Photovoltaic Arc-Fault Detection and Mitigation

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System Reliability Session
PV Module Reliability Workshop

25 February 2016
Golden, CO

SAND2016-1470C

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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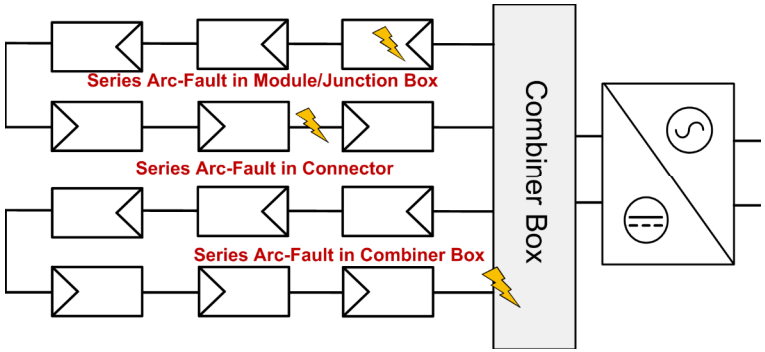
Presentation Outline

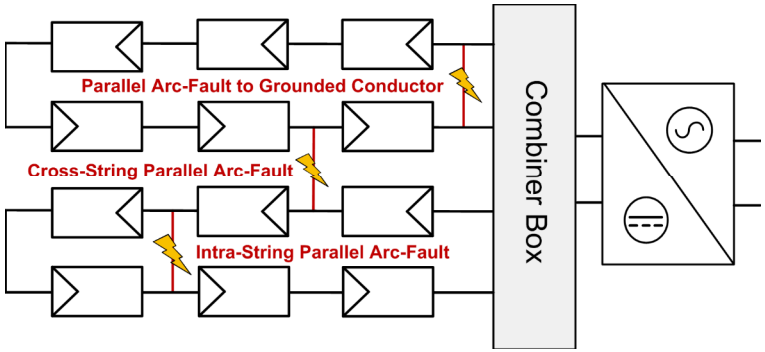
- PV Arc-Fault Types and the National Electrical Code
- Arc Detection Methods
- Arc-Fault Product Requirements in UL 1699B
- Arc-Fault Product Limitations and Tigo Energy Product Survey
- Conclusions

Arc-Fault Types

- 2011 and 2014 *NECs* require **series** arc-fault protection in PV installations above 80 V
- Types of arc-faults
  - Series Arc-Fault – Arc from discontinuity in electrical conductor
  - Parallel Arc-Fault – Electrical discharge between conductors with different potentials
  - Arcing Ground Fault – Parallel arc-fault to the equipment grounding conductor



Series Arc-Faults



Parallel Arc-Faults

Most Inverters Have series AFCIs

- Joe Schwartz, “2016 Single and 3-Phase String Inverter Specifications” SolarPro 9.1, Jan/Feb 2016.

