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Performance Model for Characterizing AC Modules and Predicting Their Power

Daniel Riley

Sandia National Laboratories, Albuquerque, NM, 87185, USA

***Abstract* — PV modules and their inverting electronics are becoming increasingly more integrated. When a PV module and microinverter are completely integrated a new class of PV system, the AC module, is created. Unfortunately, existing characterization and modeling techniques require separate characterization of PV and inverting components. Thus, existing methods are incapable of modeling AC modules. We have developed an empirical performance model capable of characterizing and modeling an AC module. The model is capable of predicting the active power from an AC module in a typical application with RMSE of approximately 1% of the reference power of the AC module. This paper describes the model form and presents the validation results in terms of model residuals.**

***Index Terms* — solar energy, photovoltaic systems, power electronics.**

I. INTRODUCTION

Over the past 4 years, the use of microinverters in residential and commercial PV systems has increased dramatically [1, 2] due to the myriad benefits which microinverters can provide in smaller, space-constrained systems. As the solar industry seeks to reduce the cost of system installation, manufacturers are increasingly attempting to fully integrate microinverters with PV modules, creating an AC module [3]. To date, PV system models, which predict active AC power out of a PV system when given environmental inputs, sequentially exercise a model of the PV panel and a separate model of the inverter/microinverter. However, as PV modules and microinverters are integrated into a single device, modelers lose the ability to characterize and model each component separately. Therefore, a model and characterization method must be developed for describing the performance of fully integrated AC modules.

Sandia National Laboratories Photovoltaics and Distributed Systems Department has developed a series of test procedures and analysis capabilities to characterize the performance of a fully-integrated AC module. The AC module performance model predicts the active AC power produced by an AC module as a function of cell temperature and incident solar irradiance. The model is an empirical model, and therefore requires testing of the AC module in order to develop the model parameters.

Once an AC module is characterized by the AC module performance model, it is possible to estimate the energy which the module may generate under a series of provided weather conditions. The predicted energy or other performance metrics estimated by the model may be compared with the performance of other modeled AC modules. Furthermore, the measured power of an AC module (or system of AC modules) may be compared against the active power estimated by the performance model in order to determine anomalous operation (e.g. module failure, shading). We also believe that the performance model may serve as a basis for generating a performance rating standard for AC modules.

The test processes necessary for characterization have been briefly described in [4] and fully described in [5]. Therefore, the test processes will not be covered in this paper. Here we present the model form and show the results of model validation against measured system data. Also, determination of model coefficients from test data is a lengthy process and therefore must be presented in other publications such as [5].

II. DESCRIPTION OF THE AC MODULE MODEL

A. Model Description

As shown in Fig. 1, the active AC power output of an AC module shows an abrupt change in performance of an AC module due to nonlinearities in the microinverter output as a function of its input power.

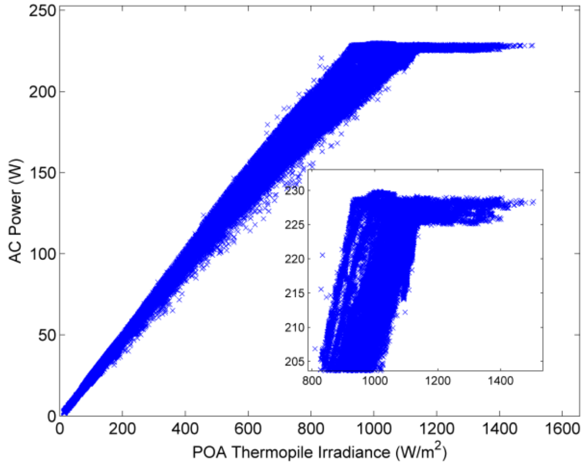

Fig. 1. Active AC power from an AC module as a function of plane-of-array irradiance. Inset: a close view of the inverter's self-limiting.

From Fig. 1, it is clear that the AC module has at least two different states of operation. One state in which increasing irradiance and changes in other environmental factors are causing changes in the active AC power output, and another state where the inverter is self-limiting its power output (and input) in order to protect the electronics. However, Fig. 1 does not show the output of the AC module under zero irradiance conditions (i.e. night), when the module consumes a very small amount of power; in this case approximately 0.8 watts. The extremely low irradiance conditions create a third state. Thus, the AC module performance model takes the form of a piecewise function with three sub-domains where each sub-domain represents an operating state of the embedded microinverter. These states are graphically shown in Fig. 2, and the equation governing the piecewise function of the power at each state is provided in (1).

