Arc-fault Protection in PV Installations: Ensuring PV Safety and Bankability

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Introductions

Presenters

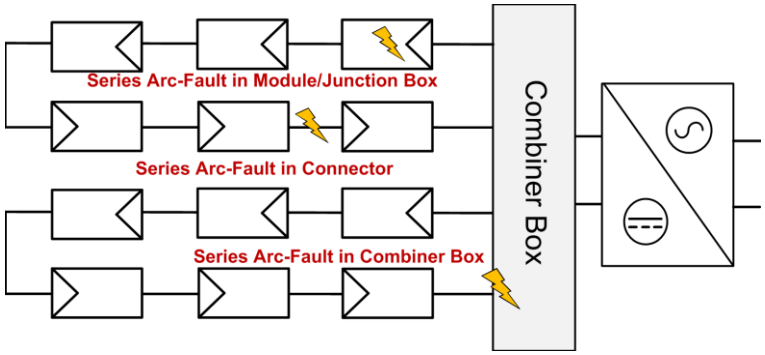
- Jay Johnson - Sandia National Laboratories
  - Manager of PV Arc-Fault Detection and Mitigation Program at Sandia National Labs
- Bill Moore – Duke Energy
  - Program Manager for Duke Energy's North Carolina Solar Program
- Chris Oberhauser – Texas Instruments
  - Lead Engineer of TI's Arc-Fault Detector
- Scott McCalmont – Tigo Energy
  - Director of Solar Technologies at Tigo Energy
- Bob LaRocca – Underwriters Laboratories
  - Author of UL 1699B – UL Standard for Testing Series and Parallel Arc-Fault Circuit Interrupters and Detectors

Outline

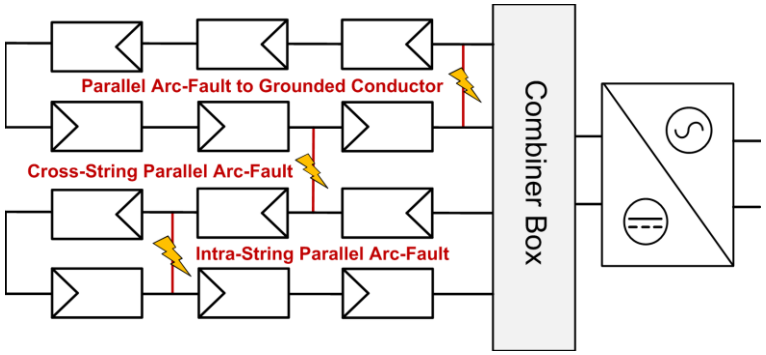
- Introduction - Jay Johnson
  - Introduction to PV arc-faults.
- Description of the ground fault and arc-fault problem - Bill Moore
  - How do arc-faults affect PV bankability and safety?
  - How arc-faults and fires have the power to influence public perception.
- Technical solutions for arc-faults - Chris Oberhauser
  - Texas Instruments arc-fault detection method and product description.
  - Pros/cons of this approach: cost vs. arc-fault isolation.
- Future of arc-fault protection - Scott McCalmont
  - Tigo Energy's arc-fault detector product.
  - Goals for module-level detection and switching to address parallel arc-faults.
- Testing Arc-Fault Circuit Interrupters - Bob LaRocca
  - Description of UL 1699B standard.
  - Industry status and future needs.
- Question and Answer Session

Arc-Fault Basics

- Arc-Fault Physics
  - Arc causes air to ionize and generate a plasma at 5000+ ^{o}C
  - Temperatures melt metals, burn polymers
- Types of arc-faults
  - Series Arc-Fault – Arc from discontinuity in electrical conductor
  - Parallel Arc-Fault – Electrical discharge between conductors with different potentials
- 2011 NEC requires series arc-fault protection in PV installations on or penetrating a building above 80 V



Series Arc-Faults

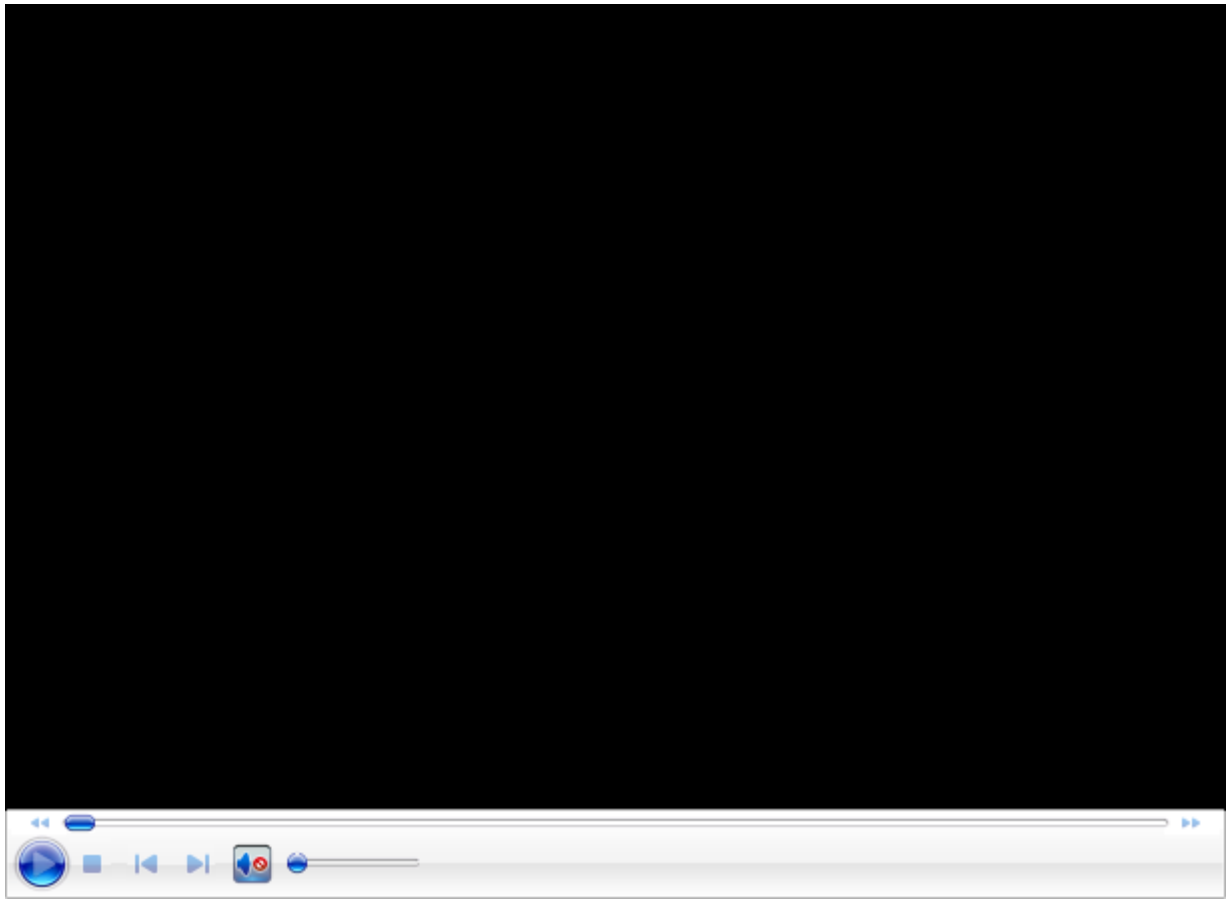


Parallel Arc-Faults

Arc-Fault Video

Sandia National Laboratories

Series arc-fault as a result of a cut conductor in the junction box.



Arc-fault video courtesy of John Wohlgemuth at NREL

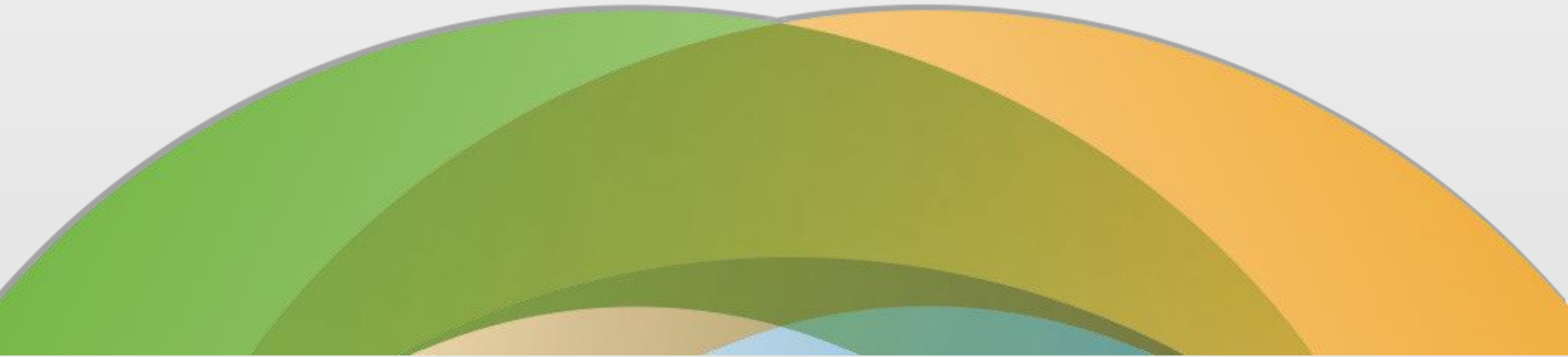
NC PV DG Program
WREF Presentation

renewable energy

our commitment to a sustainable future

Duke Energy

May 2012



PV Solar Rooftop Incident

- April 16th 2011 Incident
  - What Happened
- Customer Impact
  - Safety of Rooftop Solar PV Generation called into question.
- The Journey – What Happened Next?

PV Solar Rooftop Incident

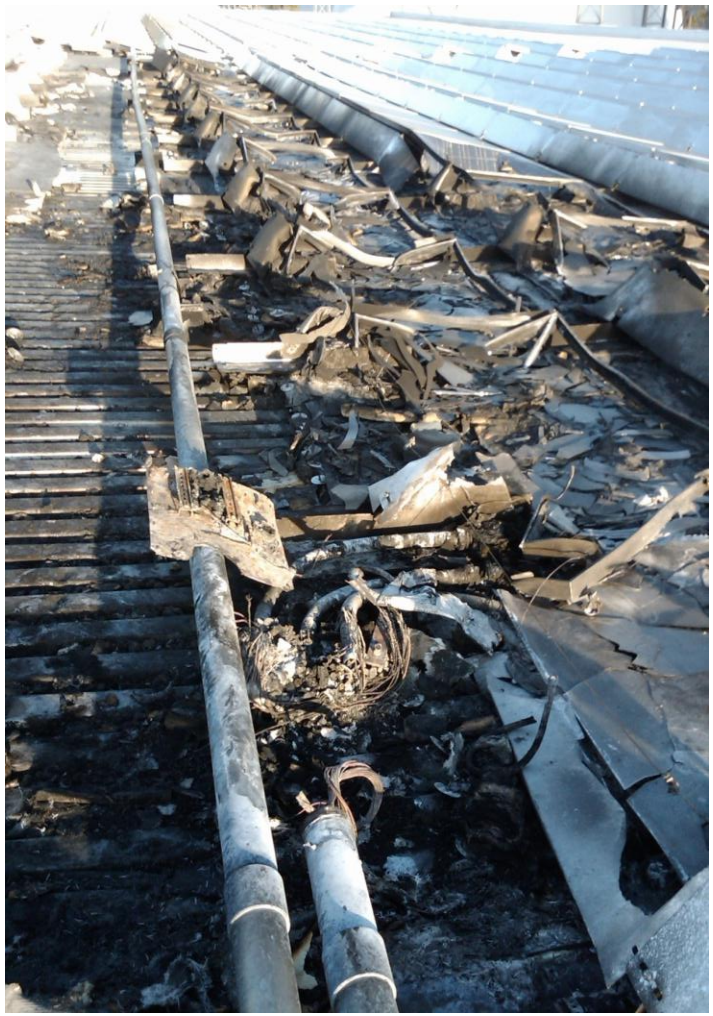
1.13 MW Facility, 5252 Panels, 3 Inverters

Needed to secure resources

Needed to secure the site and do it safely to prevent injury and more property damage.