Manufacturer	Model	Integrated Disconnects and Combiners			
		DC disconnect standard	AC disconnect standard	Fused combiner standard	Arc-fault protection
ABB	UNO-2.0-I-OUTD-S-US-A	yes [4]	no	no [4]	yes [4]
ABB	UNO-2.5-I-OUTD-S-US-A	yes [4]	no	no [4]	yes [4]
ABB	UNO-7.6-TL-OUTD-S-US-A	yes [4]	no	no [4]	yes [4]
ABB	UNO-8.6-TL-OUTD-S-US-A	yes [4]	no	no [4]	yes [4]
ABB	PVI-3.0-TL-OUTD-S-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-3.6-TL-OUTD-S-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-3.8-TL-OUTD-S-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-4.2-TL-OUTD-S-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-5000-TL-OUTD-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-6000-TL-OUTD-US-A	yes [4]	no	yes [4]	yes [4]
ABB	TRIO-20.0-TL-OUTD-S1-US-480-A	yes [4]	no	yes [4]	yes [4]
ABB	TRIO-27.6-TL-OUTD-S1-US-480-A	yes [4]	no	yes [4]	yes [4]
Chint Power Systems	CPS SC14KTL-DO/US-208	yes	yes	yes	option
Chint Power Systems	CPS SC20KTL-DO/US-480	yes	yes	yes	option
Chint Power Systems	CPS SCA23KTL-DO/US-480	yes	yes	yes	option
Chint Power Systems	CPS SCA28KTL-DO/US-480	yes	yes	yes	option
Chint Power Systems	CPS SCA36KTL-DO/US-480	yes	yes	yes	option
Delta	SOLIVIA 3.0 TL	yes	no	yes	yes
Delta	SOLIVIA 3.8 TL	yes	no	yes	yes
Delta	SOLIVIA 5.2 TL	yes	no	yes	yes
Delta	SOLIVIA 6.6 TL	yes	no	yes	yes
Delta	SOLIVIA 7.6 TL	yes	no	yes	yes
Fronius USA	GALVO 1.5-1	yes	no	no	yes
Fronius USA	GALVO 2.0-1	yes	no	no	yes
Fronius USA	GALVO 2.5-1	yes	no	no	yes
Fronius USA	GALVO 3.1-1	yes	no	no	yes
Fronius USA	PRIMO 3.8-1	yes	no	no	yes
Fronius USA	PRIMO 5.0-1	yes	no	no	yes
Fronius USA	PRIMO 6.0-1	yes	no	no	yes
Fronius USA	PRIMO 7.6-1	yes	no	no	yes
Fronius USA	PRIMO 8.2-1	yes	no	no	yes
Fronius USA	PRIMO 10.0-1	yes	no	yes	yes
Fronius USA	PRIMO 11.4-1	yes	no	yes	yes
Fronius USA	PRIMO 12.5-1	yes	no	yes	yes
Fronius USA	PRIMO 15.0-1	yes	no	yes	yes
Fronius USA	SYMO 10.0-3 208/240	yes	no	yes	yes
Fronius USA	SYMO 12.0-3 208/240	yes	no	yes	yes
Fronius USA	SYMO 10.0-3 480	yes	no	yes	yes
Fronius USA	SYMO 12.5-3 480	yes	no	yes	yes
Fronius USA	SYMO 15.0-3 280	yes	no	yes	yes
Fronius USA	SYMO 15.0-3 480	yes	no	yes	yes
Fronius USA	SYMO 17.5-3 480	yes	no	yes	yes
Fronius USA	SYMO 20.0-3 480	yes	no	yes	yes
Fronius USA	SYMO 22.7-3 480	yes	no	yes	yes
Fronius USA	SYMO 24.0-3 480	yes	no	yes	yes
Ginlong	Solis-2.5K-2G-US	yes	no	no	yes
Ginlong	Solis-3K-2G-US	yes	no	no	yes
Ginlong	Solis-3.6K-2G-US	yes	no	no	yes

