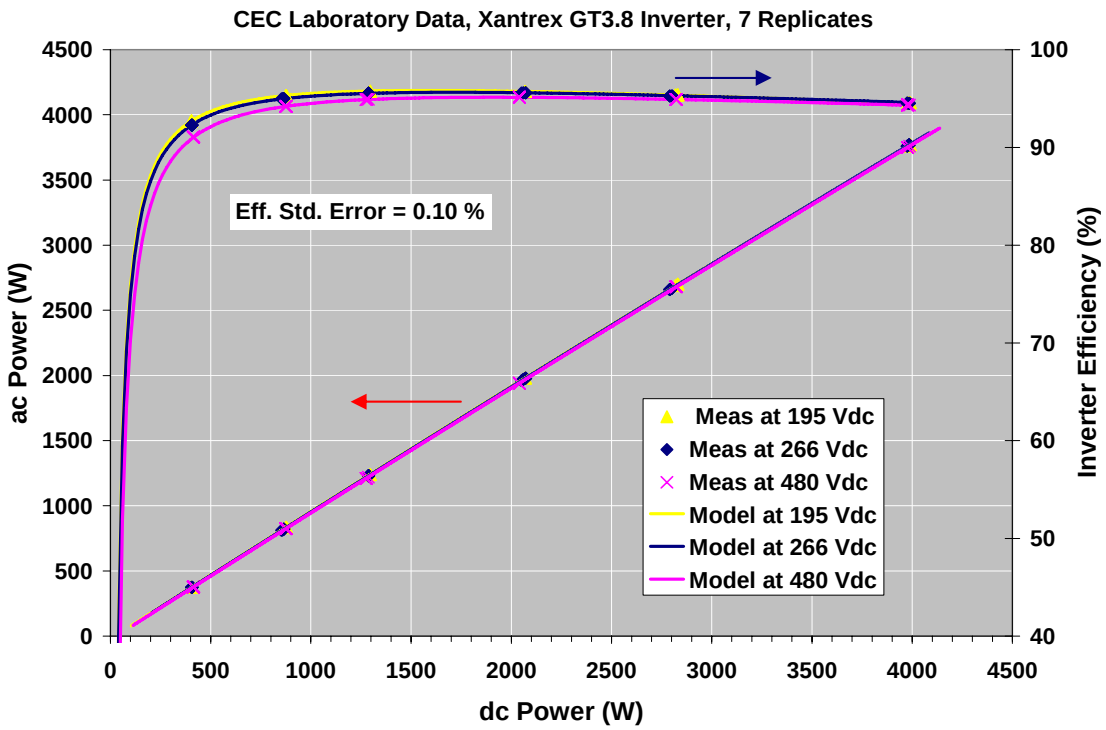

Figure 9. Comparison of measured versus Sandia performance model using CEC laboratory test data for the Xantrex GT3.8 inverter at six power levels and three dc-voltage levels.

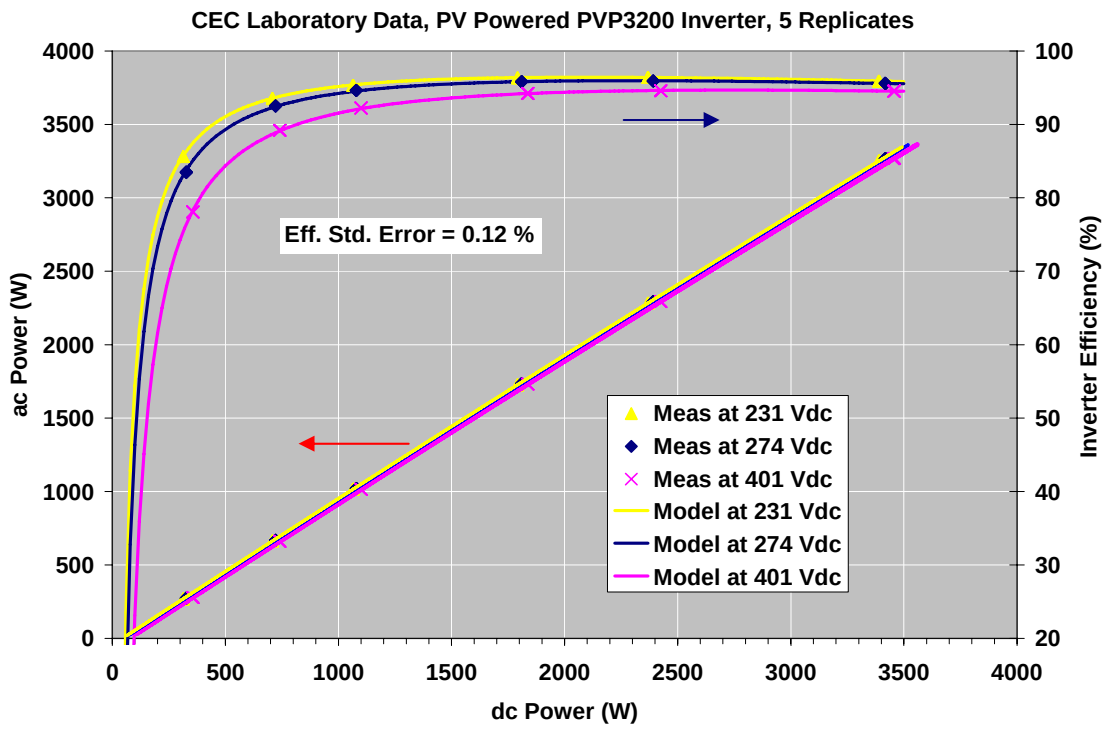

Figure 10. Comparison of measured versus Sandia performance model using CEC laboratory test data for the PV Powered PVP3200 inverter at six power levels and three dc-voltage levels.

