CODES AND STANDARDS FOR PV ARC-FAULT DETECTION & MITIGATION

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Introduction

- What is an “Arc-fault”
- Arc-faults in installed systems –
- What is done for other (ac) systems
- The emerging codes and standards for PV
- Overview of technical challenges
- Technical developments underway
- Summary

Arc Fault Detection and Standards in Non-PV Applications

- AC Arc Fault Detection for Dwelling Electrical Systems (60Hz, 80-600V)
  - Def: A DEVICE intended to provide protection from the effects of arc faults by recognizing characteristics unique to arcing and by functioning to de-energize the circuit when an arc fault is detected.
  - Required beginning in 1999 via *NEC* Article 210.12 (Arc-fault Circuit Interrupter Protection), 550.25 (Mobile Homes)
  - Devices listed for safety through UL Standard 1699
- Aircraft (400Hz)
  - Hardware and diagnostics are commercially available and in use
  - Technologies tested include: Frequency Signatures, Time Domain Reflectometry, Frequency Domain Reflectometry, Multi-carrier Reflectrometry, Standing Wave Reflectometry, Noise Domain Reflectometry, Spread Spectrum TDR…
- Automotive (Low Voltage dc)

Arc Faults in Systems
Arc-faults & Standards and Codes

Fire at on-roof PV-System in Buerstadt, Germany

Unknown Location

Fighting the Fire is Difficult!

National Electrical Code DC Arc-fault Changes

The new 2011 NEC

New arc-fault requirements for dc PV circuits

- **Article 690.11** (New)
  - **Written to detect and interrupt "series" arc-faults in modules, connections, wiring, and other components**
  - **Requires inverters, charge controllers or other devices in the arcing circuit to be disconnected and disabled**
  - **Requires manual resets and reconnects once an arc is detected and fixed**

NEC ARC FAULT DETECTION REQUIREMENT 690.11 (NEW)

690.11 Arc-Fault Circuit Protection (direct current): Photovoltaic systems with dc source circuits, dc output circuits, or both, on or penetrating a building operating at a PV system maximum system voltage of 80 volts or greater, shall be protected by a listed (dc) arc-fault circuit interrupter, PV type, or other system components listed to provide equivalent protection. The PV arc-fault protection means shall comply with the following requirements:

(1) The system shall detect and interrupt arcing faults resulting from a failure in the intended continuity of a conductor, connection, module, or other system component in the dc PV source and output circuits.

(2) The system shall disable or disconnect one of the following:

a. Inverters or charge controllers connected to the fault circuit when the fault is detected.

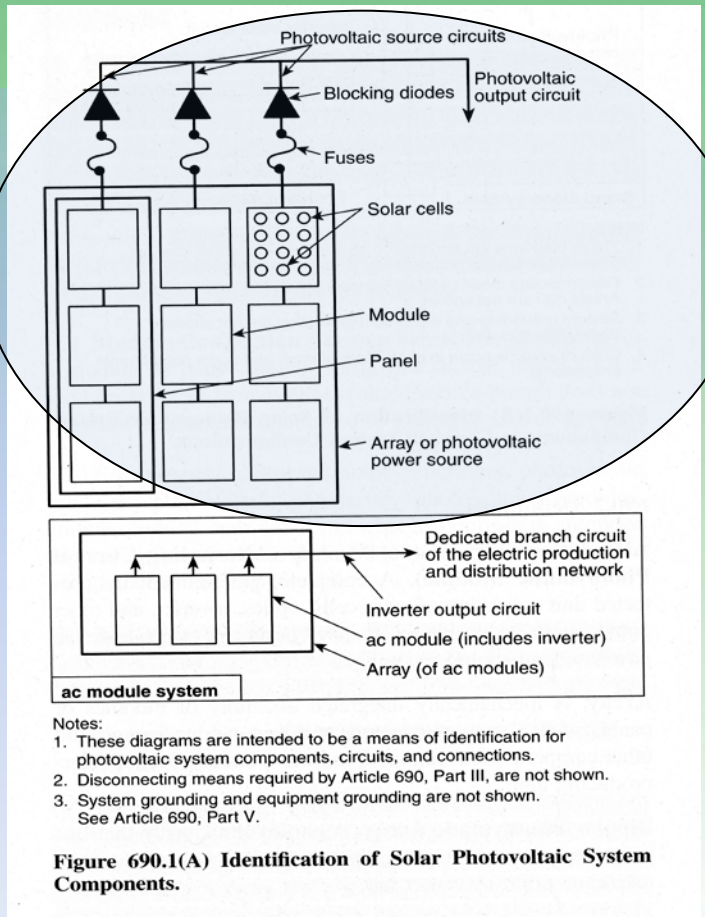
b. System components within the arcing circuit.