Manufacturer	Model	Integrated Disconnects and Combiners			
		DC disconnect standard	AC disconnect standard	Fused combiner standard	Arc-fault protection
Ginlong	Solis-4K-2G-US	yes	no	no	yes
Ginlong	Solis-4.6K-2G-US	yes	no	no	yes
Ginlong	Solis-5K-2G-US	yes	no	no	yes
Ginlong	Solis-1P6K-3G-US	yes	no	no	yes
Ginlong	Solis-1P7K-3G-US	yes	no	no	yes
Ginlong	Solis-1P7.6K-3G-US	yes	no	no	yes
Ginlong	Solis-1P8K-3G-US	yes	no	no	yes
Ginlong	Solis-1P9K-3G-US	yes	no	no	yes
Ginlong	Solis-1P10K-3G-US	yes	no	no	yes
Ginlong	Solis-6K-US [6]	yes	no	no	option
Ginlong	Solis-10K-US [6]	yes	no	no	option
Ginlong	Solis-15K-US	yes	no	no	option
Ginlong	Solis-20K-US	yes	no	no	option
Ginlong	Solis-25K-US	yes	no	no	option
Ginlong	Solis-30K-US	yes	no	no	option
Ginlong	Solis-36K-US	yes	no	no	option
Ginlong	Solis-40K-US	yes	no	no	option
HiQ Solar	TrueString TS208-5k75	yes [7]	yes [7]	no	yes
HiQ Solar	TrueString TS480-8k	yes [7]	yes [7]	no	yes
Ingeteam	INGECON SUN 1Play 2.8TL U M	option	no	no	yes
Ingeteam	INGECON SUN 1Play 3.3TL U M	option	no	no	yes
Ingeteam	INGECON SUN 1Play 5TL U M	option	no	no	yes
Ingeteam	INGECON SUN 1Play 6TL U M	option	no	no	yes
Ingeteam	INGECON SUN 3Play 16TL U M480	option	no	option	yes
Ingeteam	INGECON SUN 3Play 24TL U M480	option	no	option	yes
Ingeteam	INGECON SUN 3Play 40TL U M480	option	no	option	yes
KACO new energy	1502xi [8]	yes	yes	no	no
KACO new energy	2502xi [8]	yes	yes	no	no
KACO new energy	3502xi [8]	yes	yes	no	no
KACO new energy	5002xi [8]	yes	yes	no	no
KACO new energy	6400xi	yes	no	yes	no
KACO new energy	7600xi	yes	no	yes	no
KACO new energy	6400M [8]	yes	no	yes	no
KACO new energy	7600M [8]	yes	no	yes	no
KACO new energy	2.0 TL1	option	no	option	yes
KACO new energy	3.0 TL1	option	no	option	yes
KACO new energy	4.0 TL1	option	no	option	yes
KACO new energy	5.0 TL1	option	no	option	yes
KACO new energy	XP10U-H4	option	option	option	no
KACO new energy	10.0 TL3 US	option	option	option	yes
KACO new energy	32.0 TL3 M1	yes	yes	no	no
KACO new energy	40.0 TL3 M1	yes	yes	no	no
KACO new energy	50.0 TL3 M1	yes	yes	no	no
KACO new energy	32.0 TL3 M3 [12]	yes	yes	no	no
KACO new energy	40.0 TL3 M3 [12]	yes	yes	no	no
KACO new energy	50.0 TL3 M3 [12]	yes	yes	no	no
Schneider Electric	CL18000 NA	option [4]	no	option [4]	option [4]
Schneider Electric	CL25000 NA	option [4]	no	option [4]	option [4]

Manufacturer	Model	Integrated Disconnects and Combiners			
		DC disconnect standard	AC disconnect standard	Fused combiner standard	Arc-fault protection
SMA America	SB 3000-US	yes	no	yes	option
SMA America	SB 3800-US	yes	no	yes	option
SMA America	SB 4000-US	yes	no	yes	option
SMA America	SB 5000-US	yes	no	yes	yes
SMA America	SB 6000-US	yes	no	yes	yes
SMA America	SB 7000-US	yes	no	yes	yes
SMA America	SB 8000-US	yes	no	yes	yes
SMA America	SB 3000TL-US	yes	no	no	yes
SMA America	SB 3800TL-US	yes	no	no	yes
SMA America	SB 4000TL-US	yes	no	no	yes
SMA America	SB 5000TL-US	yes	no	no	yes
SMA America	SB 6000TL-US	yes	no	no	yes
SMA America	SB 7000TL-US	yes	no	no	yes
SMA America	SB 7700TL-US	yes	no	no	yes
SMA America	SB 9000TL-US	yes	no	no	yes
SMA America	SB 10000TL-US	yes	no	no	yes
SMA America	SB 11000TL-US	yes	no	no	yes
SMA America	STP 12000TL-US	option [17]	no	option [17]	yes
SMA America	STP 15000TL-US	option [17]	no	option [17]	yes
SMA America	STP 20000TL-US	option [17]	no	option [17]	yes
SMA America	STP 24000TL-US	option [17]	no	option [17]	yes
SMA America	STP 60-10-US	option [17]	no	option [17]	no
SolarEdge	SE3000A-US	yes	yes	no	yes
SolarEdge	SE3800A-US	yes	yes	no	yes
SolarEdge	SE5000A-US	yes	yes	no	yes
SolarEdge	SE6000A-US	yes	yes	no	yes
SolarEdge	SE7600A-US	yes	yes	no	yes
SolarEdge	SE10000A-US	yes	yes	no	yes
SolarEdge	SE11400A-US	yes	yes	no	yes
SolarEdge	SE9KUS	yes	yes	no	yes
SolarEdge	SE10KUS	yes	yes	no	yes
SolarEdge	SE14.4KUS	yes	yes	yes	yes
SolarEdge	SE20KUS	yes	yes	no	yes
SolarEdge	SE33.3KUS	yes	yes	yes	yes
Sungrow	SG30KU	yes	option	yes	yes
Sungrow	SG36KU	yes	option	yes	yes
Sungrow	SG60KU	yes	yes	yes	yes
Sungrow	SG60KU-M	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 3800TL	yes	no	yes	yes
Yaskawa (Solectria)	PVI 5200TL	yes	no	yes	yes
Yaskawa (Solectria)	PVI 6600TL	yes	no	yes	yes
Yaskawa (Solectria)	PVI 7600TL	yes	no	yes	yes
Yaskawa (Solectria)	PVI 14TL	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 20TL	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 23TL	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 28TL	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 36TL	yes	yes	yes	yes