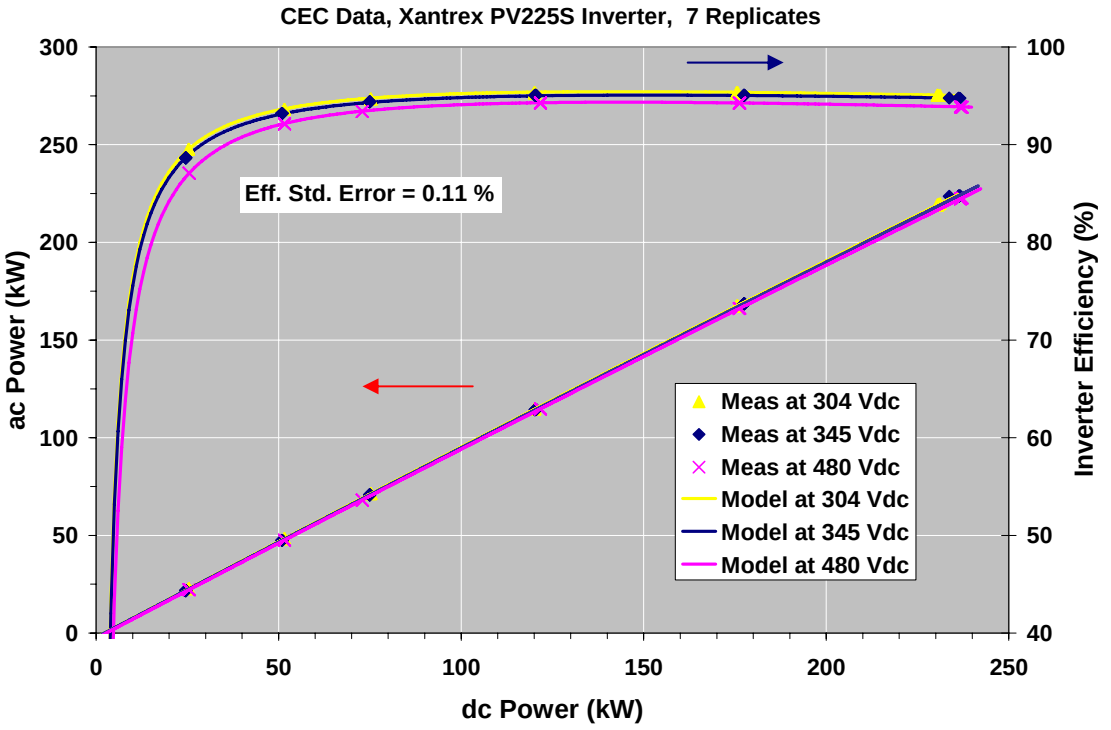

Figure 11. Comparison of measured versus Sandia performance model using CEC test data for the large 225-kW Xantrex PV225S inverter at six power levels and three dc-voltage levels.

Anomalous Test Results

Performance models and test results are rarely perfect. Significant discrepancies between the model and measured values may occur for a variety of reasons: an inadequate model, errors in test measurements, irregular inverter behavior, or unexpected interactions between the inverter and the test equipment.

Figures 12 and 13 show an example of CEC test data where the standard error for all measurements was reasonably good (0.55%); however, relatively large discrepancies (±3%) occurred between the measured and modeled efficiency at the lowest power level. This variability at the low power level was likely the result of instabilities introduced by the inverter test equipment. Note that this inverter was of the same type measured during field tests at Sandia, shown in Figure 2, where variability in the measured efficiency was much smaller at low power levels.

Figures 14 and 15 illustrate CEC test data where relatively large discrepancies between measured and modeled efficiency occurred at all power levels. In this case, the variability was due to inherent instability in the inverter itself because the replicate measurements were not repeatable.

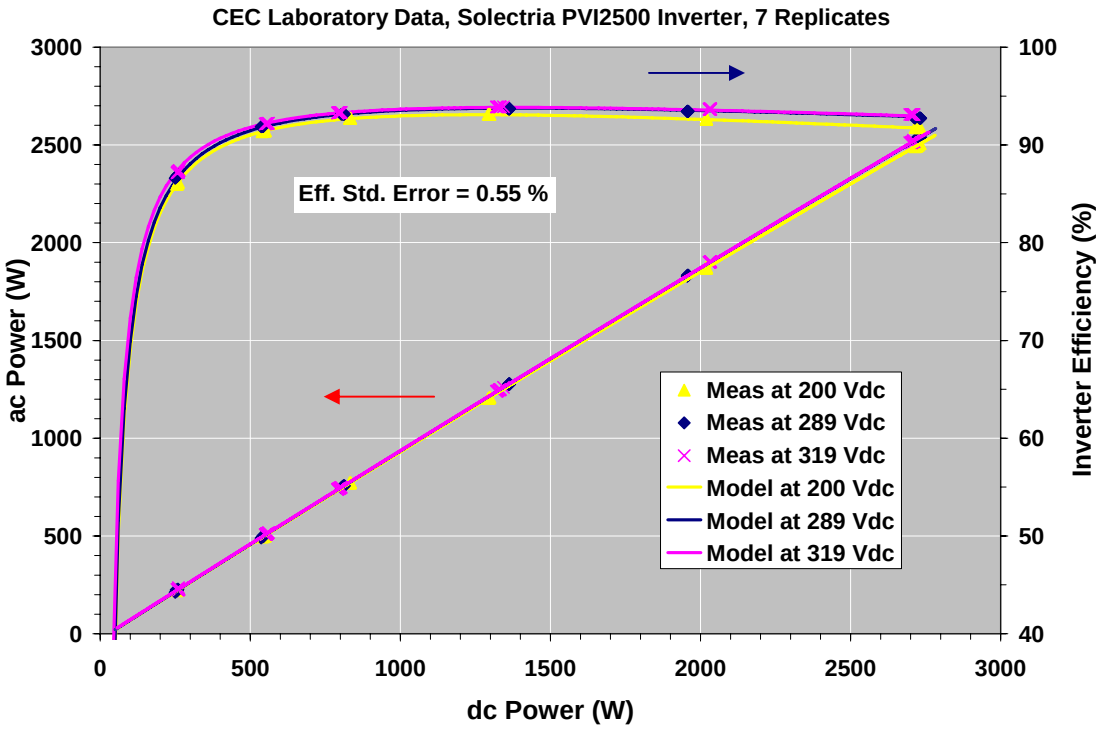

Figure 12. Measured versus model comparison using CEC laboratory test data for the Solectria PVI2500 inverter at six power levels and three dc-voltage levels.

