Characterizing and Modeling AC PV Modules

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AC Module Definition

• An AC photovoltaic module is created when a PV module and a microinverter are fully integrated
  • AC power is generated when exposed to sunlight
  • No access to the DC circuit

• AC modules provide benefits
  • Reduced installation time
  • Design flexibility and shade tolerance
  • Lower DC voltages
AC Module Difficulties

- Describing AC module performance is difficult
- No standard rating definition
- Performance metrics on spec sheets are not consistent across manufacturer
- Performance metrics on spec sheets unhelpful
- How are I-V curves or I_{MP} and V_{MP} helpful when talking about an AC module?

<table>
<thead>
<tr>
<th>Temperature Coefficients (DC)</th>
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<tbody>
<tr>
<td>NOCT</td>
</tr>
<tr>
<td>Pmpp</td>
</tr>
<tr>
<td>Voc</td>
</tr>
<tr>
<td>Isc</td>
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<table>
<thead>
<tr>
<th>Rated Voltage</th>
<th>V_{mpp}</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>40.5 V</td>
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<table>
<thead>
<tr>
<th>Rated Current</th>
<th>I_{mpp}</th>
</tr>
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<td></td>
<td>5.93 A</td>
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</table>
The Question for AC Modules

• How do we compare or describe the performance of AC modules?
Sandia National Laboratories historical work

• In 2014 Sandia National Laboratories
  • Developed AC Module characterization tests
  • Developed a performance model for AC Modules
  • Evaluated the characterization techniques and performance model on 4 AC Modules

• Funded by the United States Department of Energy, Solar Energy Technologies Office
Typical PV System

Weather data (irradiance, temperature, etc.)

Irradiance translation and/or decomposition model

In-plane irradiance, module temperature, spectrum

PV module model

DC power, voltage

Inverter model

Active AC power

AC Module System

Weather data (irradiance, temperature, etc.)

Irradiance translation and/or decomposition model

Erbs, DISC, HDKR, Perez

Sandia Array Performance Model

Single diode models

Sandia Inverter Model

Fixed efficiency model

Active AC power

No DC circuit access, so the module and inverter cannot be separately characterized
Basic AC Module Model Description

- Active AC power is controlled by the microinverter and has three principle operating states:
  - $P_3$ – Low irradiance self-consumption
  - $P_2$ – Maximum power self-limiting
  - $P_1$ – Typical operating state

- The performance model is a piecewise function with three subdomains:

$$P_{AC} = \begin{cases} 
  P_1 & P_3 \leq P_1 \leq P_2 \\
  P_2 & P_1 > P_2 \\
  P_3 & P_1 < P_3 
\end{cases}$$
Equation Subdomains

\[ P_3 = -1 \times P_{NT} \]

- \( P_{NT} \) is the night tare value, obtained by testing or via spec sheet
- \( P_3 \) could be a function of input conditions

\[ P_2 = P_{AC,max} \]

- \( P_{AC,max} \) is the maximum active AC power output, obtained by testing or spec sheets
- Spec sheets may be quite inaccurate, so I recommend testing
- \( P_2 \) could be a function of input conditions
Equation Subdomains (continued)

- $P_1$ is a function of environmental conditions

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

- Absolute airmass, as a proxy for spectrum
- Absorbed plane of array (POA) irradiance
  - Accounts for surface reflections
- PV cell temperature
- Model parameters must be obtained by outdoor testing
  - 6 parameters listed above
    - $P_{ac_{ref}}$ – Reference active AC power at reference conditions
    - $C_0, C_1$ – Adjust estimated power for irradiance
    - $E_{ref}$ – Reference irradiance (may not be 1000 W/m²)
    - $\gamma_{ac}$ – Temperature coefficient for AC power
    - $T_0$ – Reference cell temperature
  - 3 parameters are embedded in $f_1$ for airmass adjustments – $A_1, A_2, A_3$
  - 1 used to account for surface reflection losses (model by Martin & Ruiz) – $a_r$
    - If the module has flat glass without AR coating, a representative parameter may be used
Validating the AC Module Model

• Tested 4 different AC modules on a two axis tracker and developed model parameters for each module

• Placed modules 3 and 4 in a fixed-tilt orientation for several days.

• Compared the active AC power predicted by the model to the measured AC power from the module
Model Errors in the Parameter Generation Data

- Errors less than 2% of $P_{ac_{\text{ref}}}$
- Approximately 0 mean
  - As expected
- Shows that the model form is capable of modeling an AC module

\[
\frac{P_{ac_{\text{model}}} - P_{ac_{\text{measure}}}}{P_{ac_{\text{ref}}}} \times 100
\]

Model Residuals as a percentage of the reference power
Results from Module 3, Fixed Tilt

Two of nine test days presented here with measured and modeled power

- A warm, calm, sunny day
- A cool, breeze, partly-cloudy day
- Good transition to power limiting

Shading of the module but not the irradiance sensor. Data omitted from subsequent analyses.
Model Errors for Typical Use – Fixed Tilt

- Slight positive bias in model residuals (indicates model over-prediction of power)
- Errors still mostly less than 2% of Pac_{ref}

<table>
<thead>
<tr>
<th></th>
<th>MBE (watts)</th>
<th>MBE (% of Pac_{ref})</th>
<th>RMSE (watts)</th>
<th>RMSE (% of Pac_{ref})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime data only</td>
<td>1.700</td>
<td>0.6776</td>
<td>2.484</td>
<td>0.9903</td>
</tr>
</tbody>
</table>
How can the model help industry?

- The same way that performance models have helped the PV industry in general
  - Performance evaluation of potential (unbuilt) systems
    - Expected energy
    - Selecting between two types of AC modules
  - Measured vs. Modeled comparison of existing systems for health evaluation
- As a basis for a standard performance rating conditions and metrics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$P_{\text{max}}$</td>
<td>250 W$_{\text{DC}}$</td>
</tr>
<tr>
<td>$I_{\text{SC}}$</td>
<td>9 A$_{\text{DC}}$</td>
</tr>
<tr>
<td>$V_{\text{OC}}$</td>
<td>36 V$_{\text{DC}}$</td>
</tr>
<tr>
<td>$\beta_{\text{Voc}}$</td>
<td>-0.45 %/°C</td>
</tr>
<tr>
<td>$\alpha_{\text{Isc}}$</td>
<td>0.05 %/°C</td>
</tr>
</tbody>
</table>

Is this useful for an AC module?
Conclusions

• As PV modules and power inverting electronics become more highly integrated, current methods for characterizing and modeling performance become obsolete.

• Sandia has developed an AC module performance model to characterize and model AC modules
  • Test processes
  • Analysis techniques
  • RMSE approximately 1% of the reference power
  • MBE 0.68% of the reference power
More information

• A complete white paper (SAND2015-0179) with test processes, analysis techniques, more discussion, and model validation is available at

  http://1.usa.gov/1B3sxum

• Or just search for SAND2015-0179 in your favorite search engine
Thank you

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