DC Arc-Fault Experiment

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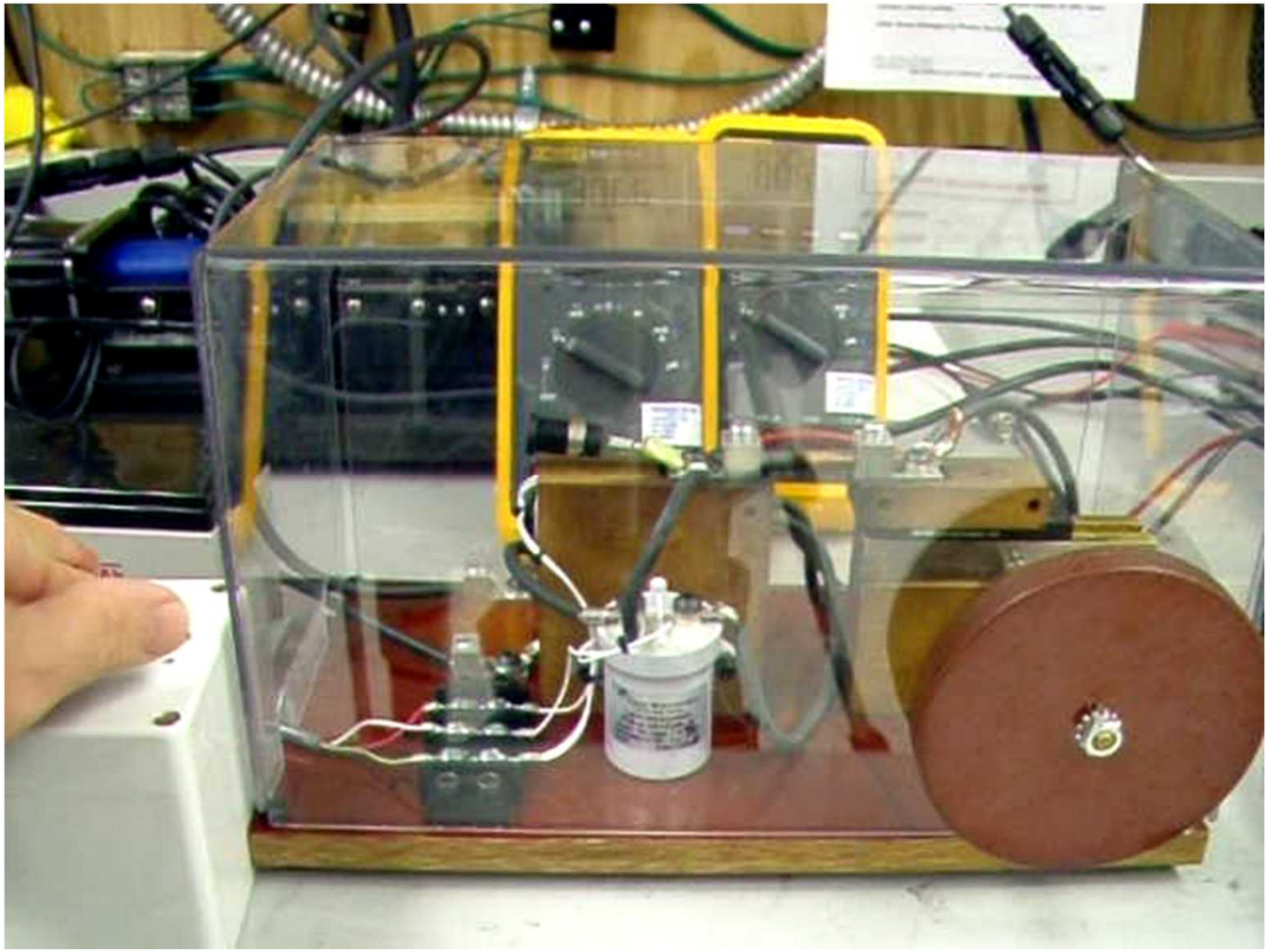
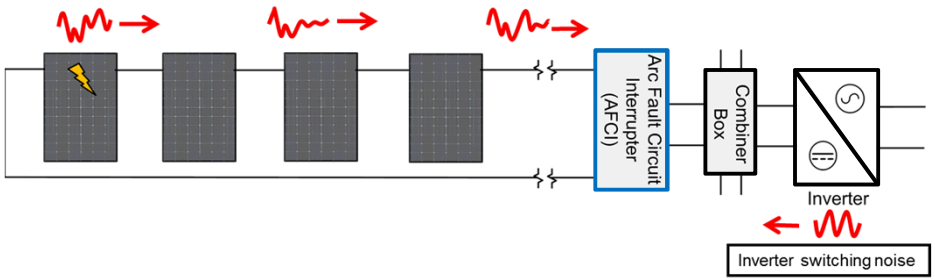