When the maximum power point of the PV module has reached or exceeded the maximum output power of the integrated microinverter, the microinverter will self-limit (also known as "clipping") and the model predicts that the AC module is limited to a maximum power of P_2.

When the maximum power point of the PV module is less than the power required for the microinverter to produce power, the model predicts that the AC module consumes power of P_3, which is the minimum power output of the AC module.

When the AC module is operating between these two extremes its output power is affected by changes in module temperature, irradiance, spectral conditions, and incident angle. This state, denoted by power P_1, is the primary focus of the AC module performance model.

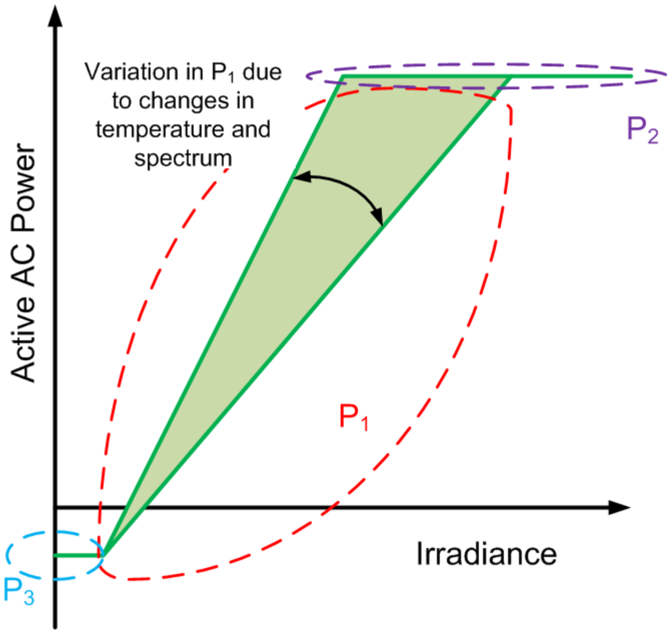

Fig. 2. Three operating states of the AC module microinverter and corresponding model operating states.

$$P_{AC} = \begin{cases} P_1 & P_3 \le P_1 \le P_2 \\ P_2 & P_1 > P_2 \\ P_3 & P_1 < P_3 \end{cases} \qquad (1)$$

P_2 and P_3 are relatively straightforward to determine:

$$P_2 = P_{AC,max} \qquad (2)$$

$$P_3 = -1 \times P_{NT} \qquad (3)$$

Where $P_{AC,max}$ is the maximum power output of the microinverter (in watts), generally a constant value which may be obtained by specification sheet or (preferably) empirical testing, and P_{NT} is the night tare losses (in watts) of the microinverter, also generally a constant value which may be obtained from the specification sheet or empirical testing. Equations 2 and 3 assume that both P_2 and P_3 are constant values; however, they may be changed to functions of other inputs (e.g. temperature, AC voltage) if desired. When operating at power levels P_2 and P_3 the model is extremely simple and accurate.

P_1 represents a much more complex operating state of the AC module, where changes in environment (e.g. irradiance, temperature, spectrum) affect changes in the output power. We have designed the model for state P_1 as a reference power, Pac_{ref}, and several normalized scaling factors which modify the reference power based upon the operating environment of the module. This equation is given in (4). The environmental factors are:

- Difference between the observed airmass (AMa) and a reference airmass (AMa_{ref})
- Ratio between the absorbed plane of array irradiance (E_{POA}) and a reference absorbed irradiance (E_{ref})
- Difference between the observed (or modeled) cell temperature (T_c) and a reference cell temperature (T_0)

$$P_1 = Pac_{ref} \times f_1\left(AMa - AMa_{ref}\right) \times \left[C_0 \times \frac{E_{POA}}{E_{ref}} + C_1 \times \ln\left(\frac{E_{POA}}{E_{ref}}\right)\right] \times \left[1 + \gamma_{ac}(T_c - T_0)\right] \qquad (4)$$

The model parameters are Pac_{ref}, AMa_{ref}, E_{ref}, T_0, the AC power temperature coefficient (γ_{ac}), two empirical coefficients for describing power output as a function of $\frac{E_{POA}}{E_{ref}}$ and the natural logarithm of $\frac{E_{POA}}{E_{ref}}$ (C_0 and C_1, respectively), coefficients of f_1 which is a third order polynomial with coefficients 1, A_1, A_2, and A_3. We also employ an incident angle loss model as described by Martin and Ruiz in [6], introducing model parameter a_r. Lastly, if a model is required to estimate cell temperature from ambient temperature, irradiance, and wind speed we use the model provided in equation 11 and 12 of [7], thus introducing the parameters a, b, and ΔT.