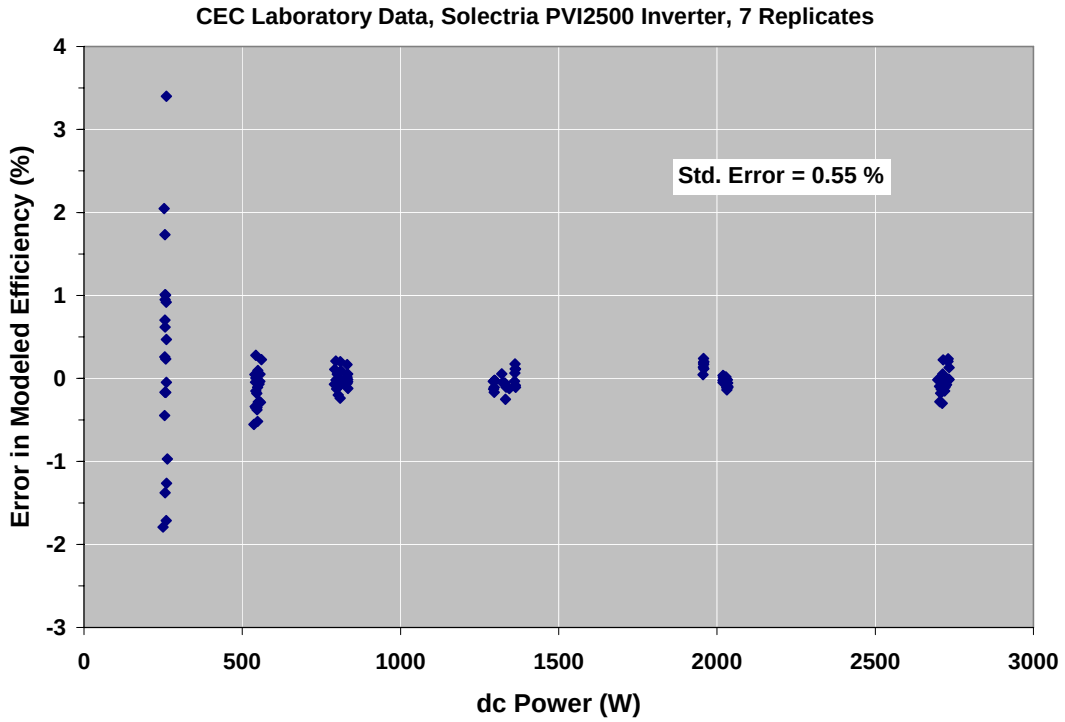

Figure 13. Calculated errors between modeled and measured efficiency based on CEC laboratory test data for the Solectria PVI2500 inverter at six power levels and three dc-voltage levels. Relatively large errors resulted at the lowest power levels only.

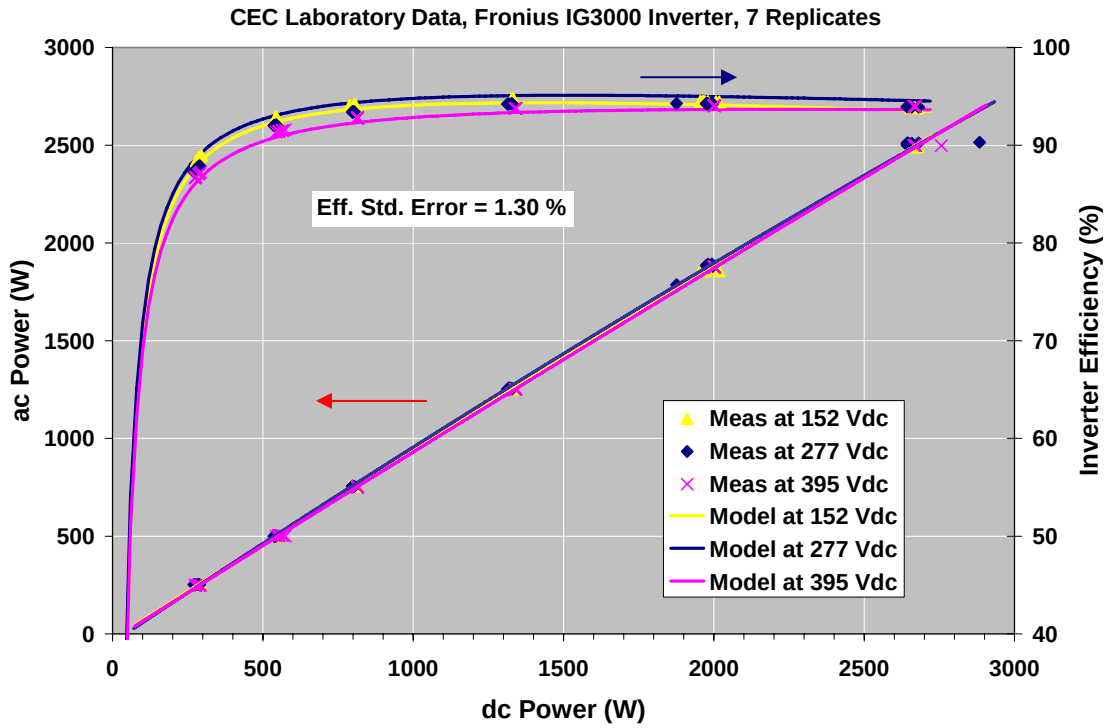

Figure 14. Measured versus model comparison using CEC laboratory test data for the Fronius IG3000 inverter at six power levels and three dc-voltage levels.