Arc-Fault Detection

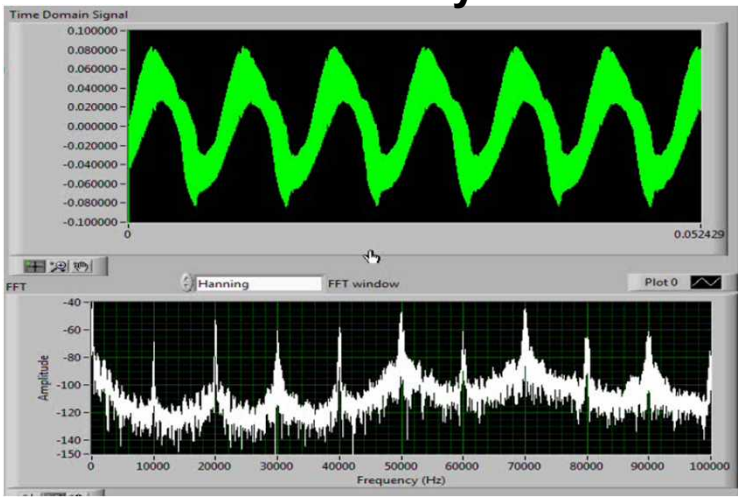
The **conducted noise** on the PV DC conductors is often **used to identify** when series **arcing** occurs in PV systems.

- Generally **frequency domain techniques are used** to trigger the interrupting device.
- Time-based methods have been proposed, but susceptible to noise.
- New techniques using wavelets and learning algorithms are actively being researched.