We previously determined that the temperature of the microinverter is unlikely to cause large variations in the power output of the AC module system, thus the microinverter temperature is omitted from the model [8].

The model parameters are derived from data collected during a series of test processes. The tests are conducted on a two axis solar tracker to isolate the effects of temperature, spectrum, and incident angle on AC module performance. The test processes and analysis techniques are not presented here due to length, but can be found in [5].

B. Model Modularity and Sub-Models

As noted, the primary function for P_1 is a reference power with a series of normalized scaling factors. The normalized scaling factors create a relatively modular model which can be improved easily by modifying the underlying sub-models. For example, we have used a simple third order polynomial to describe the effect of absolute airmass on the active AC power out of the system. However, we realize that absolute airmass is merely a simple proxy for spectrum. If a more detailed spectral model is desired, the scaling factor for the airmass model may be replaced by a scaling factor for the more detailed spectral model. Likewise, if a different cell-temperature calculation is desired, it may be implemented rather than the model given in [7] that is used for the analyses presented here.

III. EVALUATING THE ACCURACY OF THE MODEL

The proposed model is evaluated here in two ways, first by examining the ability of the model to reproduce the test data which were used to generate the model parameters, and second by examining the accuracy of the model in predicting the power of an AC module during common operations and using data which were not used to generate model parameters. The first evaluation is not validation of the model, but rather serves to show how well the model form can describe the AC module under ideal conditions. The second evaluation is a validation of the entire model, demonstrating how well the model predicts AC module performance under real-world conditions including variations in incident angle.

A. Model Accuracy on Coefficient-Generation Data set

In order to develop the AC module model, we tested four different AC modules with varying types of PV modules and microinverters. The test data allowed for generation of model parameters for each module. We compare the modeled AC power with the AC power from the electrical performance test data which were used to generate the parameters. The data from the electrical performance test represent the power produced by each AC module under a range of temperature, irradiance, spectral conditions, and a solar angle of incidence (AOI) of 0°. This comparison simply shows how well the model form can describe the performance data used to generate the model parameters.

The difference between the modeled power and the measured power for each module is expressed in Table 1 as both the mean bias error (MBE, positive values indicate the model over-predicted the power) and the root mean square error (RMSE). Table I provides the MBE and RMSE in the units of power (watts) and as a percentage of Pac_{ref}; the latter allows for a simpler comparison between modules of different power ratings. The data in Table I reflect only daytime data when the sun was above 6 degrees in solar elevation to avoid likely shading periods.

TABLE I

ERROR STATISTICS ON COEFFICIENT-GENERATION DATA

	MBE (watts)	MBE (% of Pac_{ref})	RMSE (watts)	RMSE (% of Pac_{ref})
Module 1	0.1213	0.0507	2.2287	0.9321
Module 2	0.0739	0.0419	2.1578	1.2230
Module 3	0.0572	0.0228	2.5448	1.0142
Module 4	0.1075	0.0421	2.5000	0.9801

Histograms of the model errors for each AC module, as a percent of Pac_{ref}, are shown in Fig. 3. The histograms show that for data within the parameter generation data set, the model is generally within ±2% of the measured data and produces errors with a mean value near 0. The good agreement of the model with the model-generation data set merely indicates that the model is not ill-formed.