(3) The system shall require that the disabled or disconnected equipment be manually restarted.

(4) The system shall have an enunciator that provides a visual indication that the circuit interrupter has operated. This indication shall not reset automatically.

Series Arc Detect/Interrupt - 690.11 (1)

(1) The system shall detect and interrupt arcing faults resulting from a failure in the intended continuity of a conductor, connection, module, or other system component in the direct current PV source and output circuits.



Notes:
1. These diagrams are intended to be a means of identification for photovoltaic system components, circuits, and connections.
2. Disconnecting means required by Article 690, Part III, are not shown.
3. System grounding and equipment grounding are not shown. See Article 690, Part V.

Figure 690.1(A) Identification of Solar Photovoltaic System Components.

Source: 2011 *NEC*

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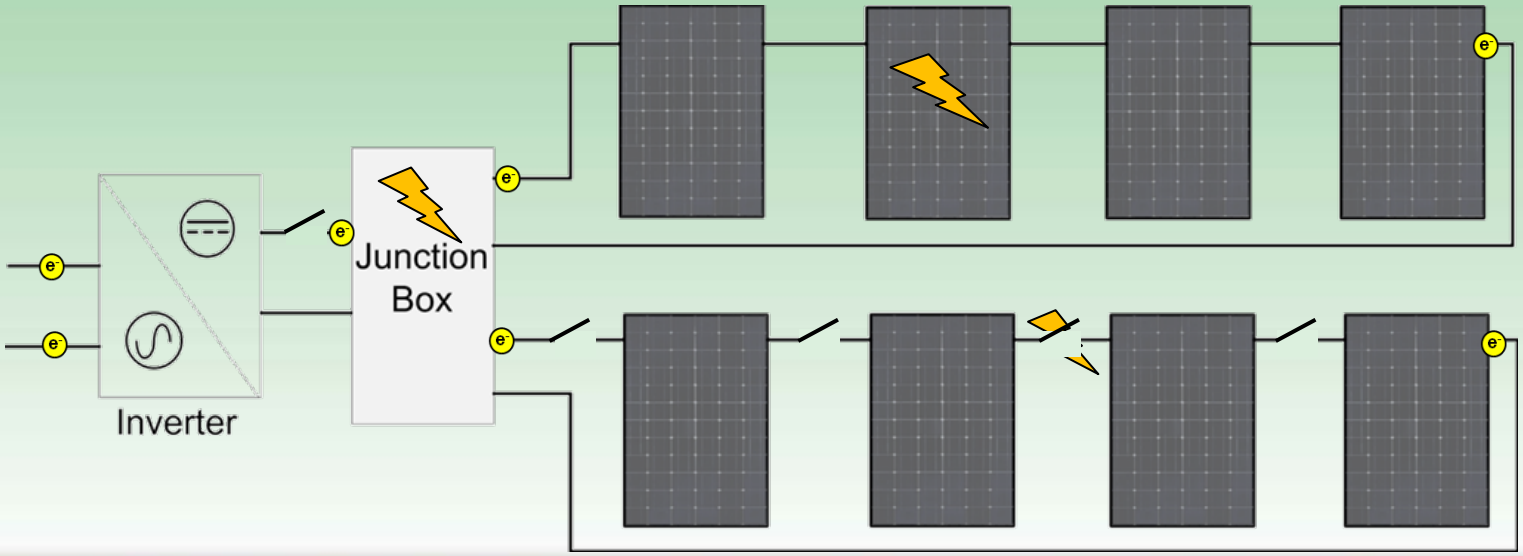
NEC Article 690.11(1&2)

(1)The system shall detect and interrupt arcing faults resulting from a failure in the intended continuity of a conductor, connection, module, or other system component in the direct current PV source and output circuits.

