Electrical and Thermal Finite Element Modeling of Arc Faults in Photovoltaic Bypass Diodes

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Outline

• Arc Fault Introduction
• Description of the Model
• Simulations
  – Normal Operation
  – Solder Corrosion
  – Burn Time
• Conclusions
Arc Faults in PV Systems!

• Arc: Luminous discharge of electricity across an insulating medium
• Arc faults ionize the atmosphere to create a high temperature plasma
  – 5000+ °C
  – Melts metals, burns plastics
• Rare but some examples exist:
  – Bakersfield, CA
  – Mount Holly, NC
• Article 690.11 in the 2011 National Electrical Code requires arc fault circuit interrupters on rooftop installations

Arc fault video courtesy of John Wohlgemuth at NREL
Selection of Subdomain for Simulations

Series Arcing Locations

- Diode solder connections to bus
- Solder connection between connector and bus
- Connector interfaces
- Connections between buses, collector ribbons, and cell leads

COMSOL Modeling Domain

Close-up of solder bond (blue)

Bypass Diode Operation

Nameplate Polarity

- Shaded
- Sunny

Current

Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical Conductivity $\sigma$ [S/m]</th>
<th>Relative Permittivity $\varepsilon_r$ [-]</th>
<th>Thermal Conductivity $k$ [W/m-K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoplastic</td>
<td>0.004</td>
<td>2.25</td>
<td>0.5</td>
</tr>
<tr>
<td>Sn-plated Cu</td>
<td>$3.43 \times 10^7$</td>
<td>1.00</td>
<td>234</td>
</tr>
<tr>
<td>60Sn-40Pb Solder</td>
<td>$6.67 \times 10^6$</td>
<td>1.00</td>
<td>50</td>
</tr>
</tbody>
</table>
**Normal Bypass Diode Operation**

- **Diode Heating = Semiconductor Heating + Joule Heating**
- **High-power Si Schottky diodes**
  - Internal Semiconductor Heating = (turn-on voltage) x (module current) = 0.45 V x 5 A = 2.25 W generated by the diode

![Normal current density (A/m²)](image1)

![Electron traces through the diode](image2)

![Current vector field](image3)

(a) Joule heating with diode heating
Diode temperature: 88.37 °C

(b) Joule heating without diode heating
Diode temperature: 20.32 °C

Warm, but no arcing.
Corrosion in Diode Leads

- What level of corrosion is required to generate the gap voltage required to cause an arc fault?

- Transition from diode acting as a conducting path to the plastic back sheet.

Significant reduction in conductivity is required to establish an arc.

Dielectric strength of air is 3000 V/mm or 3 V/μm.

Location of contact resistance from corrosion
Burn Times

- Back sheet burn time calculated with radiation model

Assuming arc fault power is 100 W, the 1x1 mm surface would experience **4100 kW/m²** of incident radiation.

View factor = % of radiation absorbed by surface = 4.1%

Back sheet ignition time is less than 0.1 seconds.

Conclusions

• Arc faults in PV systems are rare, but do happen.
• Arc fault circuit protection is now required by the *National Electrical Code*.
• Ignition of arcs at the solder connection of a bypass diode was simulated:
  – Normal operation is warm (68 K above ambient), but will not melt the surrounding materials.
  – With large (6 orders of magnitude) reductions in conductivity from corrosion or solder fractures, micron-scale gaps will establish an arc
  – Once the arc fault has initiated, it will take less than 0.1 seconds for a polymeric back sheet to ignite.