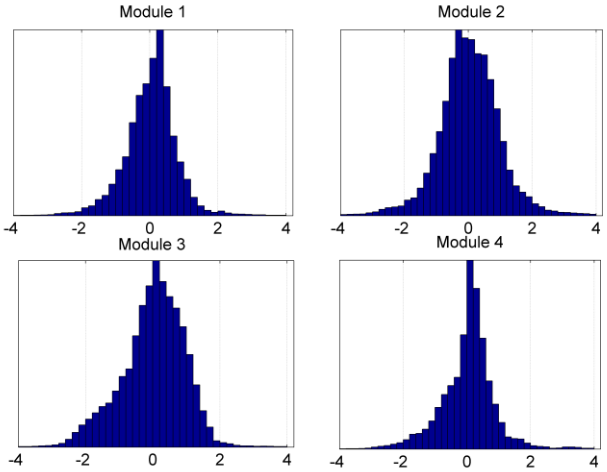

Fig. 3. Histograms of model errors as a percent of Pac_{ref} for four AC modules

B. Model Validation on Fixed-Tilt AC Modules

While the study of model accuracy against the coefficient generation data shows the ability of the model form to account for some environmental changes (e.g. spectrum, temperature, irradiance), a true validation of the model requires evaluation of model predictions against the measured performance of an

AC module in a typical operating environment such as a fixed-tilt PV system. For this validation, we mounted Module 3 at a fixed latitude-tilt in Albuquerque, NM for approximately 9 days while measuring the active AC power, average module temperature, and incident irradiance. The model coefficients derived from prior testing were used to model the performance of the AC module with varying solar AOI, spectrum, and irradiance.

The measured power and modeled power from a cold windy day are shown in Fig. 4, which shows that the model correctly transitions to the inverter self-limiting condition and appears to provide good accuracy during the clear and cloudy portions of a partly-cloudy day. Near the end of the day, the AC module was shaded by nearby buildings while the reference irradiance sensor was not shaded; these data have been noted in Fig. 4, and omitted from subsequent analyses.

A plot of the measured and modeled power for Module 5 in a fixed-tilt rack over 9 days is provided in Fig. 5 with a 1:1 line to show optimal model performance. From Fig. 5, it is possible to see that the model tends to over-predict at low power levels, but performs well at the middle and upper range for the system power.

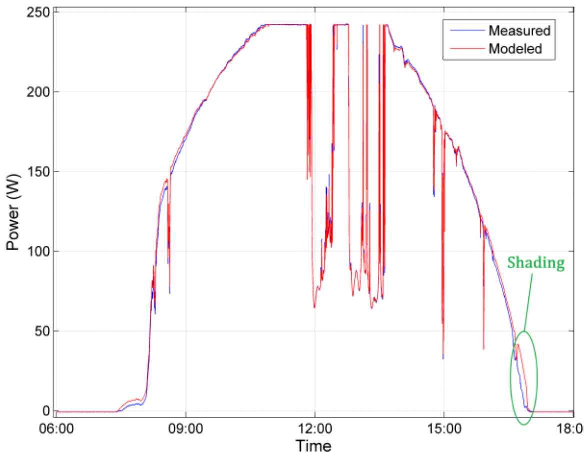

Fig. 4. Measured and modeled power from a fixed-tilt AC module on a cold, breezy, partly-cloudy day

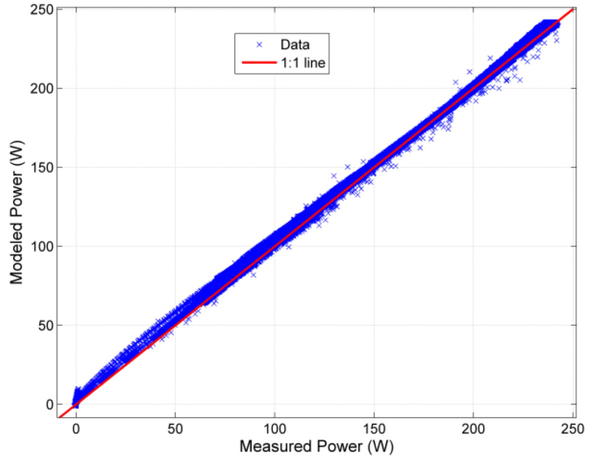

Fig. 5. Measured and modeled power from a fixed-tilt AC module over 9 days

The MBE and RMBE of the model over the 9 day period are given in Table II. The daytime data is, of course, the most useful in determining the accuracy of the model, but we have also provided error values for nighttime periods to show the model's capability in predicting power consumption at night.