(2) The system shall disable or disconnect one of the following:

a. Inverters or charge controllers connected to the fault circuit when the fault is detected.

b. The system components within the arcing circuit.



NEC Article 690.11 (3&4)

(3) The system shall require that the disabled or disconnected equipment be manually restarted.

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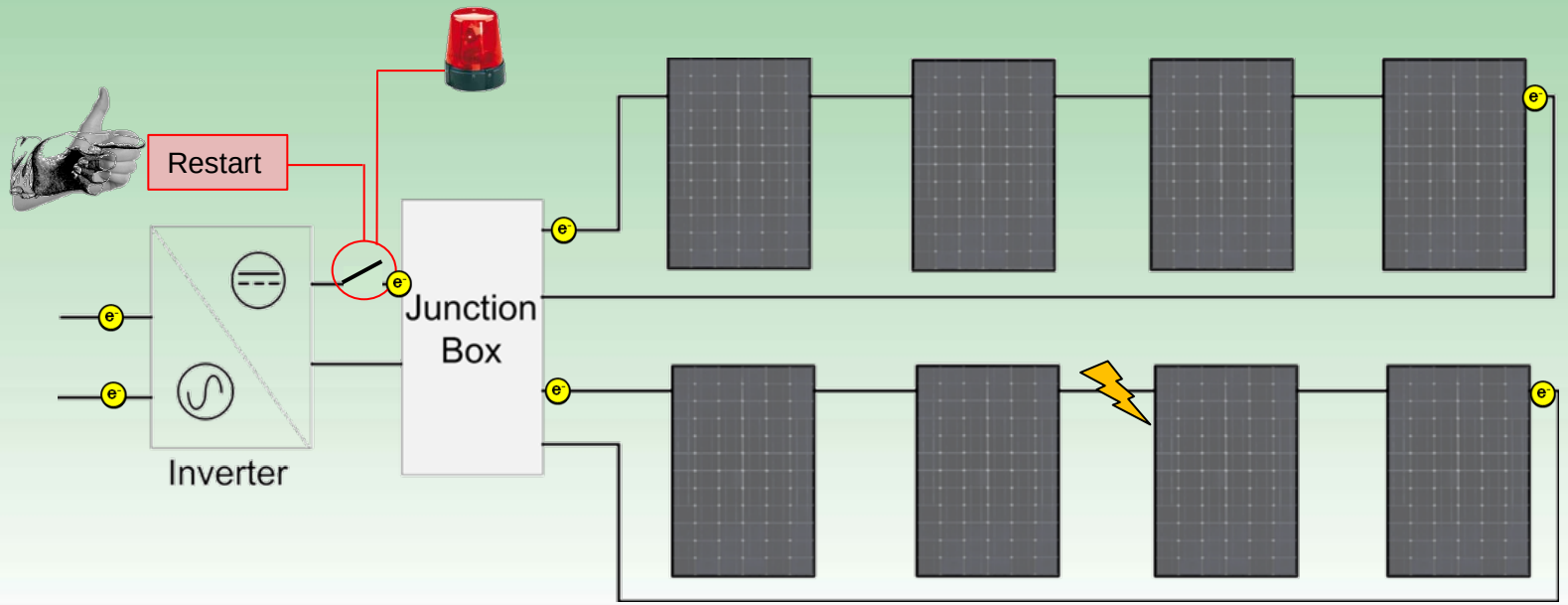