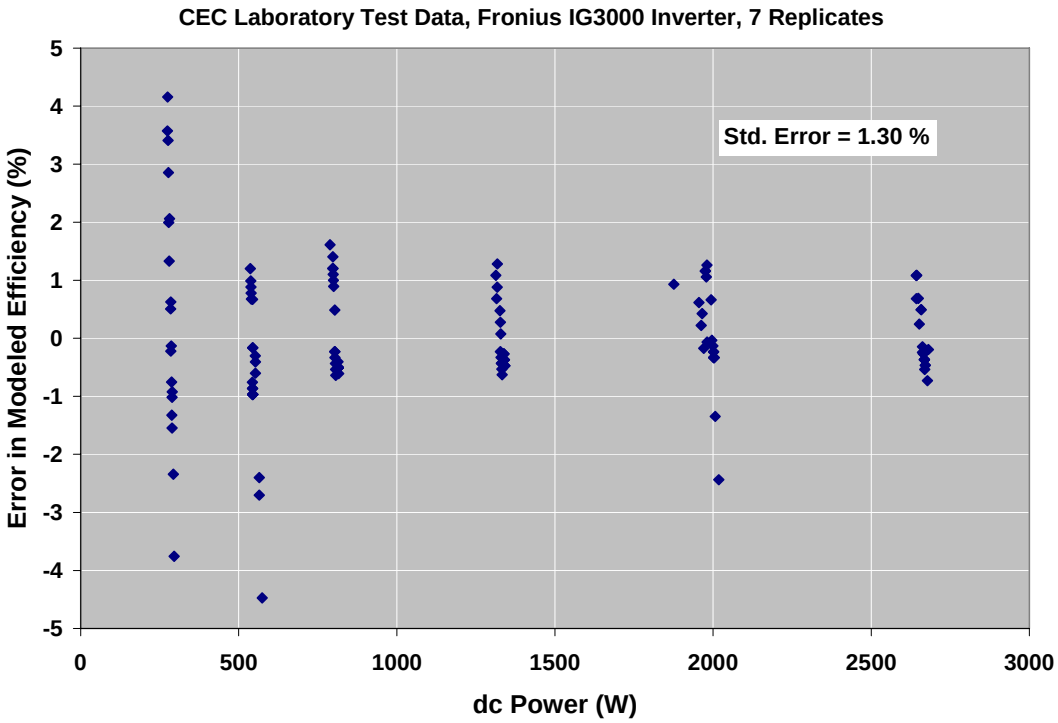

Figure 15. Calculated errors between modeled and measured efficiency based on CEC laboratory test data for the Fronius IG3000 inverter at six power levels and three dc-voltage levels. Relatively large standard error resulted at multiple power levels due to lack of repeatability.

SYSTEM PERFORMANCE ANALYSES

The inverter performance model presented in this document improves the accuracy and versatility of models used for designing PV systems; in particular, assessments of ac energy production are more accurate. The performance model, along with additional parameters included in the inverter database, provides the information needed to ensure compatibility and optimum performance of arrays and inverters. The inverter model also makes it possible to monitor the long-term performance and aging characteristics of both inverters and systems with accuracy previously unavailable.

Coupling with Array Performance Model

PV array performance models such as that previously documented by Sandia [1], and also implemented in commercial PV system design software [3], can now be coupled with an accurate and well-validated inverter performance model. The combination provides a versatile tool for designing PV systems, studying sensitivity of ac-energy production to different module and inverter combinations, verifying inverter parameter limits are not exceeded, and ensuring optimum array utilization. In order to make best use of the inverter model and associated database of performance parameters, the PV array performance model must provide calculated values for array open-circuit voltage (V_{oc}), maximum-power voltage (V_{mp}), maximum-power current (I_{mp}), as well as maximum power (P_{mp}). The V_{mp} and P_{mp} values are used directly in the inverter performance model to determine ac-power production. By using hourly solar resource and weather data in the PV array performance model, several system design criteria can be evaluated. The calculated values for V_{oc}, V_{mp}, I_{mp}, and P_{mp} should be used to verify that the array V_{oc} does not exceed the inverter's maximum dc voltage (V_{dcmax}), the array I_{mp} does not exceed the inverter's maximum dc current (I_{dcmax}), and that the calculated P_{mp} rarely exceeds the inverter's peak dc power rating (P_{dco}).

As an example, Figure 16 illustrates an optimized system design for a 3.78-kW array of SunPower SPR210 modules (6 series by 3 parallel configuration) coupled with a Xantrex GT3.8 inverter, and optimized for highest performance in the solar resource and weather conditions in Alamosa, Colorado. Inverter efficiency is highest for dc voltages near the low MPPT limit and for array maximum power that only occasionally exceeds the inverter's upper dc-power limit, resulting in an overall annual system ac efficiency of 15.5%. However, most system designers would opt to design the system a little more conservatively (9 series by 2 parallel configuration), which raises the system voltage and gives more margin for wiring losses and long-term module performance degradation, as illustrated in Figure 17. The efficiency of the Xantrex GT3.8 inverter was relatively insensitive to the dc-voltage level, so the impact on the more conservative design on annual system efficiency was minor, dropping to 15.4%. The point of this discussion is that coupling an array performance model with the inverter performance model improves the ability to design and optimize PV systems based on annual ac energy production.

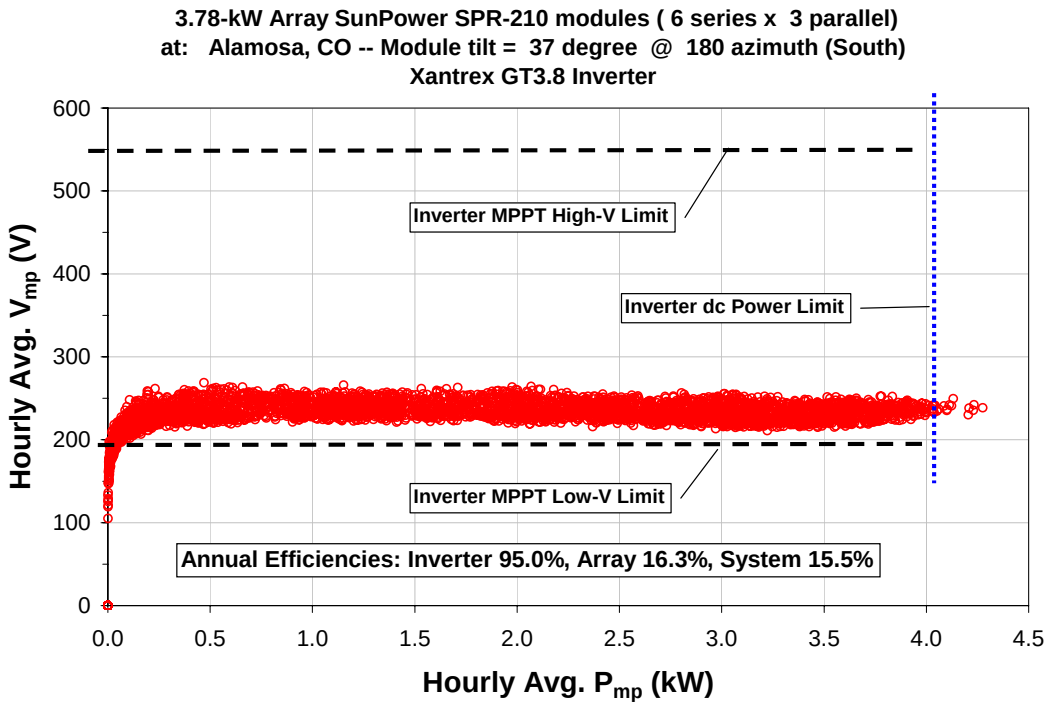

Figure 16. System annual performance analysis with combined array and inverter performance models, optimized for highest system efficiency.