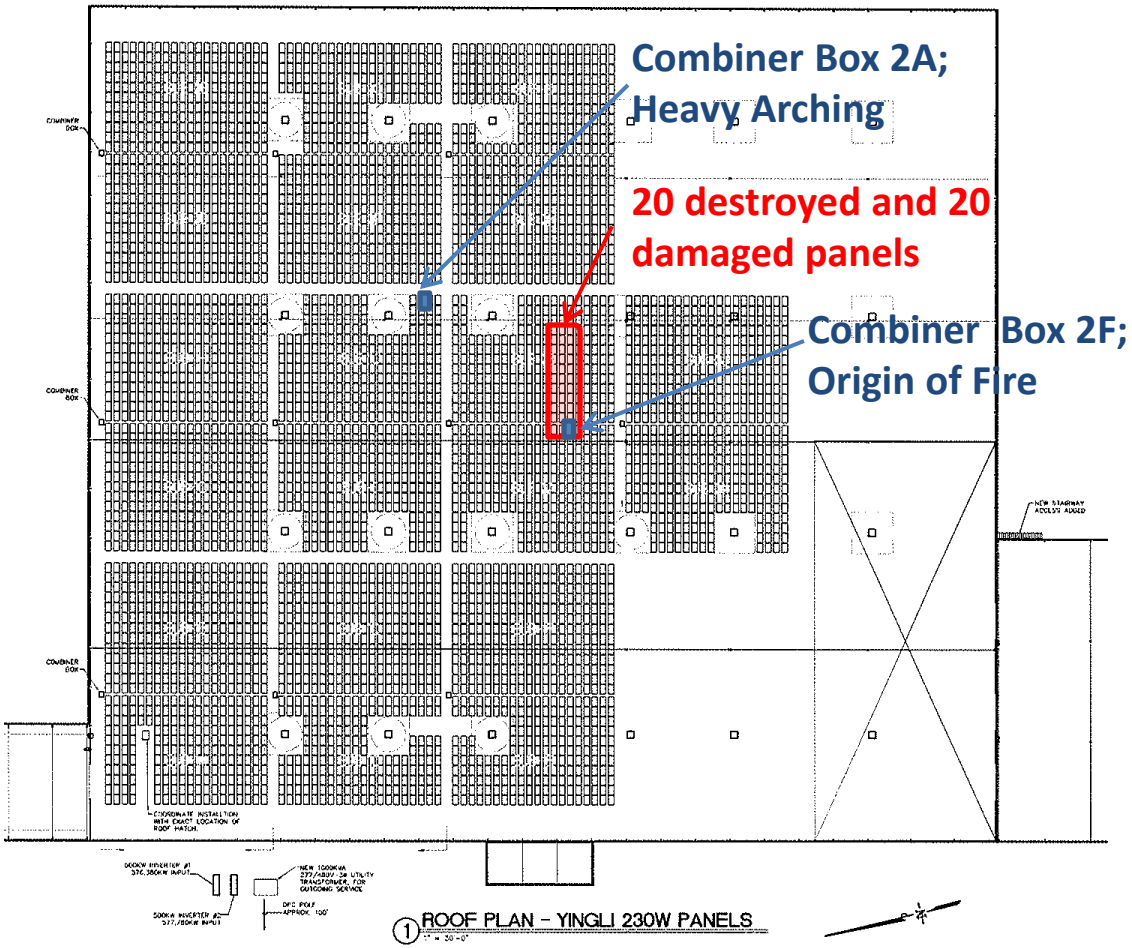
Needed to figure out what happened.

Customer Impact – Safety, Risk (Potential loss of life, Property Damage. . Had to cleanup the site. Roof repairs had already been scheduled.



PV Solar Rooftop Incident

Incident: PV Solar Fire
When: April 16, 2011
Where: Rooftop of Manufacturing Facility in Mount Holly, NC
What: Fire damaged or destroyed solar panels, combiner box 2F (fire), combiner box 2A (arching), and roofing. (Backplane pictured below).



5,252 ,230-Watt PV modules; Two inverters 500 kW inverters and one 135 kW inverter.

Duke Energy

Root Cause(s)

- **PV System Protection Design:** A low level ground fault (below 5 amps) is not detected with the GFP located in the inverter….aka the " Blind Spot"

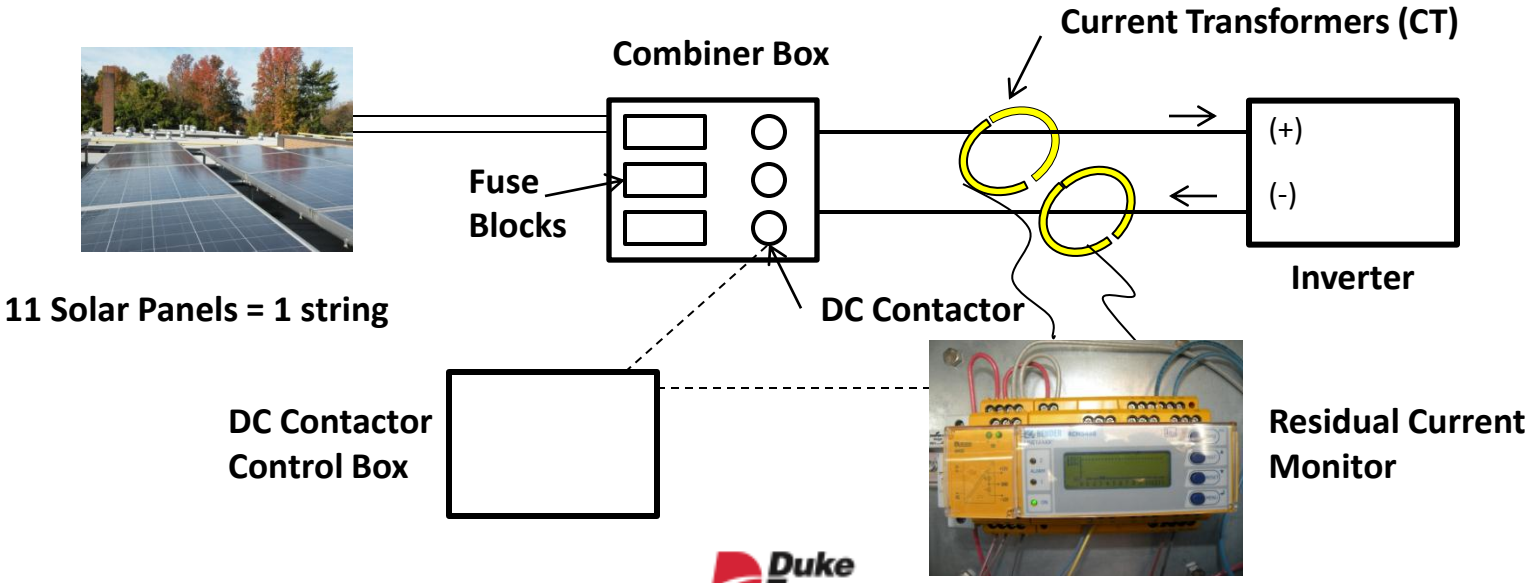
- **Undetected grounded feeder conductor (2F) fault:** A string feeder (2F) ground fault occurred at an unknown time. Only a portion of the string operating current was directed toward the inverter through the ground. It was at a level insufficient (less than 5 amps) to be detected . As a result , the inverter did not trip.

- **Second ungrounded string conductor (2A) fault:** A second ground fault on an ungrounded conductor (2A) occurred in a feeder that was connected to the same inverter. Arcing marks were identified where this feeder connected to the combiner box. The current in the ground from the second fault was large enough to trip the GFP. This current flow then went back through the ground fault connection made by the first ground fault. This current exceeded that rating of the string feeder and associated equipment. This caused these component to be heated to the point of combustions.

Contributing Factors: Increased solar irradiance after storm, strong winds, some poor installation practices, thermal expansion, certain industry practices

Remedy

- **DC Residual Current Detectors (Ground Fault Detector)**
  - ❑ Measures imbalance of current flow in the positive and negative (grounded) feeders from inverter to each combiner box.
  - ❑ Detects all ground faults in ungrounded conductor but not some lower lever (approx. 0.2 amps grounded faults) in grounded conductor during operation
  - ❑ Equipment can detect some ground type Arc Faults
  - ❑ A 60 milliamp alarm is set. A differential detected above that level results in an inverter trip and open contacts at the combiner box.



Remedy

- **Notification of ground fault(s) by monitoring system**
  - ❑ Eliminate 24 hour delay for maintenance responders and identifies fault types
  - ❑ Add additional local monitor, data acquisition and weather monitoring
- **Contact Combiner Boxes with automatic disconnect**
  - ❑ Replace or upgrade combiner boxes to include automatic feeder and string DC disconnects from a remote and/or local signal
  - ❑ New contact combiner boxes capable of future arc fault detection
- **Improved DC Wire Management**
  - ❑ Physically remove or reduce stress points
  - ❑ Increased inspections, test, thermal imaging, megger test
- **Fire/Safety Brochure**

What's Next?

Deploying the Solution

Bender Training Session

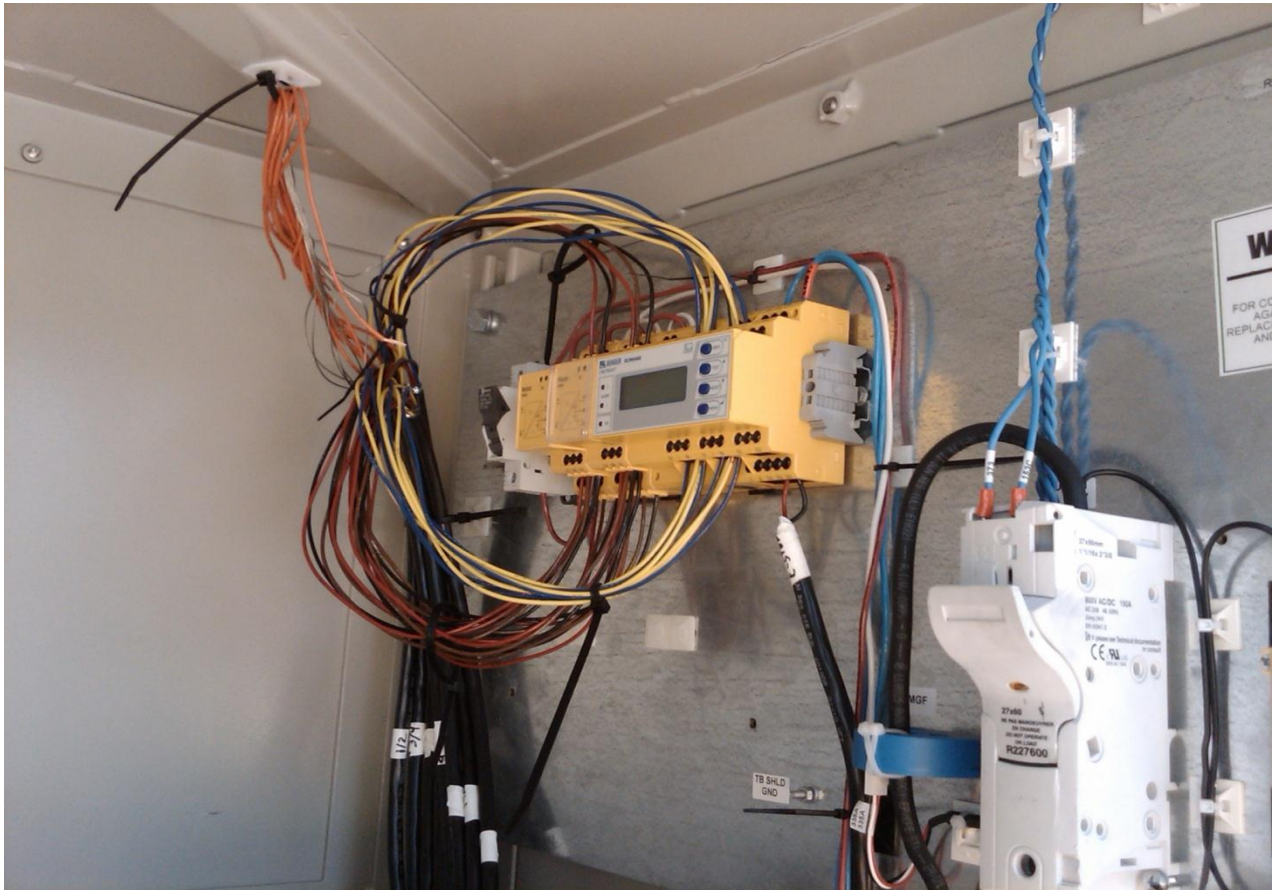
Competitors working together to solve the problem.

Bender Training Session

Simulated Installation

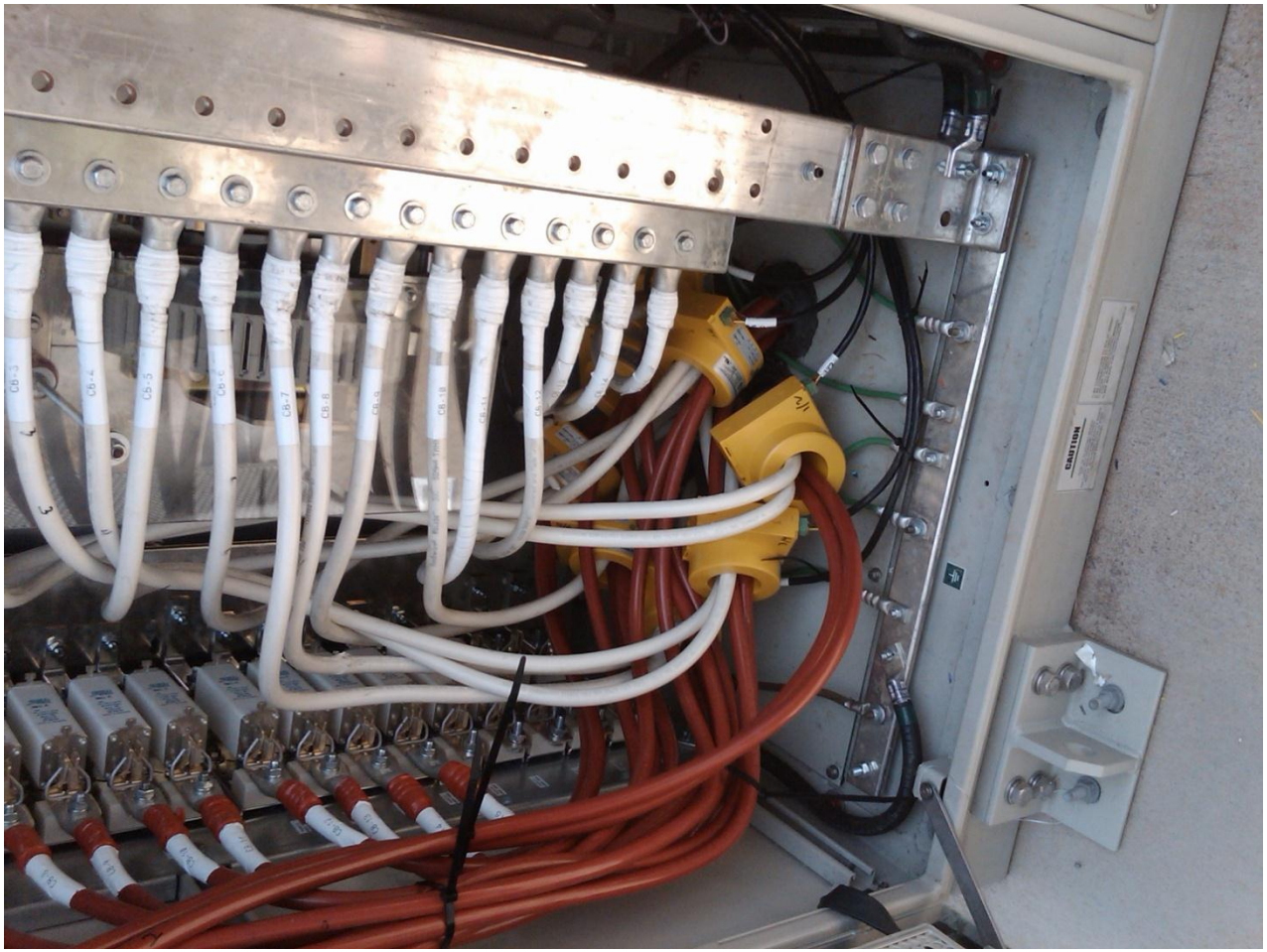
Bender Device

Inverter manufactures had to approve installation of the device into their inverters