TABLE II

ERROR STATISTICS ON FIXED-TILT DATA FROM MODULE 3

	MBE (watts)	MBE (% of Pac_{ref})	RMSE (watts)	RMSE (% of Pac_{ref})
Daytime data only	1.700	0.6776	2.484	0.9903
Day & Night	0.648	0.2584	1.688	0.6729

Fig. 6 shows a histogram of the model errors over the course of 9 days for the fixed-tilt AC module. Compared to model residuals for Module 3 in Fig. 3, the residual distribution for fixed-tilt data maintains a width of approximately 4% of Pac_{ref}, however, the residuals are positively biased by 0.7%. The positive bias indicates that the model over predicted the power of the AC module during this evaluation period. Over the course of the 9 day period, the module produced 14.377 kWh of energy, and the model predicted that the module would produce 14.584 kWh.

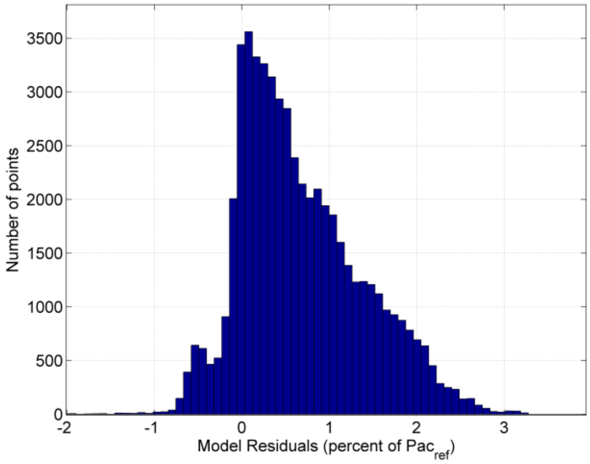

Fig. 6. Histogram of model errors as a percent of Pac_{ref} over 9 days for a fixed-tilt AC module, daytime data only

IV. CONCLUSIONS

Sandia has developed an empirical performance model for describing the performance of AC modules as a function of various environmental conditions. The model allows for characterization of AC modules as an integrated unit, without separate characterizations of the PV module and the microinverter. This is important since separate characterizations are difficult or impossible as modules and microinverters become more integrated into full AC module products.

The model may be used for the same purposes any PV system performance model, which may include system comparisons, energy prediction, or PV system health monitoring. We also note that, to date, there is no performance rating standard for AC modules. Such a performance model highlights the difficulty in generating a standard performance condition for AC modules, and may serve as the basis for development of such a standard in the future.

In Sandia's validation testing, the AC module performance model is capable of predicting the power from an AC module with an RMSE of 0.99% and an MBE of 0.68% of the reference power. However, the validation testing was only performed on a small set of modules in one location. An expansion of the validation efforts are required to show that the performance model performs well for a wider range of AC modules in a number of locations. Furthermore, it must be shown that the testing and analysis procedures produce similar model parameters when conducted by different labs under different climatic conditions.

V. ACKNOWLEDGEMENTS

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REFERENCES

[1] M. Munsell, (2014, Dec. 12). *It's Solar Balance-of-System Innovation That Will Drive Cost Reduction*. Retrieved from http://www.greentechmedia.com/articles/read/Its-Solar-Balance-of-System-Innovation-That-Will-Drive-Cost-Reduction.

[2] M. Munsell, (2014, Oct. 9). *Who Leads the US Residential Inverter Market?*. Retrieved from http://www.greentechmedia.com/articles/read/who-is-leading-the-u.s.-residential-inverter-market.

[3] E. Wesoff, (2014, Nov. 10). *Updated: SunPower Buys VC-Funded Microinverter Startup SolarBridge*. Retrieved from http://www.greentechmedia.com/articles/read/Breaking-SunPower-Buys-VC-Funded-Microinverter-Startup-SolarBridge.

[4] D. Riley, et. al. "Testing and Characterization of PV Modules with Integrated Microinverters," in *39th IEEE Photovoltaic Specialist Conference, 2013*.

[5] D. Riley, C. Hansen, M. Farr, "A Performance Model for Photovoltaic Modules with Integrated Microinverters". SAND2015-0179.

[6] N. Martin and J. Ruiz. "Calculation of the PV Modules Angular Losses Under Field Conditions by Means of an Analytical Model" *Solar Energy* vol. 70, pp. 25-38, 2001.

[7] D. King, W. Boyson, and J. Kratochvil, "Photovoltaic Array Performance Model". SAND2004-3535

[8] D. Riley and A. Fresquez. "Determining the Effect of Temperature on Microinverter Inversion Efficiency," in *40th IEEE Photovoltaic Specialist Conference, 2014.*