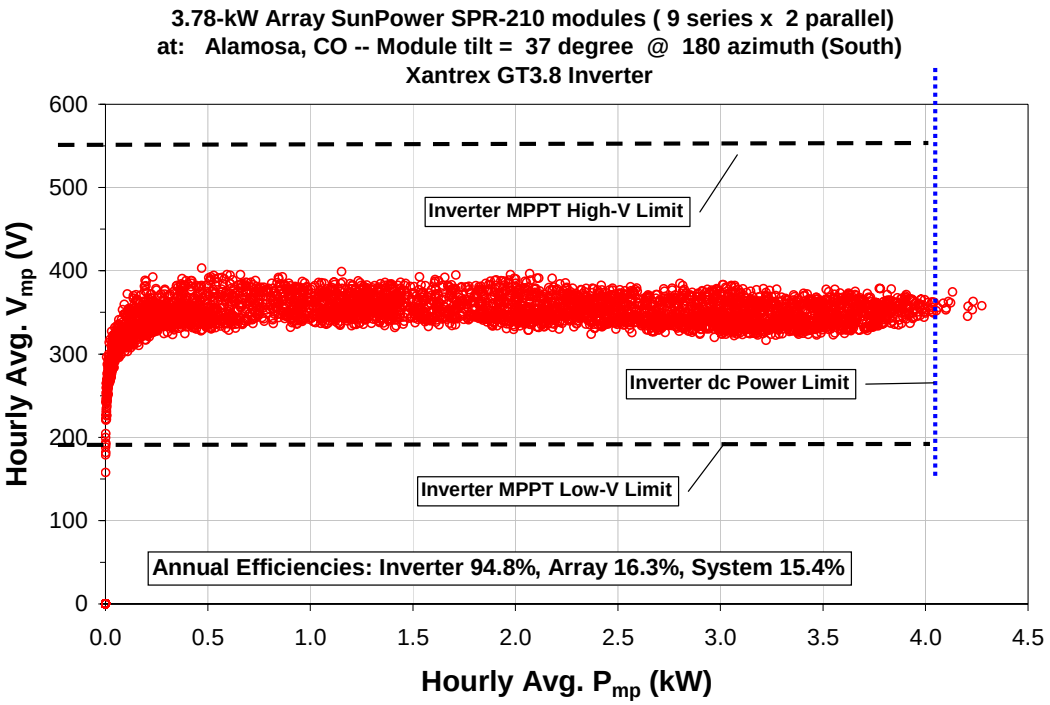

Figure 17. System annual performance analysis using array and inverter performance models, more conservative system design providing extra margin for degradation in array voltage.

Inverter Performance Monitoring

The inverter performance model provides a new opportunity for accurately monitoring the performance and health of the inverter, in real time. Inverter monitoring can be accomplished by using a data acquisition system providing periodic measurements of dc voltage and power, as well as true ac power. In real time, inverter efficiency can be calculated and compared to the inverter efficiency determined using the inverter performance model. Deviations between measured and calculated inverter efficiency would provide direct evidence of inverter malfunction or degradation in performance. It is likely, given experience, that the nature of the deviations would provide the diagnostic information needed to define required inverter maintenance.

Advanced inverter designs should have the inverter model incorporated in firmware, and should be equipped with accurate dc and ac power meters, as well as standardized communication protocol. These advanced features would provide direct inverter performance monitoring capability, help reduce the installation cost of PV systems, and facilitate expedient and cost-effective field maintenance. Conceivably the PV array performance model could also be incorporated in the inverter's firmware providing system monitoring and diagnostic functions for the entire system.

CONCLUSIONS

An empirically based inverter performance model has been developed and validated, using both field and laboratory measurements, for a variety of inverter sizes, designs, and manufacturers. The accuracy of the model, for inverters with stable and repeatable performance, has proven to be more than adequate for PV system performance modeling purposes. Based on well-controlled laboratory measurements, the standard error obtained between measured and modeled inverter efficiency was typically about 0.1%. The inverter model, particularly when coupled with an accurate array performance model, provides significant improvements in the ability to analyze PV system performance, monitor inverter and array performance, and diagnose causes of system performance degradation.

REFERENCES

[1] D. L. King, W. E. Boyson, and J. A. Kratochvil, *Photovoltaic Array Performance Model*, Sandia National Laboratories Report, SAND2004-3535, August 2004. http://www.sandia.gov/pv.

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APPENDIX: Inverter Parameter Database

The inverter parameter database provided below is a combination of performance parameters from manufacturers' specification sheets and experimental data measured at recognized testing laboratories, including field tests at Sandia. In each row, the source for the parameters displayed was provided, in some cases resulting in multiple entries for the same inverter type. Additional parameters of use to PV system designers, but not explicitly used in our performance model, were also included in the database. V_{dcmax} and I_{dcmax} are the upper limits for dc voltage and current as defined by the manufacturer. MPPT-Low and MPPT-High define the lower and upper voltage limits within which the inverter tracks the maximum-power point of the PV array. Acceptable ambient temperature extremes and the weight of the inverter are also provided.