CT Installation

Inside Inverter



Fire Safety Brochure

FIRE DEPARTMENT EMERGENCY OPERATIONS

- The PV array will always generate electricity during daylight even when cloudy, raining, snowing, etc and there is no turning off the generation of electricity. During daylight PV panels will be energized and and cannot be dedenergized!
- Consider all PV equipment and wires energized and do not touch or cut into or through PV modules, conduit and equipment!
- Do not open combiner box (square box usually only on large commercial units) – all energized wires from the solar panels are fed into the combiner box. Then they are combined into two large high current wires. Opening this box is dangerous. Boxes are normally locked.
- Wear SCBA and full protective clothing.
- Be aware that biting and stinging insects could inhabit the module frame and junction boxes.

If solar panels or batteries are on fire:

- Locate battery storage area (if applicable).
- Shelter-in-place populations-at-risk downwind.
- Extinguish lead-acid battery fires with CO_2, foam or dry chemical fire extinguishers.
- Use Class C extinguishing agents - CO_2 or dry chemical if a PV system shorts and starts a fire.
- Should the array become engulfed in a fire, use water in a fog pattern on the PV array, maintaining a minimum of 33 feet distance away from the energized source.
- Never assume that equipment is de-energized.

IN EMERGENCIES,
CALL DUKE ENERGY FOR ASSISTANCE:

- Indiana: 800-343-3525
- North Carolina: 800-769-3766
- South Carolina: 800-769-3766
- Ohio / Kentucky: 800-544-6900

Duke Energy®

526 South Church Street
Charlotte, NC 28202

www.duke-energy.com/safety

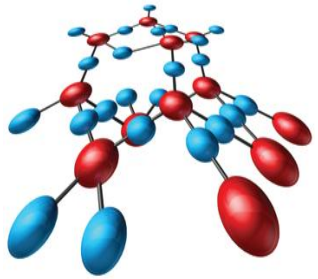
110374 | 10/11

FIRE SAFETY GUIDELINES FOR ROOFTOP- AND GROUND-MOUNTED SOLAR PHOTOVOLTAIC (PV) SYSTEMS

Duke Energy®

This brochure is designed for fire personnel responding to a fire where rooftop- and ground-mounted solar photovoltaic (PV) systems have been installed.

Delivering MORE Together



Solar DC Arc Detect Solution

16 May, 2012

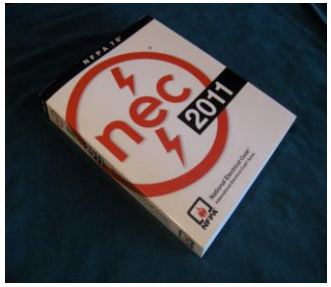
New safety standards require arc detection as part of the PV system installation to reduce the risk of fire and other hazards. TI's RD-195, Arc Detect Solution offers a highly flexible and cost effective means to PV component manufactures for incorporating arc detect feature.

New 2011 NEC Arc-Fault Requirements for PV Systems

Damage from Arcing Event

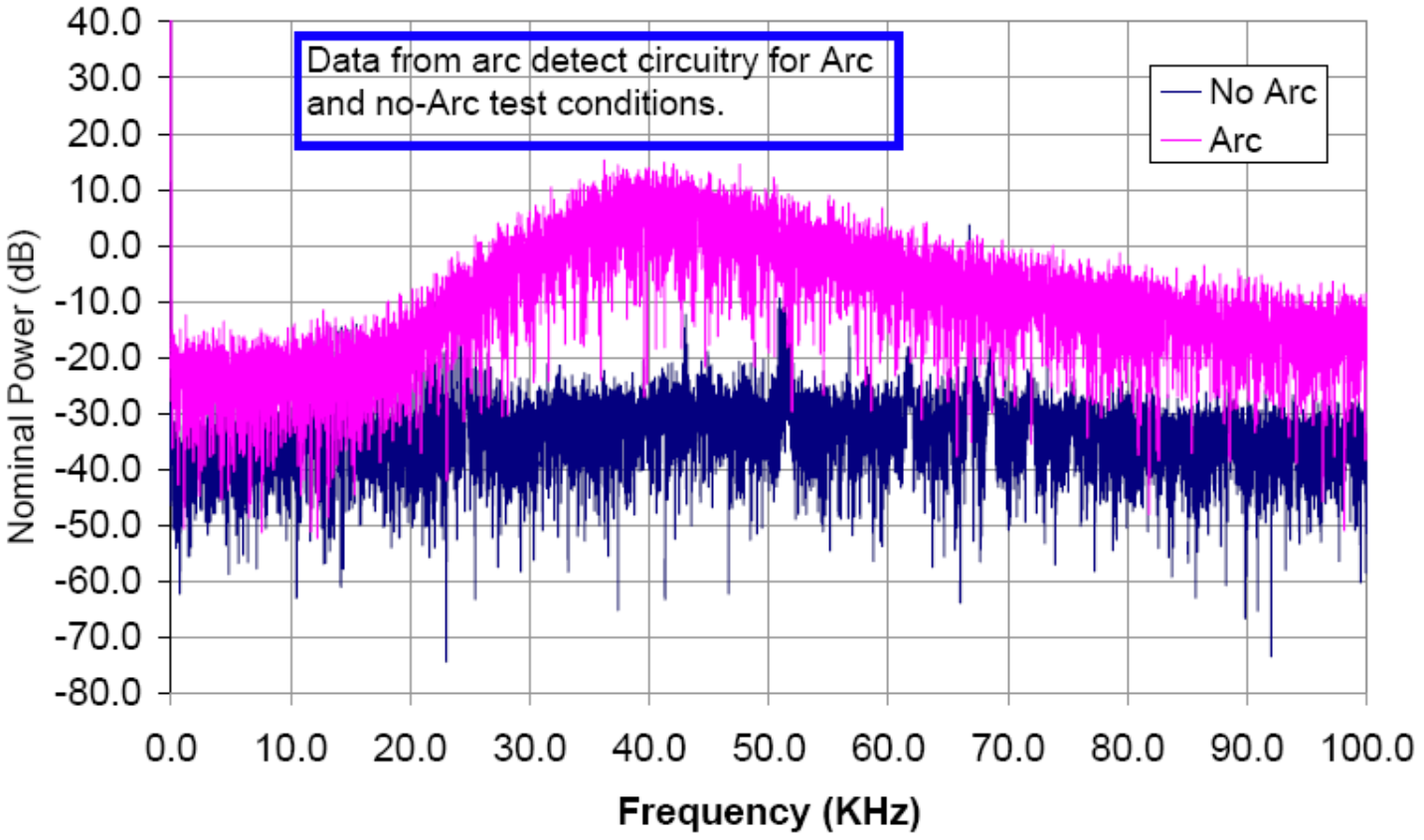
Article 690.11 US Mandate

- Written to detect and interrupt “series” arc-faults in modules, connections, wiring, and other PV System 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 addressed
- Functionality tested according to UL 1699B