Underwriters Lab PV DC AFCI Standard

SUBJECT 1699B

DRAFT

OUTLINE OF INVESTIGATION FOR PHOTOVOLTAIC (PV) DC ARC-FAULT CIRCUIT-INTERRUPTERS

version May 12, 2010

PURPOSE & STATUS

- **Requirements for Arc Fault Circuit Interrupter Devices**
  - ➢Written for new 2011 *NEC* compliance
  - ➢Uses ac arc-fault circuit interrupter standard for mechanical/device safety tests
- **Development Status**
  - Draft under development via UL/industry/user committee
  - Effective date TBD (Next Meeting Nov 30, 2010)

AC AFCI breaker

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Table 11.1 Test Sequence UL1699B

Test Name	UL1699 Section	1699B Section	Conditioning/ environmental(a)	Overload/ endurance(b)	Other (c)
Impact	35.2		X		
Drop	35.3		X		
Humidity	36		X		
Leakage	37		X		
Voltage Surge	38		X		
Environmental Sequence (d)	36		X		
Arc Fault Detection		14	X		
Unwanted Tripping		15			X
Inhibition		16			X
Temperature	45				X
Overvoltage (e)	46			X	
Overload		12		X	
Endurance		13		X	
Dielectric Withstand	43		X	X	X
Abnormal	49	13A			X
Short Circuit					X

Near Term Challenges

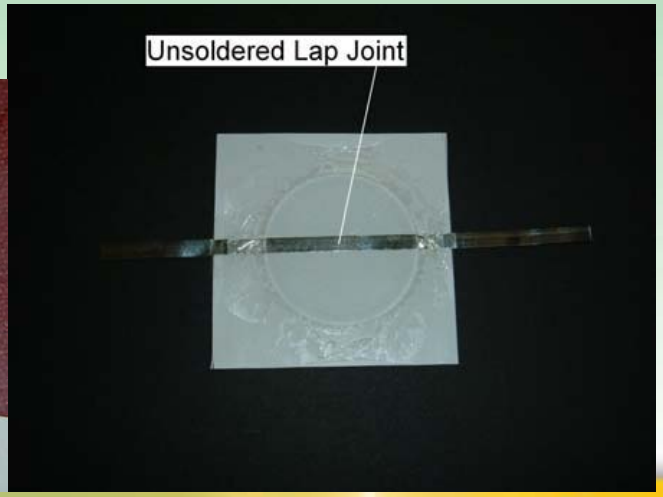
Technology Challenges for AF Detectors

- **Unequal sizing and distributions of parallel PV strings**
  - Loop inductance and stray capacitance of wiring and PV modules
  - System communications signals (conducted and radiated), noise
  - PV string combiners (smart and future)
- **Detection Spatiality**
  - At the inverter, between inverter to array, within array, in module, etc.
  - PV string combiners with isolation and MPPT functionalities (dc-dc)
  - PV string combiners with communications and switching functions
- **Arc-fault frequency signatures and characteristics response affected by materials and PV module technology**
  - Thin film, crystalline, multi-junction, slivers, etc
  - Conductors, terminal compositions, insulation types, humidity
- **Inverter topology interaction with PV array and BOS**
  - Input capacitance, EMI filters, switching noise, spurious noise
  - Anti-islanding and MPPT perturbations
  - Backfeeding and Transformerless (non-isolated) inverter topologies

Testing and Modeling Underway

- **“Testing and modeling” are being conducted at Sandia, Underwriters, industry, universities**
  - System Level “on the wiring and interconnections”
  - Module Level “under the glass”, at the J-box
- **Modeling and Analysis**
  - Component thermal analysis
  - Stress and strain modeling

UL1699B Test Fixtures



Detection and Mitigation?