Inverter Performance Parameter Database (U.S. Applications, 60 Hz)
Sandia National Laboratories
2/25/07

Manufacturer	ID	Source	ac Volts (V)	Vintage	Paco (Wac)	Pdco (Wdc)	Vdco (V)	Pso (Wdc)	Co (1/W)	C 1 (1/V)	C2 (1/V)	C3 (1/V)	Pnt (Wac)	Vdcmax	Idcmax (A)	MPPT Low (V)	MPPT High (V)	Tamb Low (C)	Tamb Max (C)	Weight (lb)
Fronius	IG2000	Spec	240	2006	2000	2100	300	7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.15	500	13.6	150	450	-20	50	26
Fronius	IG2500-LV	Spec	208	2006	2350	2489	300	7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.15	500	16.9	150	450	-20	50	26
Fronius	IG3000	CEC	240	2006	2700	2879	277	27.9	-1.009E-05	-1.367E-05	-3.587E-05	-3.421E-03	0.91	500	18	150	450	-20	50	26
Fronius	IG3000	Spec	240	2006	2700	2836	300	7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.15	500	18	150	450	-20	50	26
Fronius	IG4000	Spec	240	2006	4000	4201	300	15	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.15	500	26.1	150	450	-20	50	42
Fronius	IG4500-LV	Spec	208	2006	4500	4767	300	15	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.15	500	29.3	150	450	-20	50	42
Fronius	IG5100	Spec	240	2006	5100	5357	300	15	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.15	500	33.2	150	450	-20	50	42
PV Powered	PVP1800	Spec	120	2005	1800	1945	210	20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	360	15	120	360	-20	40	
PV Powered	PVP2800	Spec	240	2005	2800	2950	295	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	450	15	200	390	-20	40	74
PV Powered	PVP2800	Spec	208	2005	2800	2920	285	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	450	15	180	390	-20	40	74
PV Powered	PVP2000	Spec	120	2006	2000	2150	250	20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	500	15	135	360	-20	40	76
PV Powered	PVP2900	Spec	208	2006	2900	3085	350	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	500	15	205	500	-20	40	89
PV Powered	PVP3200	CEC	240	2006	3200	3348	274	53.8	-1.039E-05	8.495E-05	3.373E-03	-2.205E-04	3	500	15	230	450	-20	40	89
PV Powered	PVP3200	Spec	240	2006	3200	3385	365	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	500	15	230	450	-20	40	89
PV Powered	PVP2500	Spec	240	2006	2500	2645	295	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	500	20	140	450	-20	40	70
PV Powered	PVP3500	Spec	240	2006	3500	3665	325	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	500	18	200	450	-20	40	85
SMA	1800U	Spec	120	2005	1800	1915	270	15	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0	400	12.6	139	400	-25	60	
SMA	2500U	SNL	240	2005	2400	2625	380	19.6	-1.471E-05	0.000E+00	0.000E+00	0.000E+00	0.25	600	12	250	550	-25	60	65
SMA	2500U	CEC	240	2006	2500	2694	302	20.7	-1.545E-05	6.525E-05	2.836E-03	-3.058E-04	0.32	600	12	250	550	-25	60	65
SMA	2500U	Spec	240	2005	2500	2660	375	7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.25	600	12	250	550	-25	60	65
SMA	2500U	Spec	208	2005	2100	2234	375	7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.25	600	12	225	550	-25	60	65
SMA	3800U	Spec	240	2006	3800	4021	300	7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.1	500	20	200	400	-25	45	85
SMA	3800U	Spec	208	2006	3500	3704	290	7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.1	500	20	180	400	-25	45	85
Solectria	PVI1800	Spec	240	2005	1800	1935	235	20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1	400	11	125	350	-20	60	34
Solectria	PVI1800	Spec	208	2005	1800	1935	235	20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1	400	11	125	350	-20	60	34
Solectria	PVI2500	SNL	240	2005	2500	2701	260	30.0	-1.143E-05	0.000E+00	0.000E+00	0.000E+00	0.32	400	15	125	350	-20	60	36
Solectria	PVI2500	CEC	240	2005	2500	2695	289	27.2	-1.417E-05	-1.214E-04	-8.706E-04	-2.682E-03	0.32	400	15	125	350	-20	60	36
Solectria	PVI2500	Spec	240	2005	2500	2688	235	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.32	400	15	125	350	-20	60	36
Solectria	PVI2500	Spec	208	2005	2500	2688	235	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.32	400	15	125	350	-20	60	36
SunPower	SPR2000	Spec	120	2006	2000	2116	225	20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	450	15	135	320	-20	40	76
SunPower	SPR2900	Spec	208	2006	2900	3021	320	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	500	15	205	430	-20	40	89
SunPower	SPR3200	Spec	240	2006	3200	3333	330	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3	500	15	230	430	-20	40	89
Xantrex	GT2.5	Spec	240	2006	2500	2660	370	20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1	600	15	195	550	-25	65	49
Xantrex	GT3.0	Spec	240	2006	3000	3175	370	20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1	600	20	195	550	-25	65	49
Xantrex	GT3.3	Spec	240	2006	3300	3492	370	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1	600	20	195	550	-25	65	49
Xantrex	GT3.3	Spec	208	2006	3300	3510	370	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1	600	25	195	550	-25	65	49
Xantrex	GT3.8	CEC	240	2006	3800	4022	266	24.1	-8.425E-06	8.590E-06	7.760E-04	-5.278E-04	1	600	20	195	550	-25	65	49
Xantrex	GT3.8	Spec	240	2006	3800	4000	370	30	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1	600	20	195	550	-25	65	49
Xantrex	PV10	Spec	208	2006	10000	10989	465	100	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5	600	31.9	330	600	-20	50	115
Xantrex	PV15	Spec	208	2006	15000	16393	465	150	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5	600	47.8	330	600	-20	50	160
Xantrex	PV20	Spec	208	2006	20000	21739	465	200	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5	600	63.8	330	600	-20	50	160
Xantrex	PV30	Spec	208	2006	30000	32609	465	300	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5	600	100	330	600	-20	50	260
Xantrex	PV45	Spec	208	2006	45000	48780	465	450	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5	600	150	330	600	-20	50	260
Xantrex	PV100S	Spec	208	2006	100000	105820	450	1000	0.000E+00	0.000E+00	0.000E+00	0.000E+00	100	600	357	300	600	-20	50	1000
Xantrex	PV100S	Spec	480	2006	100000	105263	450	1000	0.000E+00	0.000E+00	0.000E+00	0.000E+00	96	600	357	300	600	-20	50	1000
Xantrex	PV225S	Spec	480	2006	225000	238095	450	2000	0.000E+00	0.000E+00	0.000E+00	0.000E+00	107	600	781	300	600	-20	50	2300
Xantrex	PV225S	CEC	480	2006	225000	237500	345	2336	-1.074E-04	7.175E-05	1.387E-03	1.513E-03	107	600	781	300	600	-20	50	2300