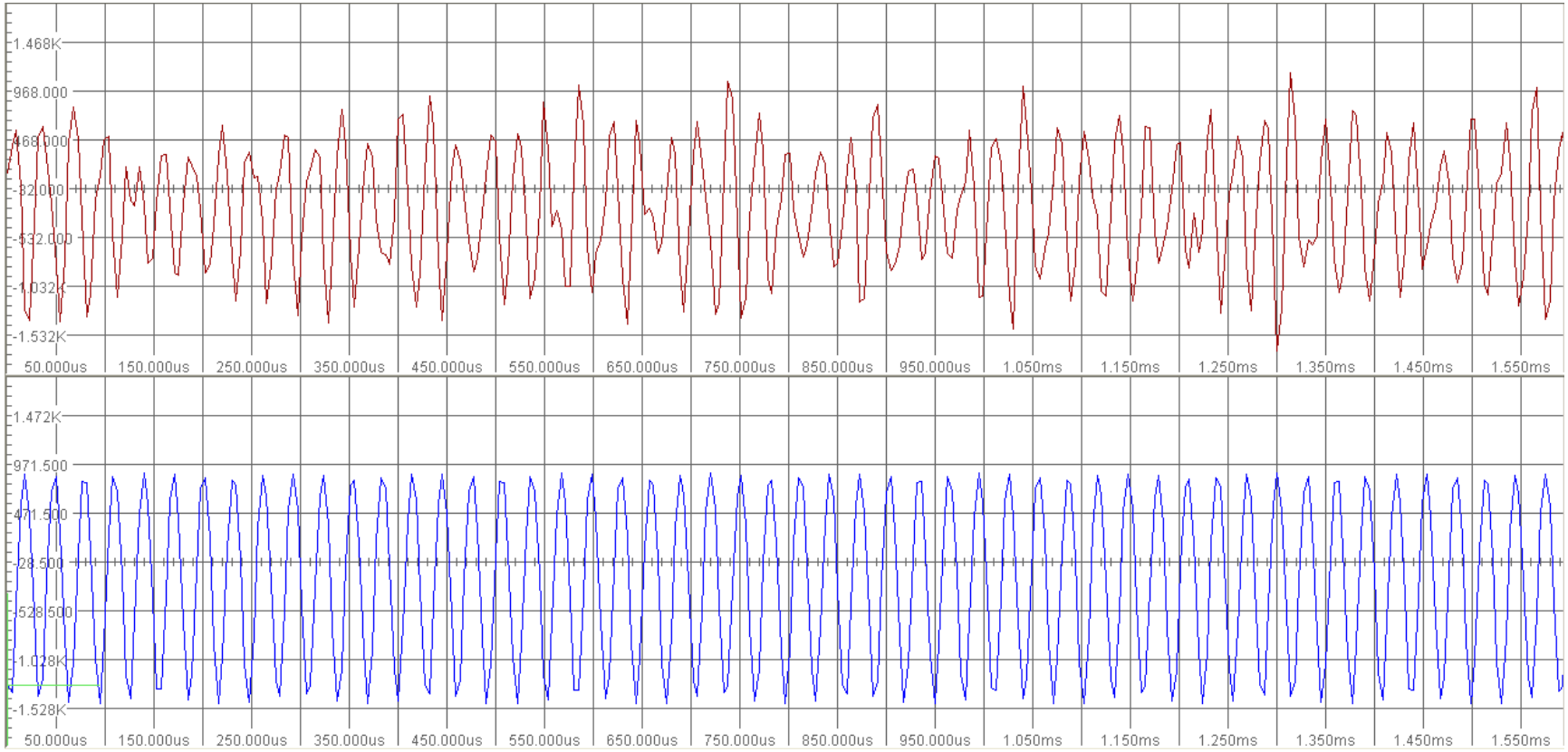


The new 2011 NEC

DC Arc Characteristics



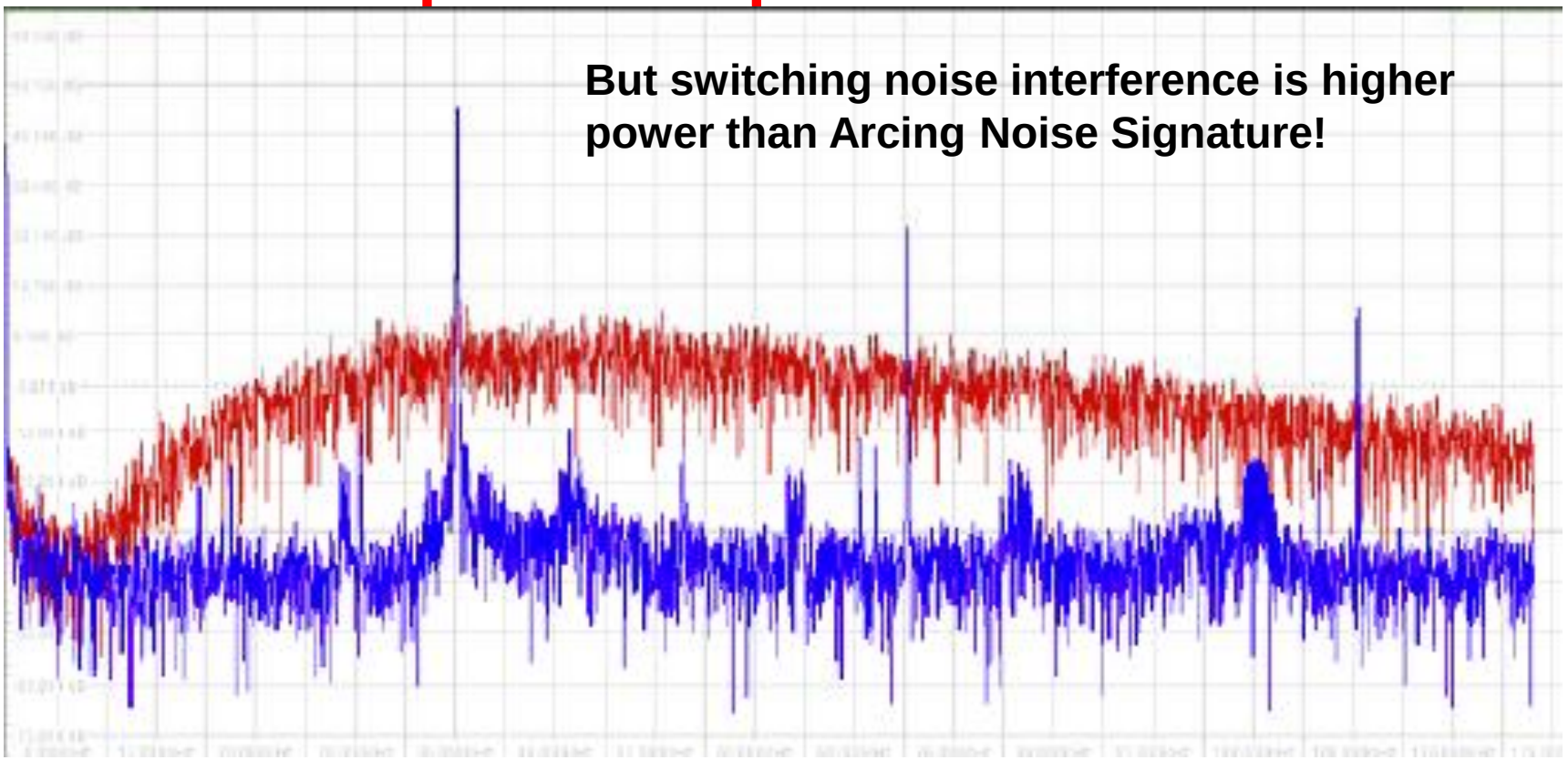
Inverter Interference



Arcing vs. Non-Arcing signals for Inverter 'A' (50µs/div**)**

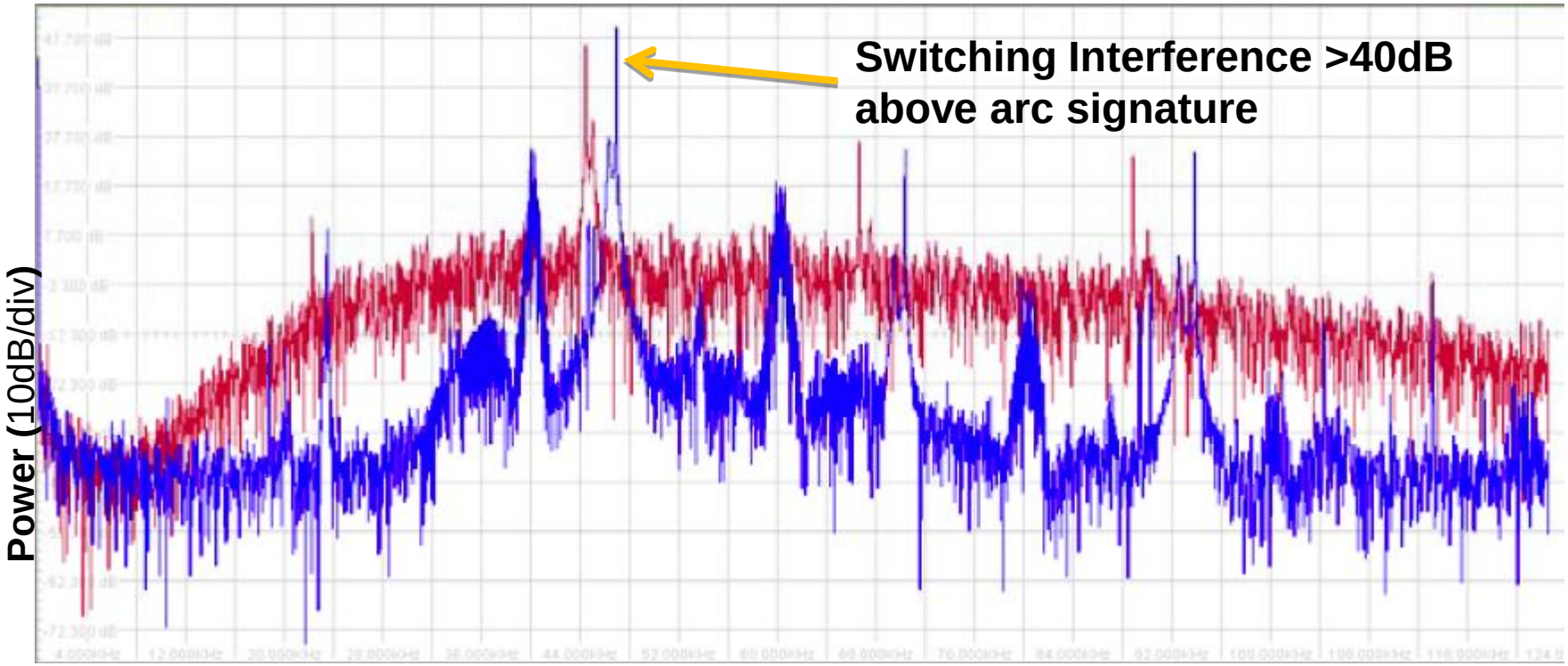
- **Arcing Condition signal magnitude is 24% lower**

Inverter Interference:
Spectral Representation



Spectrum of Arcing vs. Non-Arcing signals for Inverter 'A' (DC-120KHz)

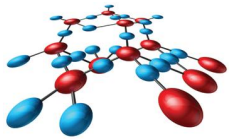
Inverter Interference (cont)



Spectrum of Arcing vs. Non-Arcing signals for Inverter B (DC-120KHz)

Switching Interference varies according to system configuration, illumination, temperature, and shading.

Arc Detection Challenges



❖ Acoustic, pressure sensor, and photo-detector based approaches not feasible for PV systems:

- Effective, but cost too high
- Require significant changes in installation procedures
- Work well in submarines

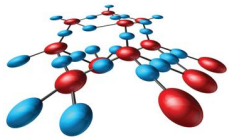
❖ Selection of Frequency range:

- Higher frequencies can have lower levels of interference, due to FCC and certifications.
- But arcing noise reduces at higher frequencies ranges

❖ Lower frequency ranges can have inverter switching interference levels much greater than arc signature:

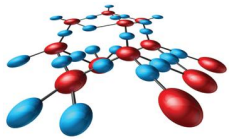
- Interference varies according to inverter architecture, system configuration, load, illumination, temperature....
- Learning Mode based solution is not a desirable approach as an arc could be present when the ‘safe’ condition is learned, resulting in no effective protection.

Arc Detection Challenges (cont.)



- Time Domain Analysis not effective:
  - RMS of inverter signals can greatly exceed arc noise magnitude.
  - Time domain correlation too prone to nuisance trips.

Implementation Approach

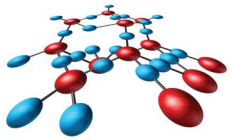


- Transformer pickup provides high-voltage isolation
  - Arcing signal is present in AC component
  - Shunt resistor implementation presents potential exposure to high voltages when arcing event occurs.

- 16-bit 250KSPS ADC with high SFDR (>100dBFS)
  - Arc signature not overwhelmed even when high levels or interference are present
  - Allows for additional headroom in case of multiple interference sources
  - Low power ADC minimizes supply current and power dissipation concerns.

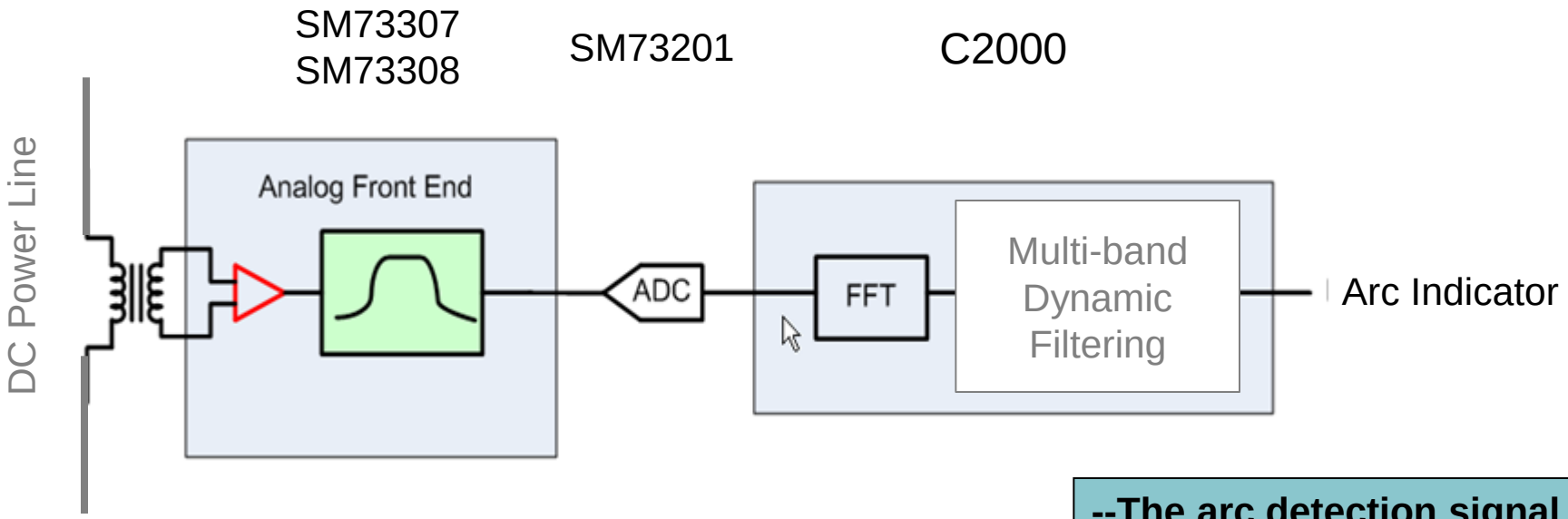
- Dynamic filtering routine
  - MBDF: Multi-Band Dynamic Filtering
  - Not based on an in-place learning-mode
  - Adjustable DSP Filter Parameters
    - Default DSP parameters effective for majority of inverters
    - Can be customized for other inverters
    - Detection bias is nuisance tripping, vs. false negative

SM73201 Arc Detection Solution



- Compliant with NEC requirements
- Detects series, parallel and ground fault arcs
- Arcing Events typically detected within 75ms
- Reference design incorporates multiple annunciators:
  - Digital Output flag
  - UART (RS-232)
  - LED
- Designed to operate in the presence of noise due to switching power electronics (inverters, power optimizers, etc…).
  - **Dynamically adaptive algorithm designed to recognize these signals and avoid false triggers.**
- Tested for all major inverters/PV technologies
- Available for integration into:
  - Smart combiner box, Decentralized PVI (up to 15 A)
  - Multi-string Option
  - Self-Test Feature

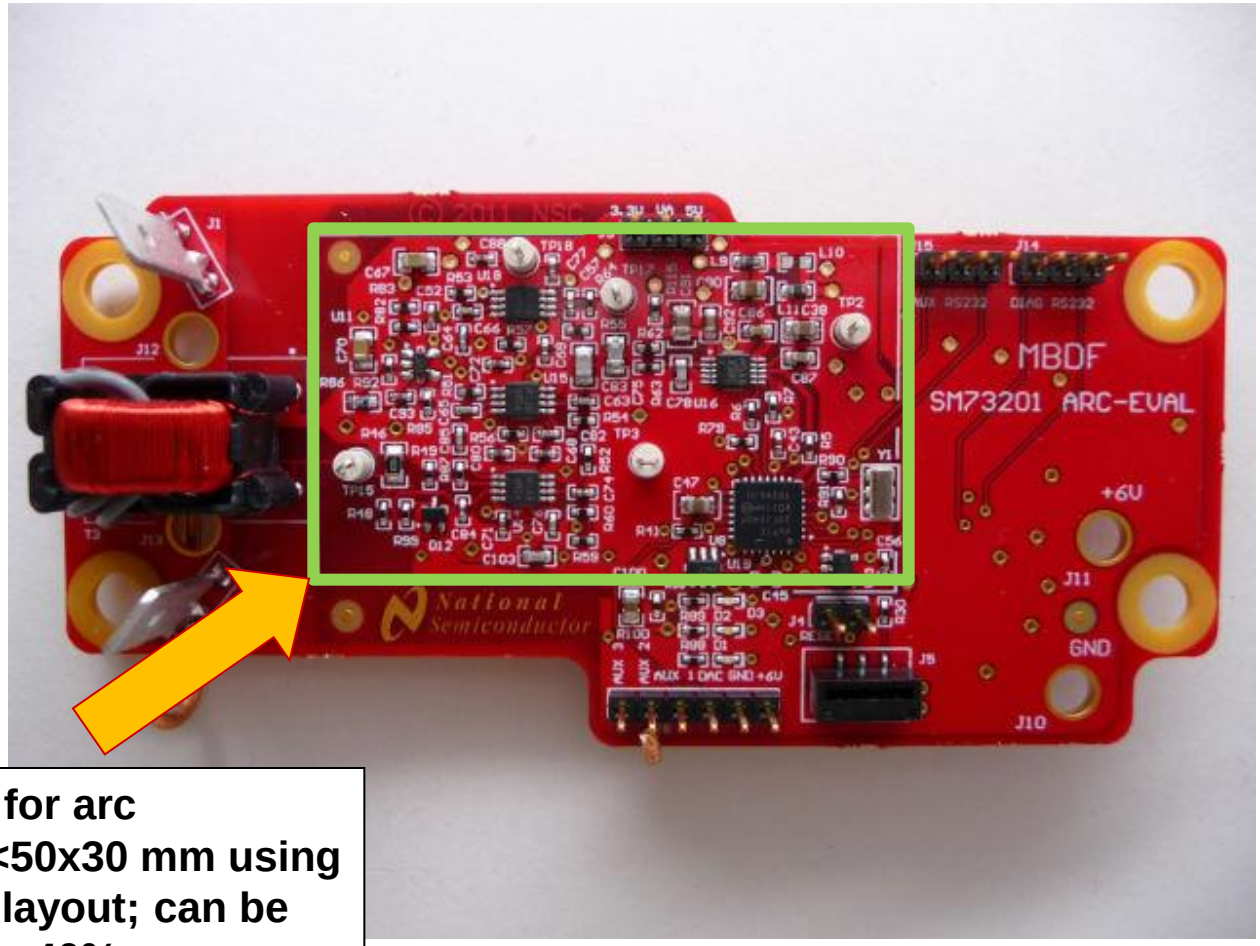
Arc Detection
Principle Block Diagram



Electrical Parameters	*SM73201-ARC-EV*
String current	15A
Multi-string Option	Yes
Max. DC Bus Voltage	1000V (3000 V isolation)
Arc Detection Time	<150 ms