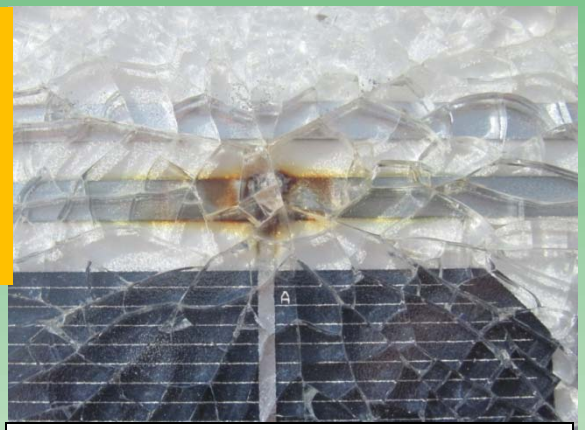
- **System Level**
  - Detect (now at inverter)
  - Determine arc location
  - Interrupt circuit (faulted circuit or entire array) (AC PV Modules?)
  - Mitigate (likely manual)
- **Module Level**
  - Detect, locate, isolate
  - Prevent by design (i.e. materials, circuit designs, dc-dc converters)
  - Eliminate by design (integrated mechanisms and techniques)

Sandia Arc-fault Modeling

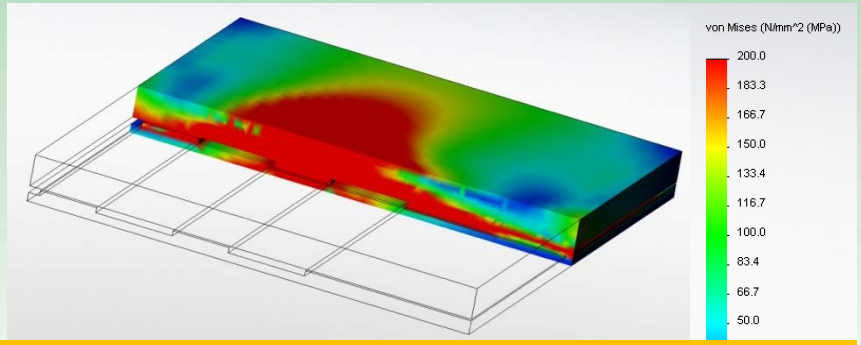
- **Sandia has developed a physics-based simulation model of a general solar module with full geometric and material details. Model based on one module, but is adaptable to other designs and types of modules.**

- **Model has been validated by confirming arc faults were the cause of a number of module failures: glass breakage, busbar deformation and EVA/backsheet burning.**

Picture of failed module glass breakage shows radial pattern centered at arc burn



Module glass breakage modeling



Close up view of glass and busbar junction stress after 2 seconds of arcing on the ~½ mm^2 connection. Patterned and tempered glass likely shatters at about 100 MPa of tensile stress.

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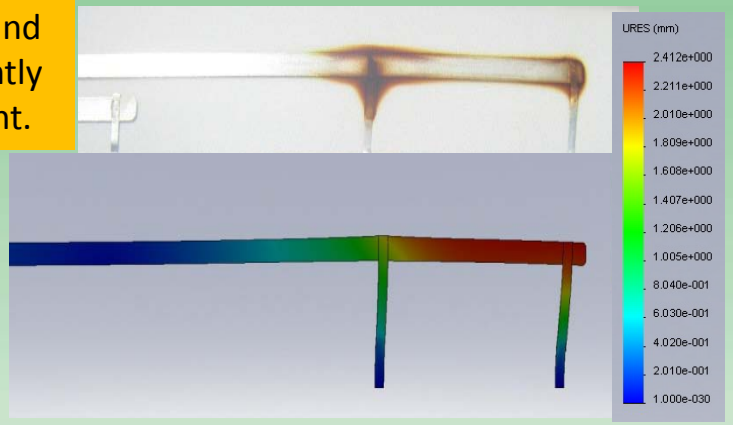
Sandia Arc-fault Modeling

- **Model used to demonstrate and verify breakdown thresholds for modules, junction boxes and systems.**

- **Testing hardware being developed to test materials used in solar modules and systems, and to assist with arc-fault sensor development.**