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Germany

1 RWE SCHOTT Solar, Inc.
Attn: Mark D. Rosenblum
4 Suburban Park Drive
Billerica, MA 01821

1 AIST
Attn: Hitoshi Kawanami
Tsukuba, Ibaraki 305-8568, JAPAN
Central 2, Umezono 1-1-1
Tsukuba, 305-8568
Japan

1 Crystal Systems, Inc.
Attn: Chandra Khattak
27 Congress Street
Salem, MA 01970

3 Powerlight Corporation
Attn: Adrianne Kimber
Greg Ball
Brian Farhi
2954 San Pablo Ave.
Berkeley, CA 94702

3 Fraunhofer ISE
Attn: Daniel Kray
Wilhelm Warta
Michael Koehl
Heidenhofstr. 2
Freiburg, D-79110
Germany

1 GE-GRC
Attn: Victor Lou
1 Research Circle
Schenectady, NY 12309

3 Shell Solar
Attn: Lisa Mandrell
Paul Norum
Steve Voss
4650 Adohr Lane
Camarillo, CA 93011

2 GE CRD
Attn: Venkatesan Manivannan
Charles Korman
1 Research Circle
Niskayuna, NY 12309

1 U.S. Department of Energy
Attn: Jeffrey Mazer
1000 Independence Ave. SW
Washington, DC 20585

2 GT Solar Technologies
Attn: John Minnucci
Heiko Moritz
243 Daniel Webster Highway
Merrimack, NH 03054

3 Motech Industries INC.
Attn: Yu-Pan Pai
Ching Yao Tang
Simon Tsuo
Tainan Science-Based Industrial Park
No. 3 Da-Shun 9th Road, Hsin-Shi,
Tainan, 74145
Taiwan

2 Georgia Tech/UCEP
Attn: Ajeet Rohatgi
Brian Rounsaville
777 Atlantic Drive, Room 119
Atlanta, GA 30332-0250

1 SRI International
Attn: Angel Sanjurjo
333 Ravenswood Avenue
Menlo Park, CA 94025

1 Ferro Corporation
Attn: Aziz Shaikh
1395 Aspen Way
Vista, CA 92081

1 HMP Associates, Inc.
Attn: Stephen Shea
89 Oakview Drive
Waynesville, NC 28786

3 SunPower Corp
Attn: Bill Mulligan
Brian Farhi
Gabriella Bunea
3939 North First Street
San Jose, CA 95134

1 BP Solar
Attn: Nathan Stoddard
995 Heritage Drive
Gettysburg, PA 17325

1 GE Energy
Attn: Oleg Sulima
231 Lake Drive
Newark, DE 19702

1 Photon International
Attn: Michael Schmela
Solar Verlag GmbH
Julicher Strasse 376
52070 Aachen
Germany

2 Konarka Technologies, Inc.
Attn: Keith Brooks
Steve Wicks
116 John Street
Suite 12, 3rd Floor
Lowell, MA 01852

1 Energy Systems Lab, Room 214
Wisenbaker Engineering Reseach Center
Bizzell Street
3581 TAMU
Texas A&M University
Attn: Michael Davis
College Station, TX 77843-3481

4 Florida State Energy Center
Attn: Neelkanth Dhere
Bob Reedy
Gobind Atmaram
Kevin Lynn
1679 Clearlake Road
Cocoa, FL 32922-5703