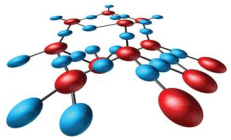
--The arc detection signal can be used in various configurations to trigger the shut-down of the affected module or string:
• Electro-mechanical string shut down
• Inverter based shut-down

Arc Detection
RD-195 Evaluation Board



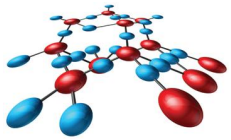
Board area for arc detection: <50x30 mm using single side layout; can be reduced by >40%

RD-195 Evaluation



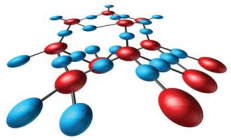
- Evaluted Inverters include:
  - Solectria 5000
  - SMA SunnyBoy 700
  - SMA SunnyBoy 5000US
  - Fronius 5000
  - Fronius IG
  - Fronius IG+
  - Xantrex GT 30 kW Bi-Polar
  - Trace 20208 20 KW
  - Kaco 360xi
- Evaluated Conditions include:
  - Panel and string arrangements (Evergreen, Sanyo, Sunpower,…)
  - Detection locations (V+ and V-)
  - Arc Locations (mid-string, high-side, low-side)
  - Weather conditions
  - Conductors (copper, aluminum, steel)

Implementation Comparison



- Inclusion in Inverters:
  - Provides advantages in reducing false trips – detection parameters (tuning) can be optimized for inverter design
  - Easier to provide supplies
  - Inverter induced events handling better (more system state information available)

- Combiner Box Implementation:
  - Default tune effective in majority of implementations
  - List of effective tuning parameters can be provided to handle others



Thank You!

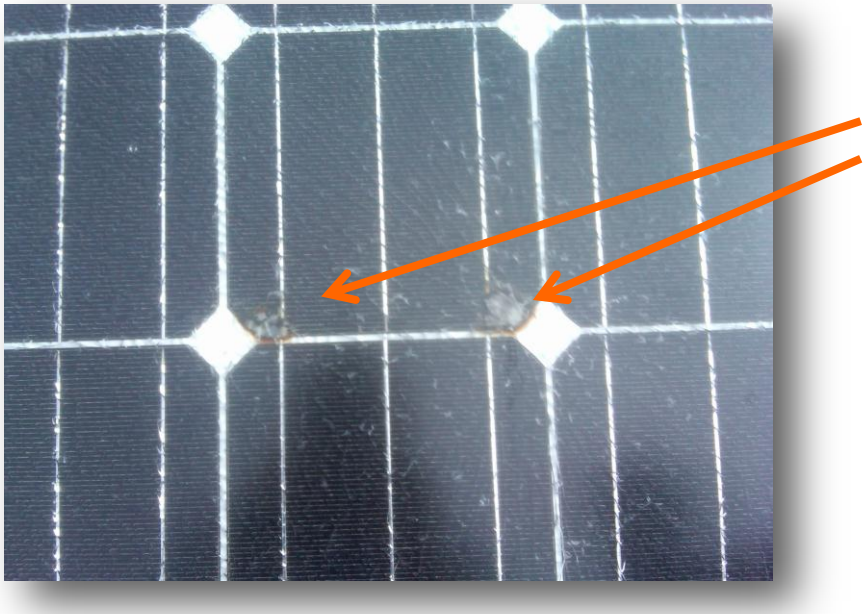
Q&A

Module-Level Electronics and Arc Fault Protection

Scott McCalmont, Ph.D., P.E.
Director of Solar Technology
Tigo Energy, Inc.

scott.mccalmont@tigoenergy.com

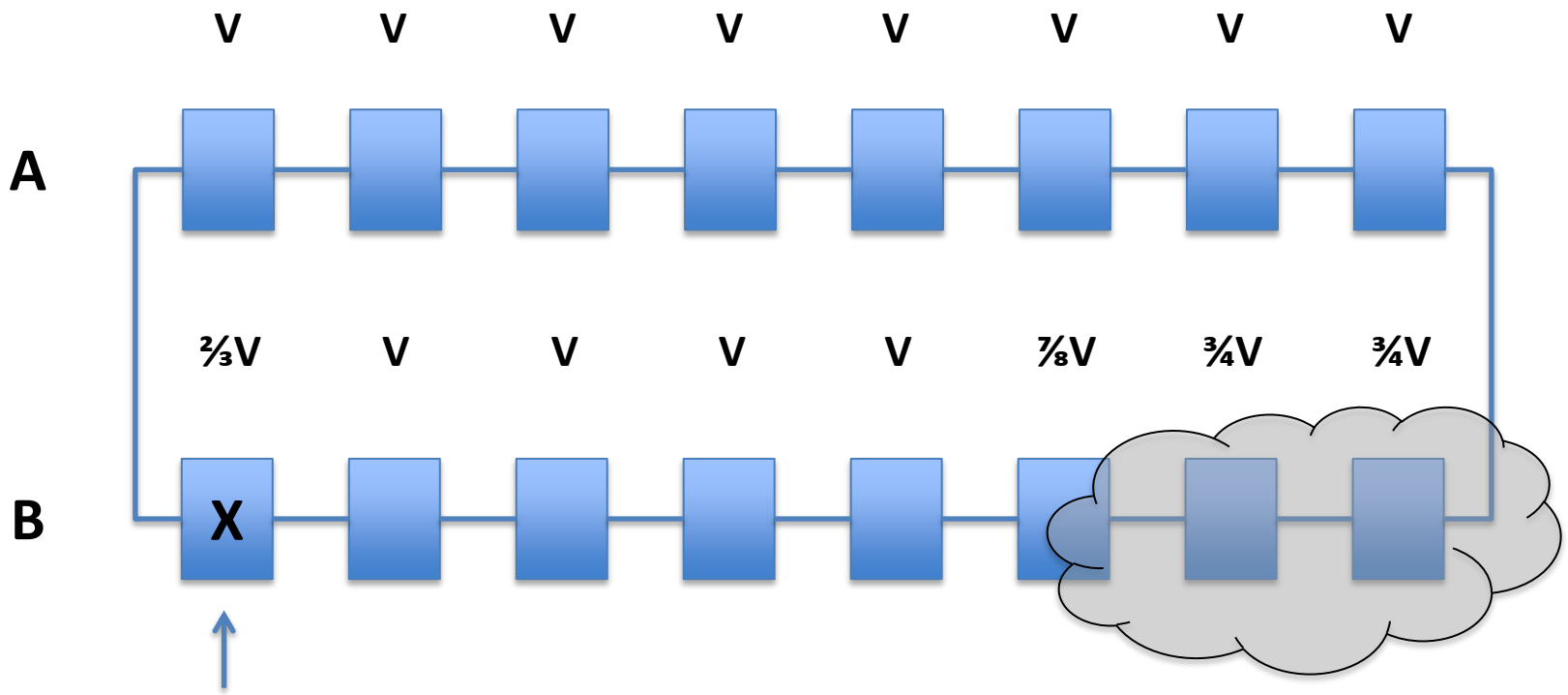
The Result of Arcing Within a Module



The front glass is shattered. The backing sheet has been burned through.

The Tigo Energy Module Maximizer limits the voltage at the PV module, helping to avoid a catastrophic arc fault and fire.

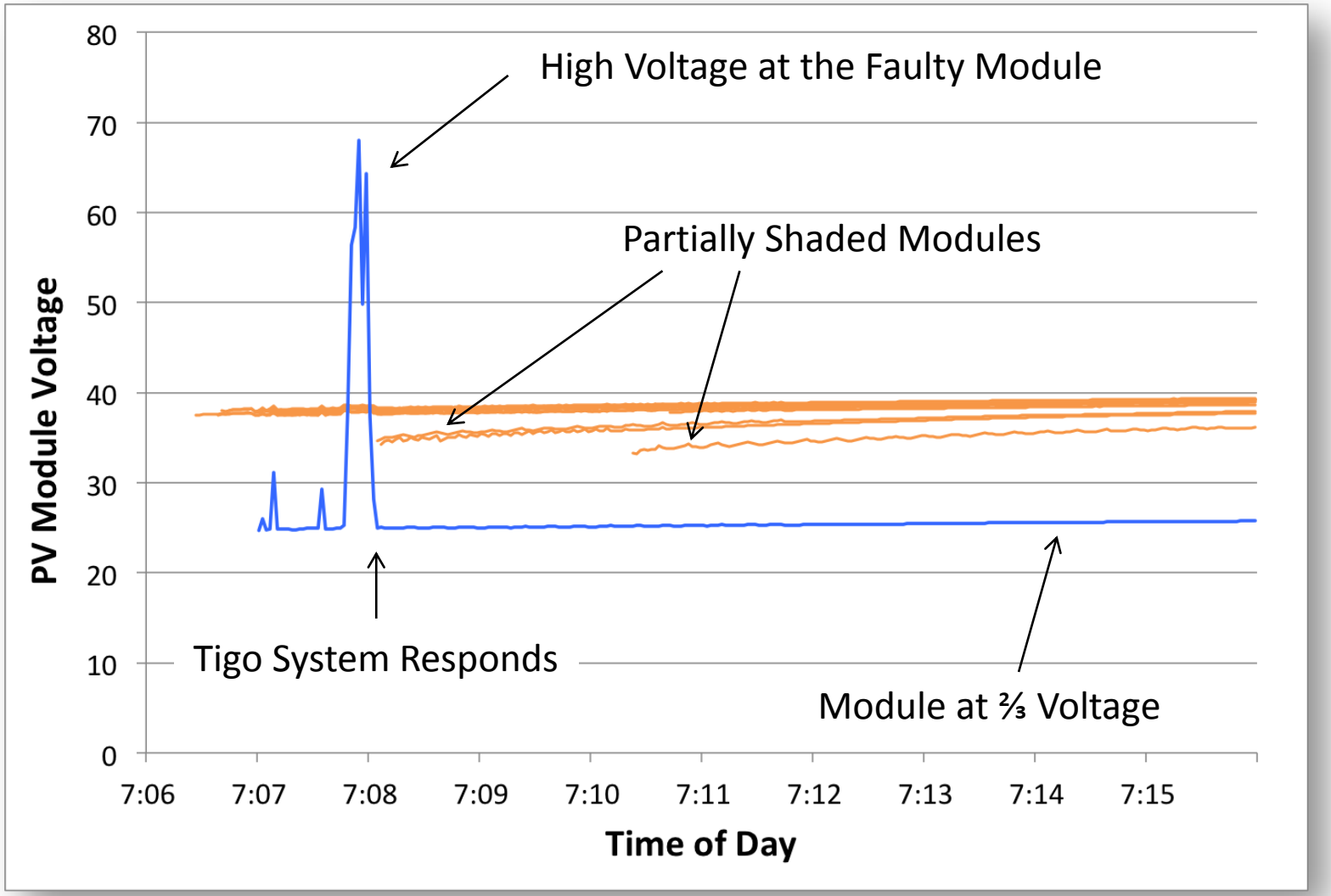
Fault in PV Module Leads to Arc Risk



String A Voltage = 8 × V
String B Voltage ≈ 7 × V

In this example, the full voltage of one panel appears across the fault in the defective module.

