Prototyping and Validation of Two Low-Cost Inline CPV Module Efficiency Characterization Methods

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The Problem

• Quantifying CPV performance is challenging!
  – Requires a collimated solar simulator (CSS) to test to Concentrator Standard Test Conditions (CSTC)
  – High CAPEX and high operating costs
  – Hard to maintain calibration
  – Requires highly trained operators and technicians
  – Repeatability $\sigma = 2.8\%$ (current system at MSI)

Is there another way?
The Solution

• Prototype new tools for low cost in-line efficiency estimation

• Use standard automation equipment to reduce complexity and minimize sources of variation

• These alternative techniques will estimate optical efficiency ($I_{sc}$) for individual optics
  – Module $P_{mp}$ can be calculated based on an average cell model (Future work!)
The Solution

• Key Question:
  – How accurate does the estimate need to be?
Agenda

1. Laser Solar Simulator
   i. Approach
   ii. Experimental Set-Up
   iii. System Performance
   iv. Results

2. Electroluminescence Imaging
   i. Approach
   ii. Experimental Set-Up
   iii. System Performance
   iv. Results

3. Conclusions
LSS: Approach

1. The output beam from a fibre-coupled laser system is collimated over the area of one optic

2. A two-axis translation stage shuttles the sample under the collimated beam

3. $I_{sc}$ is directly measured for each individual optic
LSS: Experimental Set-Up

- The sample translates under a stationary imaging system.
- Not shown: Laser source, 2-axis translation stage, LabVIEW GUI.
LSS: System Performance

• Collimation: ±0.5°
• Irradiation Non-Uniformity: ±5%
• Fast results: less than 2 seconds per optic
LSS: System Performance

• Gauge R&R results:
  – Not great!
  – Repeatability $\sigma = 3.4\%$

<table>
<thead>
<tr>
<th>Source</th>
<th>% Contribution (of VarComp)</th>
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<tr>
<td>Total Gage R&amp;R</td>
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<td>Repeatability</td>
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<td>Reproducibility</td>
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<td>Part-to-Part</td>
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<td>Total Variation</td>
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LSS: Results

Normalized Isc Measurements - LSS vs CSS

Error - LSS to CSS
LSS: Results

Fitted Line Plot

LSS Result = -0.09717 + 1.097 CSS Result

S: 0.0343135
R-Sq: 96.5%
R-Sq(adj): 96.4%
Agenda

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2. Electroluminescence Imaging
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3. Conclusions
**EL: Approach**

- Electroluminescence (EL) imaging is widely used in PV manufacturing for defect detection

- Reversible Systems
  - Solar cell -> LED
  - Concentrator -> Collimator
EL: Approach

1. Constant current is applied to the test module leads
2. The collimated output beam is imaged by the test system
3. Individual optic images are processed to make $I_{sc}$ estimate
EL: Experimental Set-Up

- The sample translates under a stationary imaging system
- Not shown: power supply, 2-axis translation stage, LabVIEW GUI
EL: Approach
EL: System Performance

• We developed a lab-scale system which provides:
  – Fast feedback → less than 5 seconds per optic
  – High resolution → 40 µm
  – Meaningful test images
  – Proof-of-concept for a production test system
EL: System Performance

- Gauge R&R results:
  - Good!
  - Repeatability $\sigma = 2.3\%$

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EL: Results

Normalized Isc Measurements - EL vs CSS

Error - EL to CSS
EL: Results

Fitted Line Plot
EL Result = - 0.3012 + 1.301 CSS Result

S = 0.0731926
R-Sq = 89.4%
R-Sq(adj) = 89.3%
Review

• Two low-cost efficiency estimation tools are in development

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<th>CCS</th>
<th>LSS</th>
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<td>Repeatability (σ)</td>
<td>2.8%</td>
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<td>Accuracy to CSS (σ)</td>
<td>-</td>
<td>3.4%</td>
<td>7.3%</td>
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• Further improvements are required to improve estimation accuracy
Conclusions

• Alternative solutions for quantifying CPV module performance at CSTC can be considered
  – Careful calibration of test results to CSTC is essential
  – Additional quality systems requirements can be designed to facilitate low-cost testing methodologies
Thank You!