1 United Solar Ovonic
Attn: Subhendu Guha
3800 Lapeer Road
Auburn Hills, MI 48326

1 The Rowan Tree Farm
Attn: Bob Hammond
1015 N. Dade 181
Dadeville, MO 65635-8136

2 Arizona Public Service
Attn: John Weidner
Herb Hayden
1500 E. University Drive
Tempe, AZ 85281

1 EPV
Attn: Kai Jansen
8 Marlen Drive
Robbinsville, NJ 08691

2 Arizona State University
Attn: William Shisler
Mani Tamizhmani
P.O. Box 875806
Tempe, AZ 85287-5806

1 Global Solar Energy
Attn: Eric Kanto
5575 S. Houghton Road
Tuscon, AZ 85747

1 ISET
Attn: Vijay Kapur
20600 Plummer Street
Chatsworth, CA 91311

2 SWTDI
New Mexico State University
Attn: Andy Rosenthal
John Wiles
Box 30001
MSC 3SOLAR
Las Cruces, NM 88003-8001

1 Iowa Thin Film Technologies
Attn: Brad Scandrett
2337 230th Street
Boone, IA 50036

2 Sacred Power Corporation
Attn: Odes Armijo-Caster
Jay Benze
2401 12th Street NW
Suite 204
Albuquerque, NM 87104-2302

2 Alpha Technologies Ltd.
Attn: Ezra Auberbach
Don Davidson
4084 McConnell Court
Burnaby, BC V5A 3N7
Canada

1 SmartSpark Energy Systems
Attn: Robert Balog
60 E. Hazelwood Drive
Champaign, IL 61820

3 Transistor Devices, Inc
Attn: Cliff Furcall
Greg Laufman
Yuriy Kats
36 Newburgh Road
Hackettstown, NJ 07840

2 United Technologies Research Center
Attn: Vlado Blasko
Suzanne Woll
411 Silver Lane MS 129-85
East Hartford, CT 06108

3 SatCon
Attn: Leo Casey
Richard Michaud
Janos Rajda
27 Drydock Avenue
Boston, MA 02210

1 Solectria Renewables
Attn: James Worden
360 Merrimack Street
Bldg. 9, Floor2
Lawrence, MA 01843

1 Heliotronics
Attn: Clayton Handleman
1083 Main Street
Hingham, MA 02043

1 PV Powered
Attn: Bill Taylor
160 SW Scalehouse Loop #208
Bend, OR 97702

1 SMA America
Attn: John Berdner
12438 Loma Rica Dr., Unit C
Grass Valley, CA 95945

1 SolarOne Solutions
Attn: Moneer Azzam
51 Marble Street
Framingham, MA 01702-7021

2 Underwriter's Laboratories
Attn: Liang Ji
Tim Zgonena
333 Pfingsten Road
Northbrook, IL 60062-2096

2 SunEdison
Attn: James Marshall
Steve Hester
5013 Robers Ave. Suite B
McClellan, CA 95652

1 Sanyo Energy Corp (USA)
Attn: Ben Collinwood
2055 Sanyo Avenue
San Diego, CA 92154-6297

1 GreenRay, Inc.
Attn: Miles Russell
96 Lexington Road
Lincoln, MA 01773

1 ESTI
CEC Joint Research Centre
Attn: Wim Zaiiman
21020 ISPRA (Varese)
Italy

1 EPRI
Attn: Tom Key
942 Corridor Park Blvd
Knoxville, TN 37932

1 Spring Ventures, Inc.
Attn: Mark Bauhaus
55 S. State Avenue
Indianapolis, IN 46201

8 U.S. Department of Energy
Solar Energy Technologies Program
Forrestal Building
Attn: Craig Cornelius
Dan Ton
Kevin Lynn
Scott Stephens
Richard King
Tommy Rueckert
Marie Mapes
Jeff Mazer
1000 Independence Ave. SW
Washington, DC 20585

1 Tucson Electric Power
Attn: Bill Henry
P.O. Box 711
Tucson, AZ 85702-0711

1 Arkansas Power Electronic
International
Attn: Marcelo Schupach
535 W. Research Center Blvd.
Fayetteville, AR 72701

6 McNeil Technologies
Attn: Euniesha Davis
Kevin Degroat
Mamatha Gowda
Lumas Kendrick
Conrad Mulligan
Leslie Thompson
6564 Loisdale Court
Springfield, VA 22150

1 Danfoss Silicon Power
Attn: Roger Cooper
North American Sales Bureau, 3
714 Andrea Lane
Rowlett, TX 75088

1 MIASOLE
Attn: Steve Croft
Shawn Everson
2590 Walsh Avenue
Santa Clara, CA 95051

2 Kyocera Solar, Inc.
Attn: James Egan
Steve Allen
7812 East Acoma Drive
Scottsdale, AZ 85260-6987

3 Airpax Dimensions, Inc.
Attn: Stefan Gabrielson
Mike Olsen
Arden Olson
807 Woods Road
Cambridge, MD 21613

3 SolarEnigma, Inc.
Attn: Andrew Foss
Miguel Gomez
Jim Hendon
3350 Thomas Road
Santa Clara, CA 95054

1 WME Tech
Attn: Bill Evarts
4703 Club View Drive
Westlake Village, CA 91362

2 EMCORE
Attn: Alan Gorenz
John Syverson
10420 Research Road SE
Albuquerque, NM 87123

1 APC – MGE
Attn: Lance Haines
Michael Schenck
85 Rangeway Road, Bldg. 2
North Billerica, MA 01862

1 Magnetek - Alternative Energy Division
Attn: Mark Haug
N50 W13605 Overview Drive
Menomonee Falls, WI 53051

1 Southern California Edison
Attn: Stephanie Hamilton
P.O. Box 800
Rosemead, CA 91770

1 Princeton Power Systems, Inc.
Attn: Darren Hammell
501 Forrestal Road
Princeton, NJ 08540

1 ConSol
Attn: Robert Hammon
7407 Tam O'Shanter Drive
Stockton, CA 95210-3370

1 North Carolina State University
Attn: Alex Huang
Campus Box 7571, NCSU-ECE-SPEC
Raleigh, NC 27695-7571

1 Exeltech
Attn: Barry Jason
7317 Jack Newell Blvd. North
Fort Worth, TX 76118-7100

2 Public Service Company of NM
Attn: Robert Broderick
Patrick Scharff
Alvarado Square MS – 0604
Albuquerque, NM 87158

2 Larankelo, Inc.
Attn: Dr. Rajan Kapur
Robert Rotzoll
422 E. Vermijo Ave. Ste. 402
Colorado Springs, CO 80903

2 Natural Resources Canada
Attn: Fred Katiraei
Dave Turcotte
CANMET Energy Technology Centre –Varennes
1615 Lionel-Boulet, C.P. 4800
Varennes, QC J3X 1S6 Canada

1 Coal Creek Design
Attn: Greg Kern
442 South 112th Street
Lafayette, CO 80026-9033

1 Xcel Energy
Attn: Frank Novachek
414 Nicollet Mall
Minneapolis, MN 55401-1993

2 EPRI, Galvin Perfect Power Initiative
Attn: Kurt Yeager
Frank Goodman
P.O. Box 10412
Palo Alto, CA 94303

1 Fronius International GmbH
Attn: Christoph Panhuber
Günter Fronius Str.1
4600 Wels-Thalheim
Austria

1 SRP - Generation Engineering
Attn: James Suell
1521 N. Project Drive
Tempe, AZ 85281-1298

1 Solar Electric Power Association
Attn: Mike Taylor
1341 Connecticut Ave. NW, Suite 3.2
Washington, DC 20036

2 Xantrex Technology, Inc.
Attn: Rick West
Chris Thompson
3547-C South Higuera St.
San Luis Obispo, CA 93401

1 Oak Ridge National Laboratory
Attn: Gui-Jia Su
P.O. Box 2088
Oak Ridge, TN 37831

1 Digite, Inc.
Attn: Suhas Patil
82 Pioneer Way, Suite 102
Mountain View, CA 94041

1 DuPont PV Solutions
Attn: Stanley Merritt
Barley Mill Plaza 26, Room 2270
Route 141 & Lancaster Ave.
Wilmington, DE 19805

2 Department of Energy
Attn: Lew Pratsch
Dan Ton
EA-2A
1000 Independence Ave. SE
Washington, DC 20585

1 South Dakota State University
Attn: Michael Ropp, Associate Professor of Electrical Engineering
Brookings, SD 57007

1 Xalyo Communications
Attn: Carlos Treves
1527 McDaniel Ave.
San Jose, CA 95126

1 Grid Point
Attn: Brian Golden
2020 K Street NW, Suite 550
Washington, DC 20006

1 Advanced Energy Conversion
Attn: David Torrey
Suite 500
10 Hermes Road
Malta, NY 12020

1 American Superconductor Corporation
Power Systems
Attn: Perry Schugart
8401 Murphy Drive
Middleton, NJ 53562-2550

1 CPES, Virginia Tech
Attn: Ming Xu
302 Whittemore (0111)
Virginia Tech
Blacksburg, VA 24061

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