PREDICTING MISMATCH LOSSES IN UTILITY-SCALE PHOTOVOLTAIC SYSTEMS

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OVERVIEW

• Background: Module and string-level electrical mismatch.

• Motivation

• Model & Methods

• Model validation

• Simulations, Results, & Discussion

• Future Work

• Q & A
1. For a 1 MW array, mismatch losses increase gradually below a bin width of 6W, and more drastically at higher distributions. At 5W, a common tolerance for DC arrays, mismatch loss is $0.501 \pm 0.003\%$ of power.

2. For an effective bin distribution of 5W, mismatch loss decreases as the array size increases, with a diminishing effect. Mismatch loss remains relatively constant for arrays above 1.5 MW.

3. The difference in mismatch losses between two arrays of the same size, one with a central inverter and the other with 60 kW string inverters, remains constant as array size increases. String inverter designs offer a constant, minimal advantage over central inverters with respect to mismatch.

4. For a ~2 MW array, the difference in mismatch losses between an array with string inverters and an array with a central inverter decreases rapidly as the string inverters rating approaches that of the central inverter (as the number of string inverters decreases). This is an expected result that further validates the model’s behavior.
ELECTRICAL MISMATCH
Module Mismatch

variations in the current-voltage characteristics of photovoltaic modules

Mismatch Loss \([P_{\text{loss}}]\)

the overall loss in power when modules are connected together in a network, compared to the sum of their individual maximum power points

\[
P_{\text{loss}} [\%] = \frac{\sum P_{\text{max, module}} - P_{\text{max, array}}}{P_{\text{max, array}}}
\]

ELECTRICAL MISMATCH: A BRIEF BACKGROUND

SERIES

\[I = \text{constant} \quad P_{\text{loss}} \propto \sigma_I\]

PARALLEL

\[V = \text{constant} \quad P_{\text{loss}} \propto \sigma_V\]
PREVIOUS WORK

- Bucciarelli’s statistical approach... mismatch loss is proportional to the variance of module electrical characteristics within a bin [1]
- F. Iannone et al. Monte Carlo approach... validates Bucciarelli’s work, especially at low standard deviations [2]
- Chamberlin et al. achieves mismatches of 0.1-0.53% for randomly arranged small arrays [3]
- S. MacAlpine et al. suggests that 1-2% derate is applicable for mismatch at the string-level [4]

MOTIVATION

...to study mismatch at the utility-scale with the most recent technology, and reevaluate industry wide energy prediction assumptions.

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MODELING METHODS
ASSUMPTIONS

- the “distribution” of all module I-V characteristics is that of $P_{mp}$... $\sigma(P) = \sigma(IV)$
- NO secondary contributions to mismatch (shading, DC losses, degradation, etc.)
- uniform distribution of maximum power points
- all DC analysis – no inverter clipping considered
- I-V curve data at STC

![Graph showing uniform distribution of module Pmp in the 110.0W Bin]
MODEL FLOWCHART

**INPUTS**
- number of strings
- number of modules per string
- I-V data query parameters: nameplate power, bin distribution
- string inverter rating (optional)

\[ P_{loss} \% = \frac{\sum P_{max,module} - P_{max,array}}{P_{max,array}} \]
MODEL VALIDATION
1. flash-test 3 individual modules, measure I-V curves
2. connect modules in parallel
3. measure “array” I-V curve
4. take individual I-V curve data and use tool to generate simulated “array” I-V curve
5. calculate error (simulated – measured)

<table>
<thead>
<tr>
<th></th>
<th>Pmp</th>
<th>Imp</th>
<th>Vmp</th>
<th>Isc</th>
<th>Voc</th>
<th>FF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average Error (natural units)</strong></td>
<td>0.1451 W</td>
<td>-5.50 mA</td>
<td>0.564 V</td>
<td>-0.867 mA</td>
<td>0.152 V</td>
<td>6.67x10^-5</td>
</tr>
<tr>
<td><strong>Average Error (%)</strong></td>
<td>0.0421</td>
<td>-0.278</td>
<td>0.322</td>
<td>-0.0389</td>
<td>0.0684</td>
<td>0.0126</td>
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</tbody>
</table>
SIMULATIONS & RESULTS
For a 1 MW array, mismatch losses increase gradually below a bin width of 6W, and more drastically at higher distributions. At 5W (a common tolerance within a given array) mismatch loss is $0.501 \pm 0.003\%$ of total power.
IMPACT OF DC ARRAY SIZE

For an effective bin distribution of 5W, mismatch loss decreases as the array size increases, with a diminishing effect. Mismatch loss remains relatively constant for arrays above 1.5MW.
The difference in mismatch losses between two arrays of the same size, one with a central inverter and the other with 60kW string inverters, remains constant as array size increases. String inverter designs offer a constant, minimal advantage over central inverters with respect to mismatch.

<table>
<thead>
<tr>
<th></th>
<th>First Solar Series 4V3</th>
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<tbody>
<tr>
<td>Module</td>
<td></td>
</tr>
<tr>
<td></td>
<td>110.0 W (-0/+2.5W) &amp;</td>
</tr>
<tr>
<td></td>
<td>112.5 W (-0/+2.5 W)</td>
</tr>
<tr>
<td></td>
<td>Effectively 5.0W bin.</td>
</tr>
<tr>
<td>Bin</td>
<td>60 kW (36 strings)</td>
</tr>
<tr>
<td># String Inverters</td>
<td>?</td>
</tr>
<tr>
<td>Central Inverter Rating</td>
<td>?</td>
</tr>
<tr>
<td># Strings in Array</td>
<td>?</td>
</tr>
<tr>
<td>Modules Per String</td>
<td>15</td>
</tr>
</tbody>
</table>
For a constant 1.98 MW array, the difference in mismatch losses between an array with string inverters and an array with a central inverter decreases rapidly as the string inverter rating approaches that of the central inverter, and subsequently the number of string inverters decreases. This expected result further validates the model’s behavior.
FUTURE WORK
FUTURE WORK

• comparative analysis: CdTe vs. c-Si

• utility-scale validation
  — measure string currents, and isolate mismatch losses from resistive losses

• secondary mismatch effects
  — shading (*in progress*)
  — temperature gradient (and temperature correction in general)
  — resistive (DC) losses
  — module degradation

• please contact with any thoughts or suggestions ... stephen.kaplan@firstsolar.com
THANK YOU!

- Fraunhofer Institute for Solar Energy Systems
- Sandia National Laboratories
- Sara MacAlpine, NREL
- Kendra Passow, Mitchell Lee, Mark Grammatico, & Bodo Littman of First Solar
- Alex Panchula, Tesla Motors (formerly of First Solar)
QUESTIONS?