Series arcing conducted noise propagating through the Dc-side of a PV array



Arcing noise propagating through the array



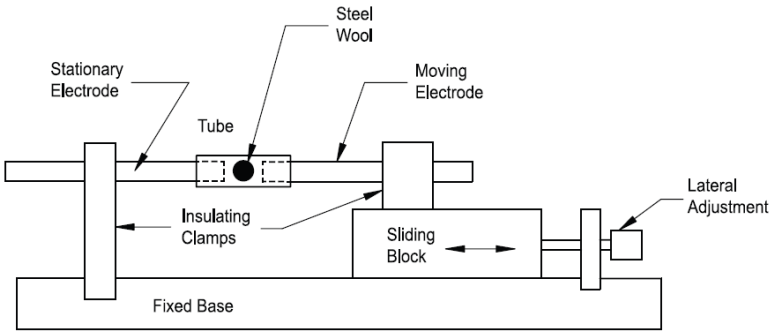
Arc-Fault Certification Standard

- Arc-fault circuit interrupters are listed using **Underwriters Laboratories (UL) 1699B**, "*Outline of Investigation for Photovoltaic (PV) DC Arc-Fault Circuit Protection*"
  - Not a standard yet! Needs to be improved and voted on by the UL Standards Technical Panel (STP) to make UL 1699B an ANSI standard.
  - STP continues to refine the test procedures, test configurations, and number/types of experiments.

- At highest level: UL 1699B needs to verify AFCIs trip when they should and not trip when they shouldn't.
  - The Sept 2013 STP meeting identified the following areas for development:
    - DC power supplies for PV simulation. Need realistic test circuits.
    - Arc generation methods. Need realistic arc-faults to detection tests.
    - Test circuit parameters (e.g., ballast resistors, capacitors). Need realistic test circuits.
    - Unwanted tripping tests. Must check AFCIs for operation on different PV arrays.

Arc-fault generation in UL 1699B

- Currently UL 1699B requires the arc to be created with a tuff of steel wool between the ¼” Cu electrodes
- Electrodes are set to a fixed gap
- 4 tests are required with arc powers between 300-900 W



Arc Powers

Trip Times

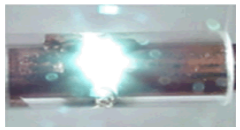
Arcing current (amps)[a, d]	Arcing voltage[b] (volts)	Average Arcing Watts [a]	Approximate electrode, inches (mm) [b]	Max time (sec) [c]
7	43	300	1/16 (1.6)	2
7	71	500	3/16 (4.8)	1.5
14	46	650	1/8 (3.2)	1.2
14	64	900	1/4 (6.4)	0.8

Trip times verified in K.M. Armijo, J. Johnson, R.K. Harrison, K. E. Thomas, M. Hibbs, A. Fresquez, “Quantifying photovoltaic fire danger reduction with arc-fault circuit interrupters,” Progress in Photovoltaics: Research and Applications, 2014, doi: 10.1002/pip.2561.

Alternative arc-fault generation methods

The following variables were parameterized:

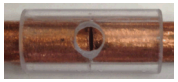
Arc Power



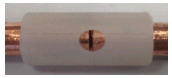
100 W

300 W

Sheath Material



Polycarbonate

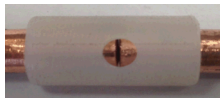


PET

Nylon 6,6

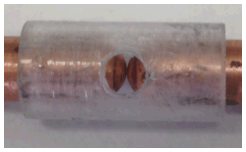
Electrode Diameter

1/8 inch

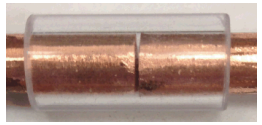


1/4 inch

Electrode Tip

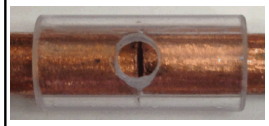


Rounded Tip

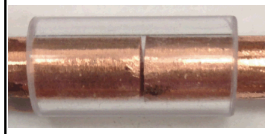


Flat Tip

Hole for O_2 Ingress

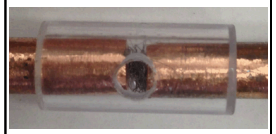


Hole

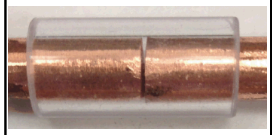


No Hole

Steel Wool Igniter



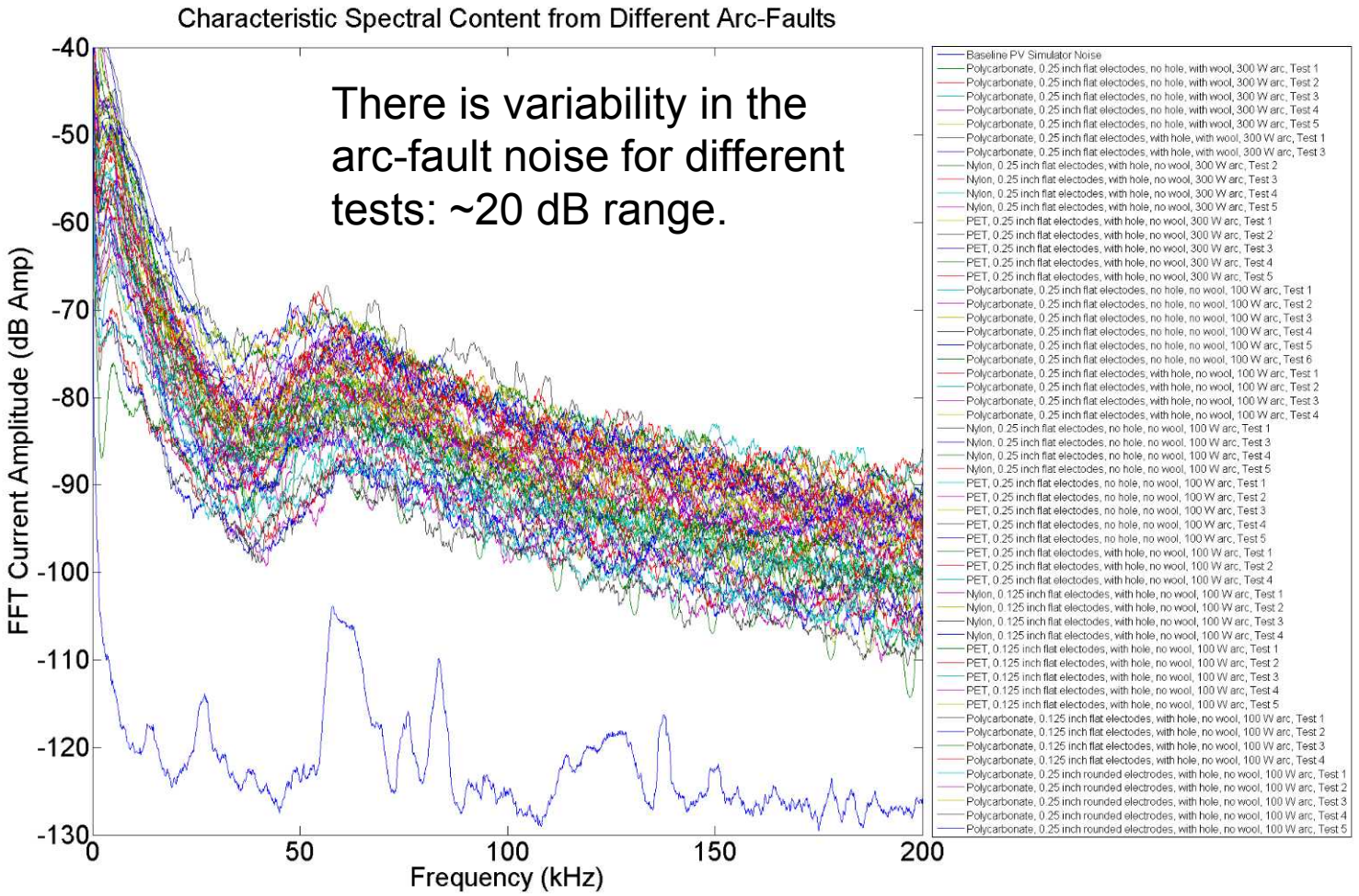
Steel Wool



No Steel Wool

Test Number	Arc Power	Polymer	Electrode Diameter	Electrode Tip	Hole	Steel Wool
1 (UL 1699B)	300 W	Polycarbonate	1/4”	Flat	No	Yes
2	300 W	Polycarbonate	1/4”	Flat	Yes	Yes
3	300 W	Polycarbonate	1/4”	Flat	No	No
4	300 W	Polycarbonate	1/4”	Flat	Yes	No
5	300 W	PET	1/4”	Flat	Yes	No
6	300 W	Nylon 6,6	1/4”	Flat	Yes	No
7	100 W	Polycarbonate	1/4”	Flat	No	No
8	100 W	Polycarbonate	1/4”	Flat	Yes	No
9	100 W	Nylon 6,6	1/4”	Flat	No	No
10	100 W	Nylon 6,6	1/4”	Flat	Yes	No
11	100 W	PET	1/4”	Flat	No	No
12	100 W	PET	1/4”	Flat	Yes	No
13	100 W	Polycarbonate	1/4”	Round	Yes	No
14	100 W	Polycarbonate	1/8”	Flat	Yes	No
15	100 W	PET	1/8”	Flat	Yes	No
16	100 W	Nylon 6,6	1/8”	Flat	Yes	No
17	300 W	Polycarbonate	1/8”	Flat	Yes	No

Arc-Fault Noise at Initiation



- SNL Recommendations for arc detection experiments:
  - Larger (1/4") diameter electrodes. "Pull-apart" generation method (no steel wool). A hole in polymer sheath. Do not use rounded electrode tips. 300 W power.

AFCI Unwanted Tripping

- Problems for manufacturers:
  - Expensive retrofits/redesigns
  - Hurt reputation
  - Loss of business
- Problems for PV owner:
  - Lost energy production – can go days (or months) before manually reset
  - If unwanted faults continue, the owner may remove the AFCI
    - No longer code-compliant
    - Safety feature designed to prevent fires, is no longer operational
      - Life and property at risk