Busbar damage modeling

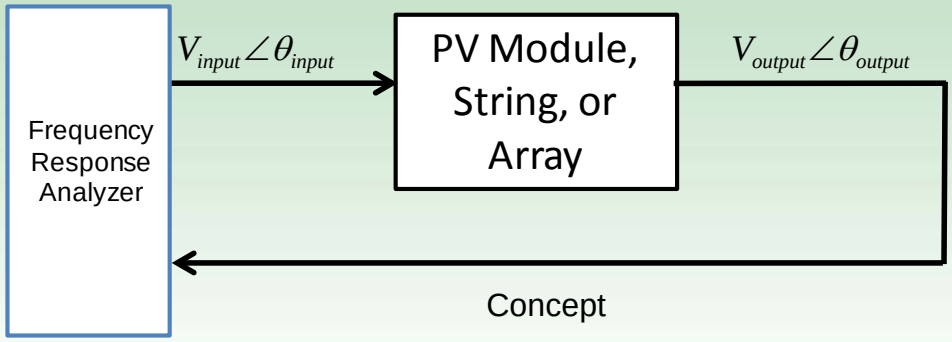
Picture of collector grid and busbar shifted permanently to the right after arc event.



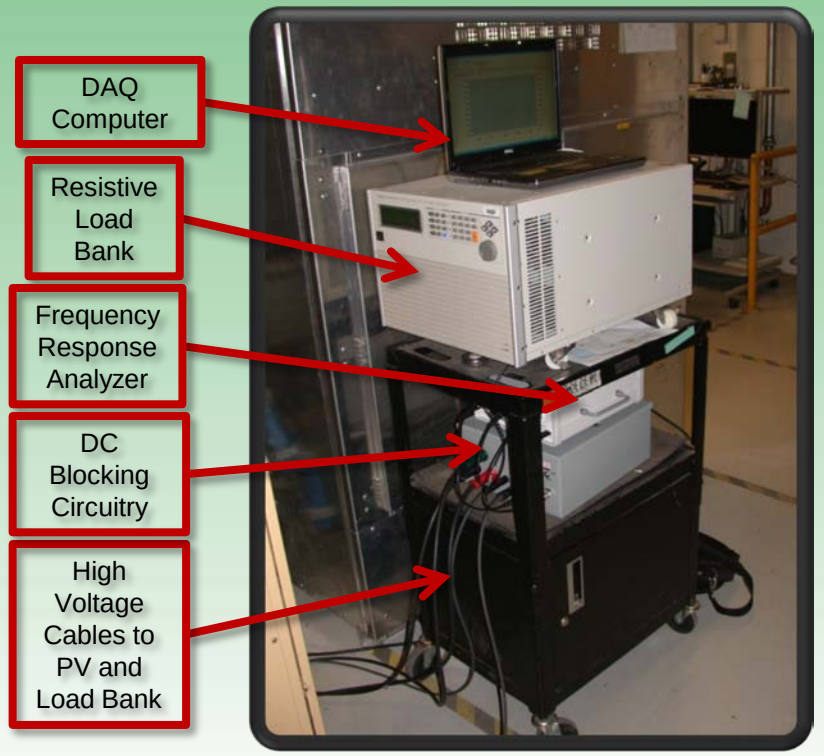
Simulation shows that the region near the arc and to the right is shifted 2 mm after just 1 second of ~½ mm^2 arcing, likely enough to break nearby solder joints

Sandia's System-Level PV Frequency Characterization

- **PV detectors are sensitive to frequency-dependant PV attenuation, electromagnetic noise, and radio frequency effects from line inductance, etc.**
- **To determine optimal bandwidths for detection, Sandia is characterizing the ac frequency response of PV modules, strings, arrays, and conductors**



Concept



Experimental Setup

Summary [Challenges & Opportunities]

Arc-faults Cause Fires

- Arc-faults Have Been Observed/Reported in:
  - PV modules
  - J-boxes
  - Conductors
  - Connectors

Codes and Standards for PV are Emerging

- National Electrical Code
  - Article 690.11 (PV)
  - Article 210.12 (ac)
- UL1699B in Progress
  - PV Standards Development
  - Collaborative and Independent Testing
  - Modeling and Arc Analysis
- International Collaboration