Module-Level Data and Control is Essential



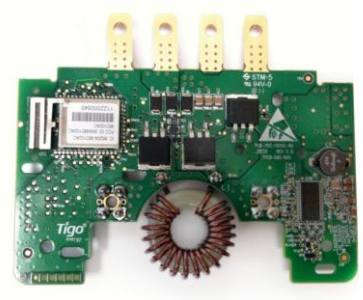
Tigo Energy Reduces the Risk from Arc Faults

Module Maximizer with PV Safe™

- Optimizes energy production
- Limits voltage at module
- Can shut module completely off

String-Level Arc Fault Detector

- Passed UL1699B testing
- Combiner box integration



Module-Level Arc Fault Protection

- Integrated with the Module Maximizer
- A detector/interrupter at every PV module
- J-box integration
- Protects against both series and parallel arcs

Tigo Energy SmartModule™

✔ More Energy ✔ Active Management ✔ **Enhanced Safety**

Arc-Fault Circuit-Interrupter Requirements for PV Systems

- Robert L. LaRocca, P.E.
- UL LLC

2011 NEC®

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:

2011 NEC®

(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

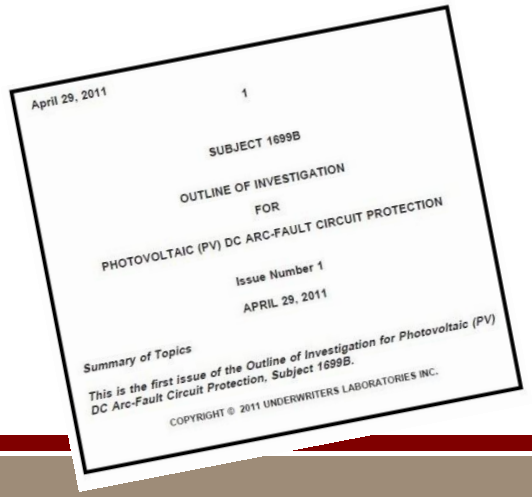
b. System components within the arcing circuit

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

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

Outline of Investigation for Photovoltaic DC Arc-Fault Circuit Protection, Subject 1699B

- PV arc-fault circuit interrupters (**PV AFCIs**)
- arc-fault detectors (**AFDs**)
- associated interrupting devices (**IDs**)
- Requirements also address **inverters**, **converters**, and **charge controllers** with integral AFCI protection.


April 29, 2011 1

SUBJECT 1699B

OUTLINE OF INVESTIGATION

FOR

PHOTOVOLTAIC (PV) DC ARC-FAULT CIRCUIT PROTECTION

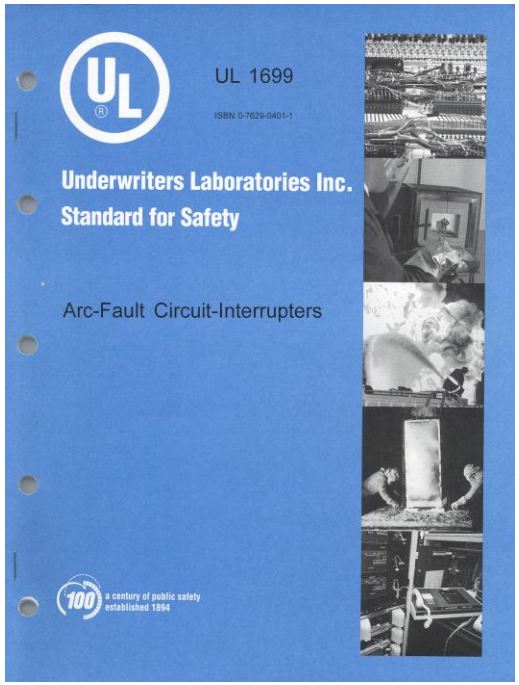
Issue Number 1

APRIL 29, 2011

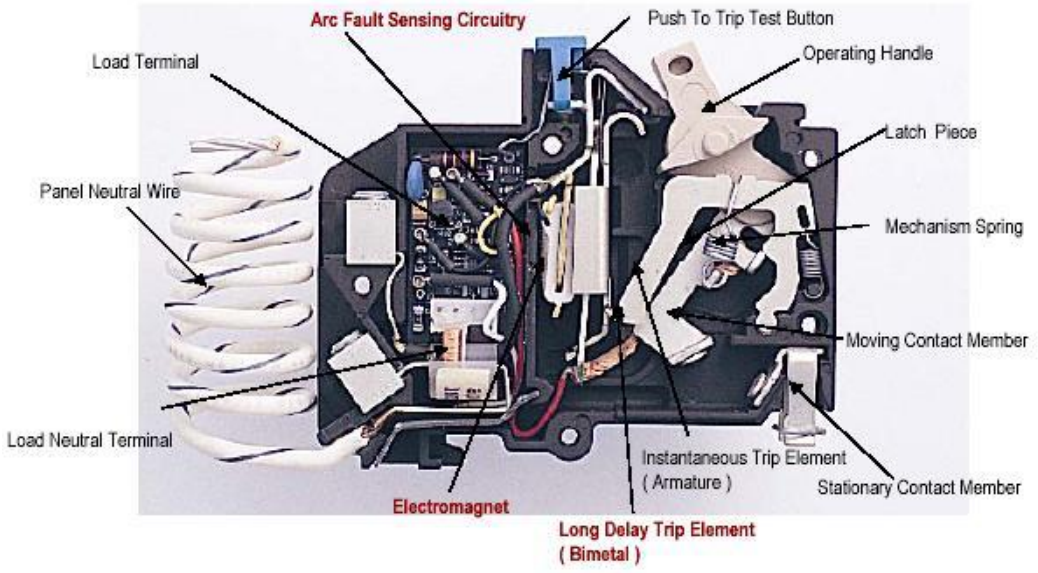
Summary of Topics

This is the first issue of the Outline of Investigation for Photovoltaic (PV) DC Arc-Fault Circuit Protection, Subject 1699B.

Arc-Fault Circuit Interrupter (AFCI)



The NEC defines an AFCI as a device intended to provide protection from the effects of arcing faults by recognizing characteristics unique to arcing and by functioning to de-energizing the circuit when an arc-fault is detected.

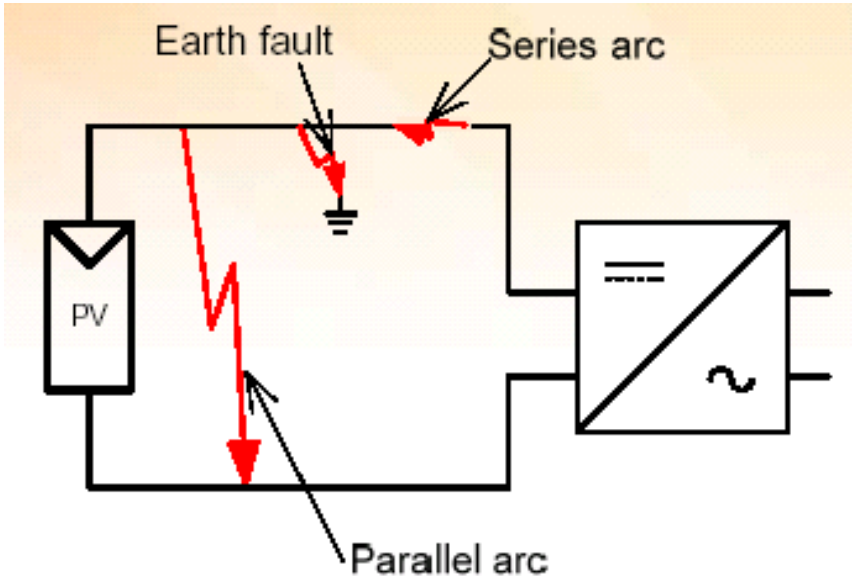


Solar ABCs and the PV DC AFCI

DC arcing to grounded PV metal frame

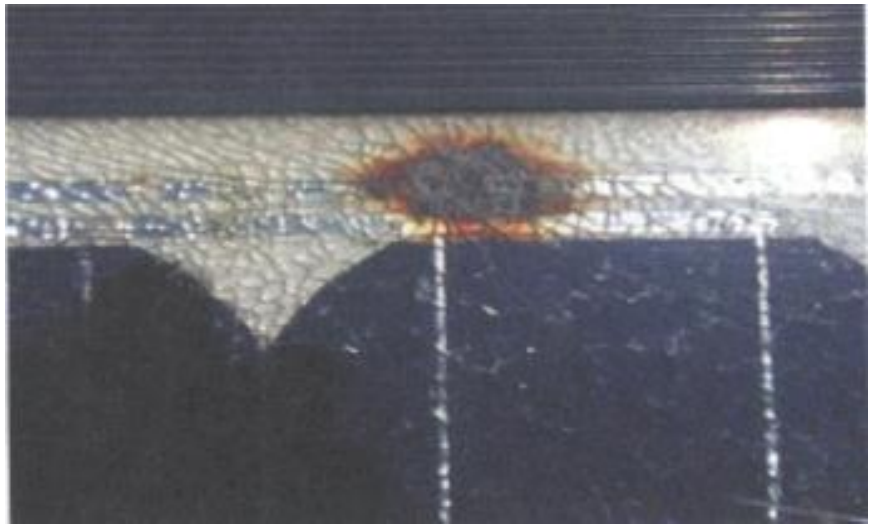
TYPES OF DC PV ARCING FAULTS

Arcing - a luminous discharge of electricity across an insulating medium



Series arc fault and parallel arc fault in PV systems

TYPES OF DC PV ARCING FAULTS



Series Arcing

TYPES OF DC PV ARCING FAULTS

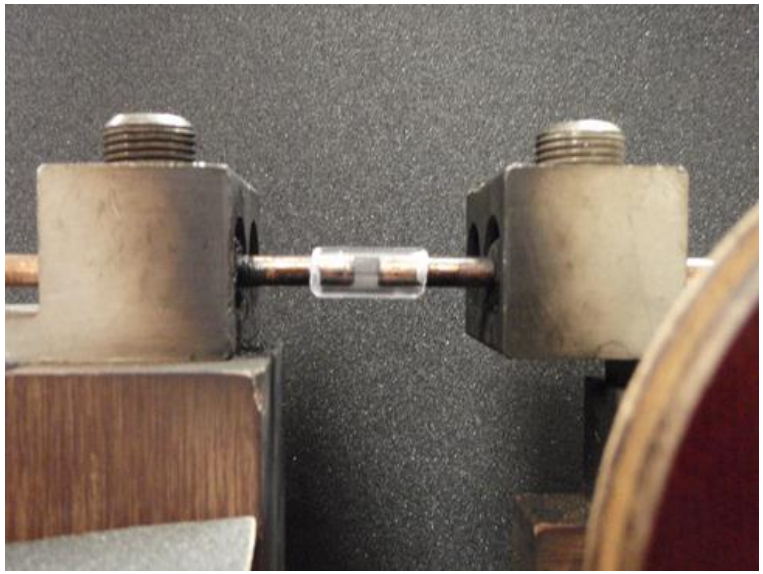
Arcing ground fault

Rodent damage

Parallel Arcing

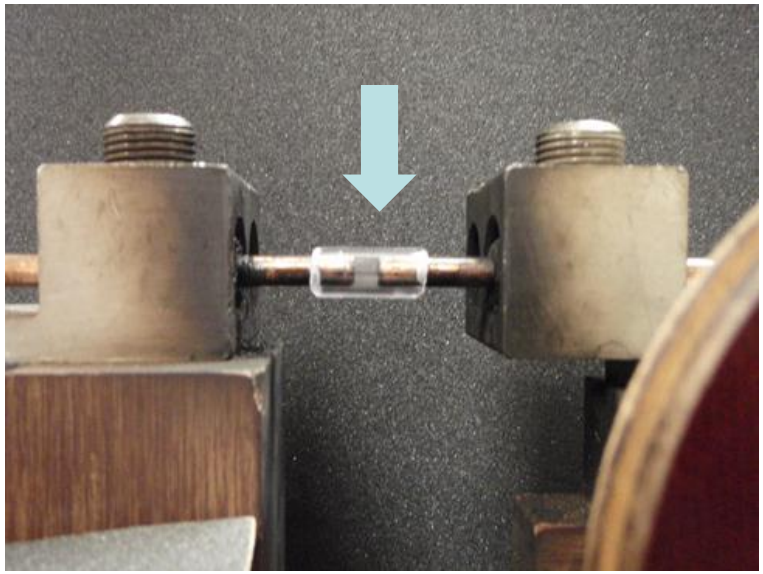
PV AFCI FOR FIRE PROTECTION

In the laboratory, an arc generator can be used to produce arcing:



Laboratory arc generator

PV AFCI FOR FIRE PROTECTION

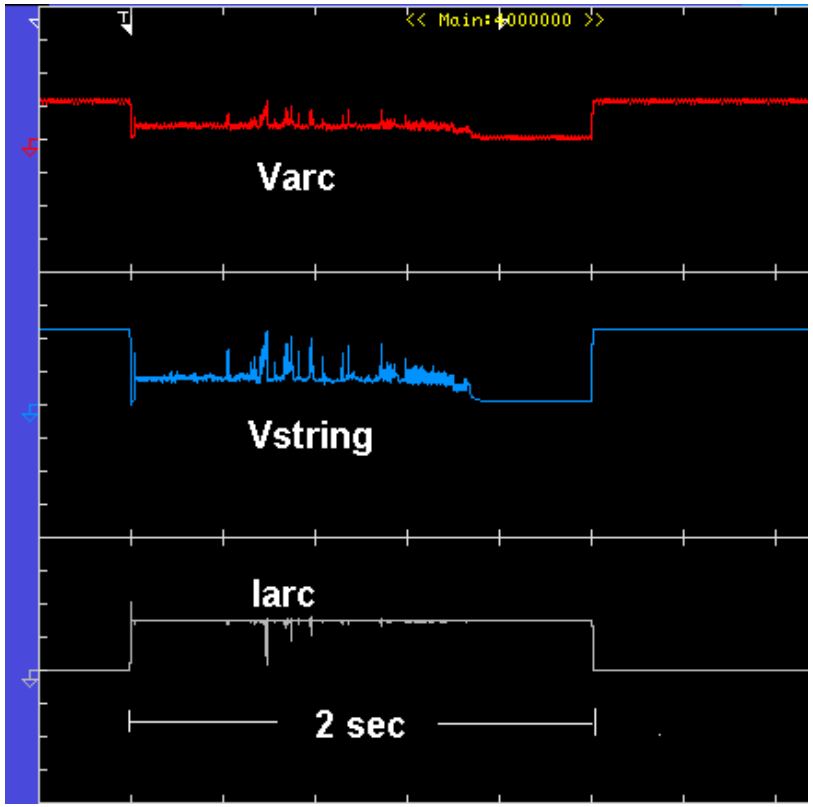


Laboratory arc generator

PV connector

PV AFCI FOR FIRE PROTECTION

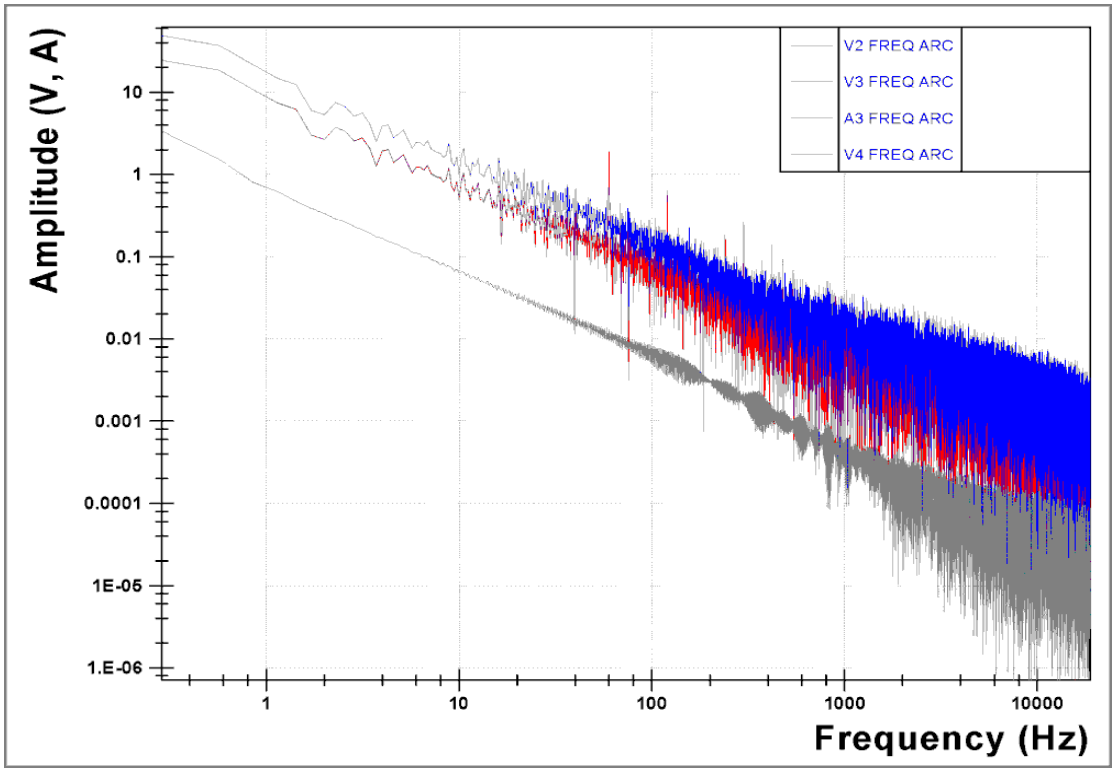
Example of the results of a test with an arc generator - (170 Volts, 7.5 Amps):



Results of arc generator test

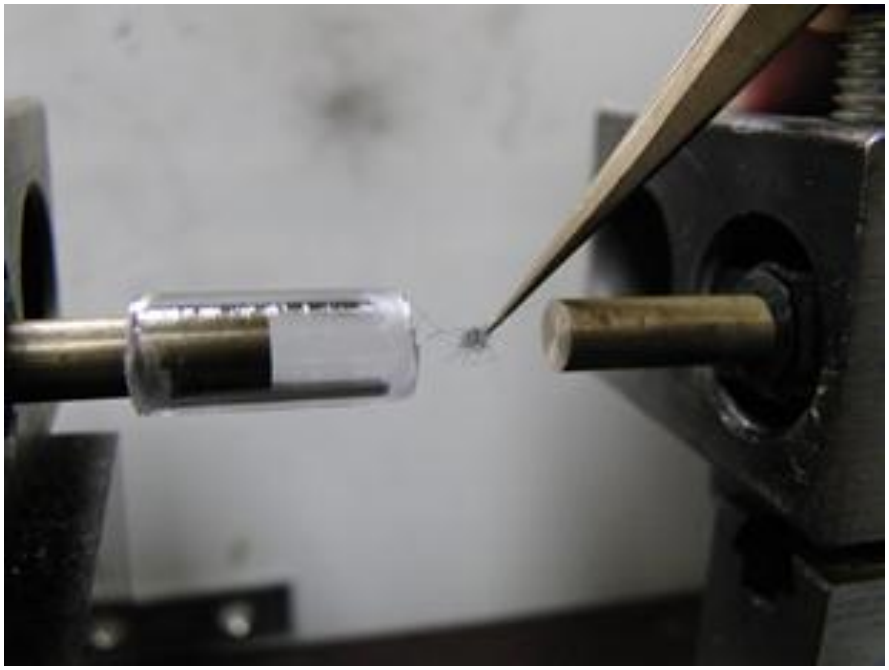
PV AFCI FOR FIRE PROTECTION

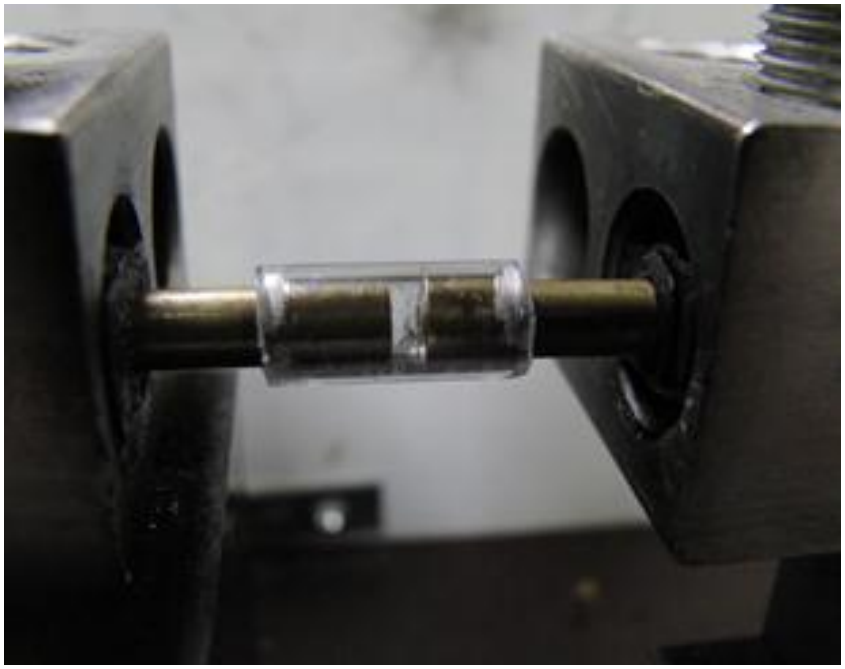
Voltage and current spectra show an inverse relationship to frequency, which is characteristic of the “pink noise” generated during electrical arcing:



Spectra of arc fault waveforms

ARC FAULT DETECTION TEST





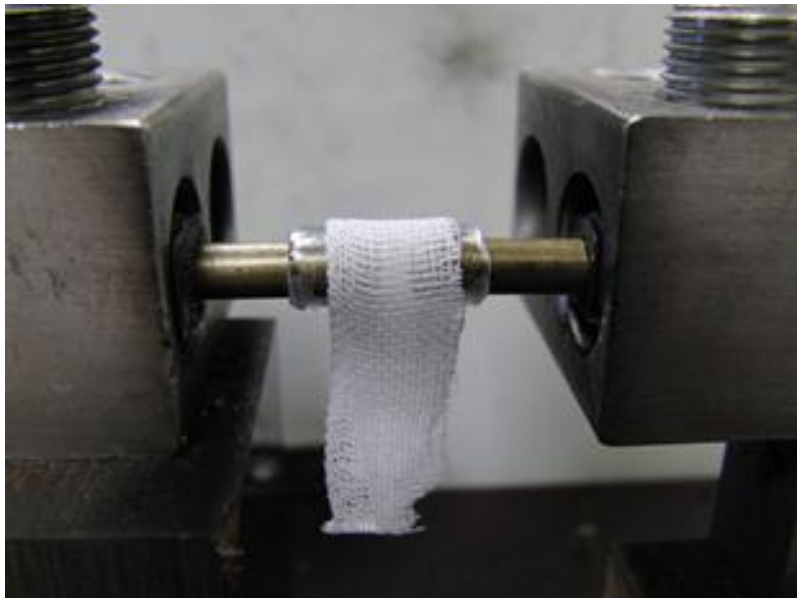
Fine steel wool in tube triggers arc

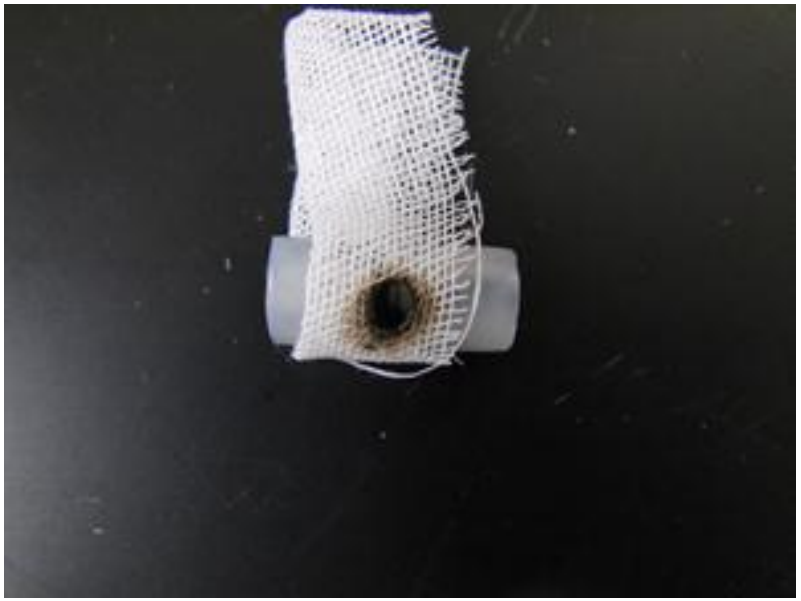
ANALYSIS OF VARIANCE (ANOVA)

Variable	R-Sq (%)	R-Sq (adj) (%)	P	N
Arcing Time	7.67	6.50	0.012	81
Arcing Current	0.52	0.00	0.5424	81
Arcing Voltage	3.78	2.57	0.082	81
Electrode Gap	10.54	9.41	0.003	81
Average Arcing Watts	1.01	0.00	0.372	81
Arc Energy	25.62	24.68	0.000	81

ARC FAULT DETECTION TEST

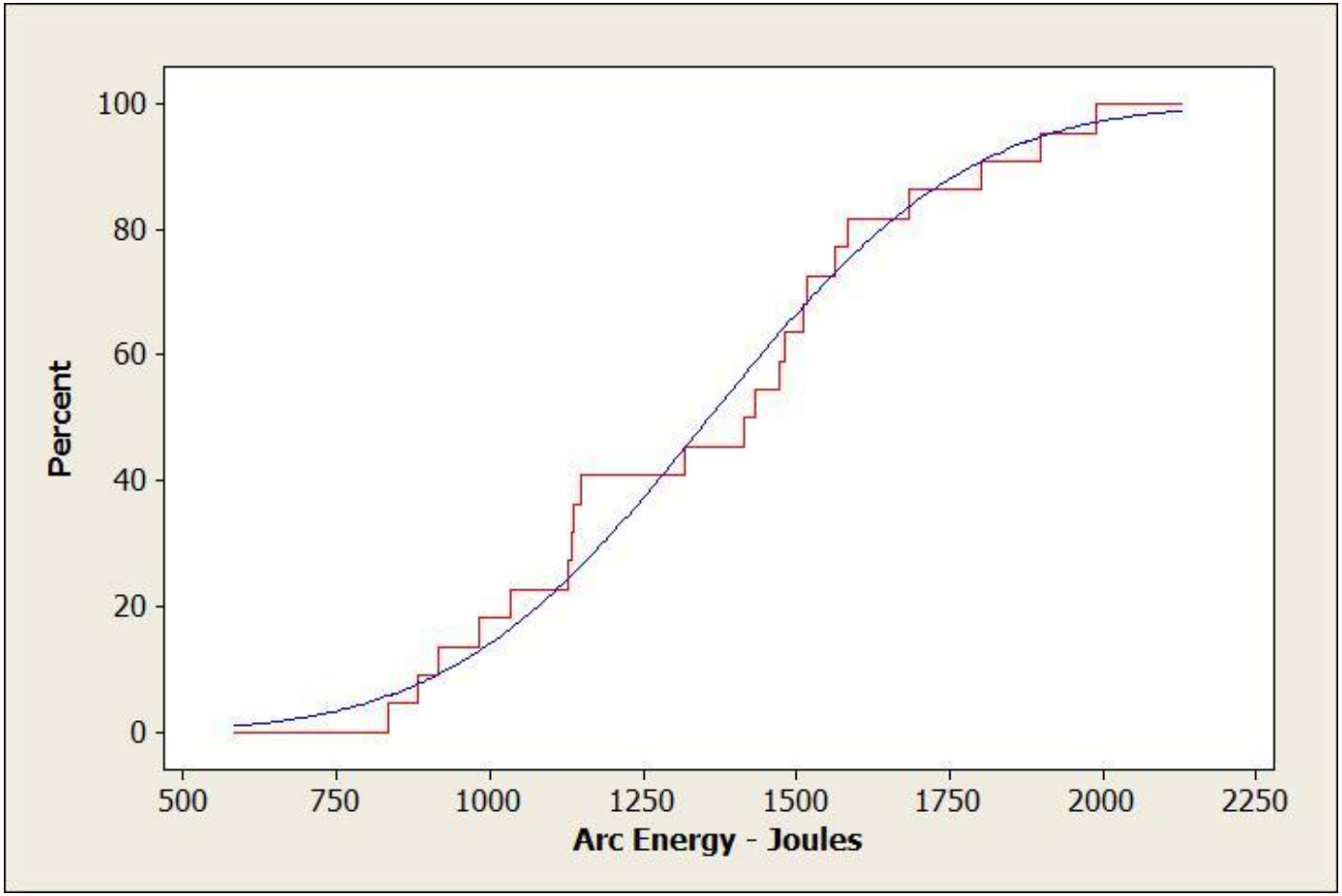
The 750 Joule requirement came from several experimental tests with the arc generator and a 1.6 mm thick polycarbonate tube to determine the arc energy level at which burn through of the tube material might occur





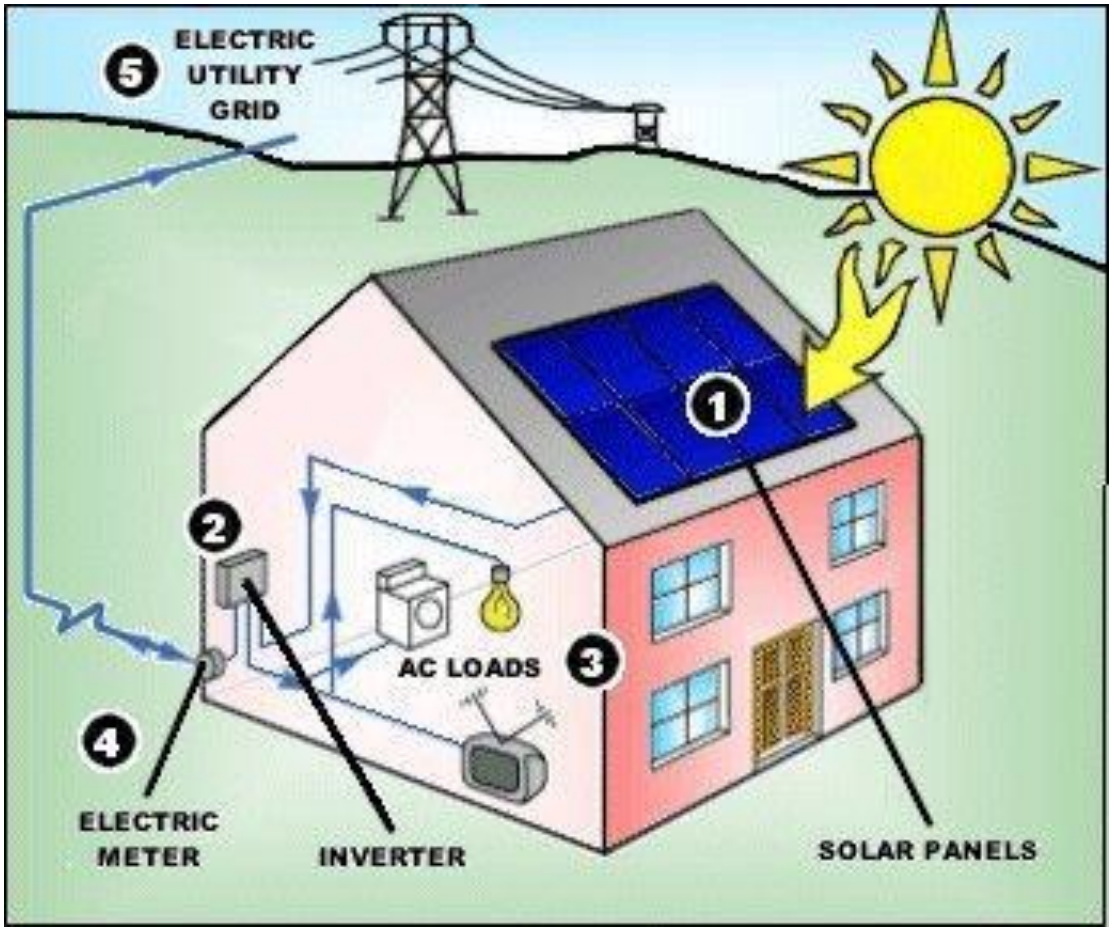
Cheesecloth indicator shows when burn through of tube material occurs

ARC FAULT DETECTION TEST



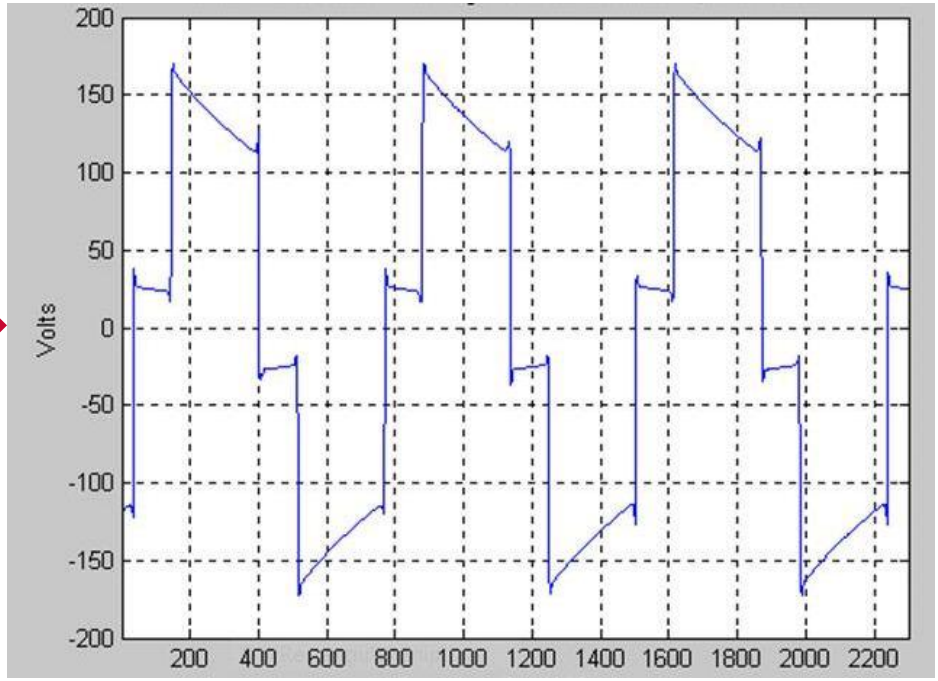
Cumulative distribution of experimental results

ADDITIONAL TESTING



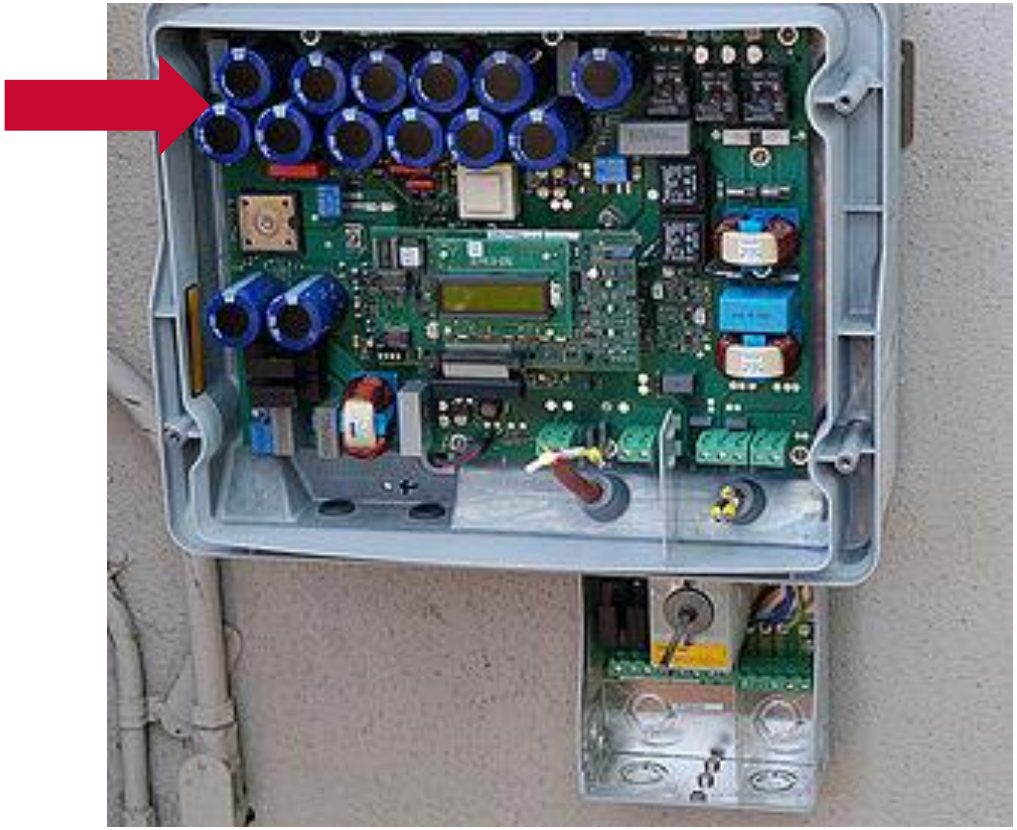
UNWANTED TRIPPING TESTING

- ✓ Input current characteristics of a typical inverter



UNWANTED TRIPPING TESTING

- ✓ Capacitors and inrush current peaks



UNWANTED TRIPPING TESTING

- ✓ DC disconnect switch operation

ADDITIONAL TESTING

OPERATION INHIBITION TESTING

- ✓ Normal operational conditions and loads

MASKING TESTING

- ✓ Multiple inverters or strings in parallel

LISTED PV AFCI

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.

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Photovoltaic DC Arc-fault Circuit Protection

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[Distributed Generation Power Systems Equipment] Photovoltaic DC Arc-fault Circuit Protection

See General Information for Distributed Generation Power Systems Equipment

GENERAL

This category covers direct-current (dc) photovoltaic (PV) arc-fault circuit-protection devices intended for use in solar photovoltaic electrical energy systems as described in Article 690 of ANSI/NFPA 70, "National Electrical Code." This protection is intended to mitigate the effects of arcing faults that may pose a risk of fire ignition under certain conditions if the arcing persists.

These devices are intended for use in circuits rated 1000 V or less. They are intended for use in dc electrical systems that are supplied by a PV source, such as a module with solar cells designed to generate dc power when exposed to sunlight.

These devices have been investigated to determine their ability to recognize and react to arcing faults. They have also been investigated to determine resistance to unwanted tripping because of the presence of arcing that occurs in control and utilization equipment under normal operating conditions, and to verify that operation is not unduly inhibited by the presence of loads and circuit characteristics that may mask or attenuate unwanted arcing.

PRODUCT TYPES

Products covered under this category include PV dc arc-fault circuit-interrupters (AFCI), PV dc arc-fault detectors, PV dc interrupting devices, and inverters, converters and charge controllers with integral arc-fault circuit-interrupter protection.

All of these products are further classified as a Type 1 or Type 2 device:

Type 1 — A device intended to detect or interrupt series arcing faults.

Type 2 — A device intended to detect or interrupt both series arcing faults and parallel arcing faults.

LISTED PV ARC FAULT PROTECTION

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Photovoltaic DC Arc-fault Circuit Protection

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SMA SOLAR TECHNOLOGY AG E210376
SONNENALLEE 1
34266 NIESTETAL, GERMANY

Inverter with integral Type 1 Photovoltaic DC Arc-Fault Circuit Protection (transformer), Model(s) SB5000-US-12, SB6000-US-12, SB7000-US-12, SB8000-US-12

Inverter with integral Type 1 Photovoltaic DC Arc-Fault Circuit Protection (transformer-less), Model(s) SB10000TLUS-12, SB8000TLUS-12, SB9000TLUS-12

LISTED PV ARC FAULT PROTECTION

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CONCLUSIONS

- **PV systems are very unique electrical systems designed to produce electric power in hostile outdoor environments. Degradation of insulating materials and deterioration of electrical connections may be the most serious problems creating series or parallel arcing faults, which can result in fire damage originating in PV system components and wiring.**

- A new concept called a PV AFCI was accepted in the 2011 Code to detect and interrupt arcing faults resulting from a failure in the intended continuity of a conductor, connection, module, or other system components in the direct current PV source and output circuits.

- UL has recently developed requirements for the PV AFCI in the form of an Outline of Investigation, designated Subject 1699B.

- This Outline consists of construction and test requirements for DC arc fault detection to meet current and future NEC requirements for listed PV AFCI protection.

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Discussion

- Are codes and standards adequately addressing the dangers of arc-faults in PV systems?
  - What additional requirements are needed in the *National Electrical Code* to make PV systems safer?
  - Is it necessary for 2014 *NEC* to include parallel arc-fault prevention?
  - What changes would be necessary for series arc-fault detection devices if parallel arc-fault detection was added to the *National Electrical Code*?
- Is industry developing appropriate tools for arc-fault prevention?
  - Could more be done to prevent arc-faults and fires in PV installations?
  - What are the methods for locating the faulty component when the arc-fault detector trips?
  - Are their methods of predicting arc-faults? Could prognostic tools address some of these dangers?
- Is PV bankability at risk due to the fire hazards? Are insurance rates for home-owners with rooftop PV systems going to increase if arc-faults are not addressed?
- Can PV components be designed to passively mitigate arcing?