- UL standard should address unwanted tripping to establish a minimum bar for market entry.

Unwanted Tripping Field Experiences

Unwanted Tripping Situation	Evidence
1. Downward power step change.	Manufacturer experienced tripping when a portion of the array was disconnected. Sandia witnessed unwanted tripping when PV simulator irradiance is stepped down and when switching between the simulator and real PV.
2. Upward power/current step change.	Manufacturer has seen high frequency noise when PV systems are energized in the middle of the day.
3. Capacitive coupling (in conduit) from dissimilar PV inverters.	Manufacturer discovered this problem and developed a new AFCI algorithm to address the issue.
4. Conducted DC/DC converter noise on the PV system.	Sandia has seen this with prototype AFCIs.
5. AC noise propagating to the DC with transformerless inverters.	University of Berne reported problems with elevators injecting noise on the AC side and causing DC tripping. A manufacturer stated a PV system on a parking garage would trip when the lights turned on.

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Sandia/Tigo AFCI Experiments

- Tests replicate unwanted tripping experiences in the field
  - 1 arc-fault test
  - 1 masking test (“hiding” the arc-fault)
  - 7 unwanted tripping tests

- Completed 9 experiments with 10 products at Tigo Energy’s Lab in Los Gatos, CA
  - 5 PV inverters (all listed)
  - 1 charge controller (unlisted)
  - 1 combiner box (unlisted)
  - 3 stand-alone AFDs (1 recognized)

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Unwanted Tripping Experiments

Sandia National Laboratories

ARC-FAULT CIRCUIT INTERRUPTER AND ARC-FAULT DETECTOR ARCING, MASKING, AND UNWANTED TRIPPING RESULTS

			Arc Detection Tests		Masking Tests		Unwanted Tripping Tests								
AFCI Product	UL 1699B Compliance	Product Specs	1. Arc-fault Generation at Different Power Levels		2. Masking with Inductance/Capacitance		3. Unwanted Tripping with Inductance/Capacitance in Circuit		4. Loading Condition I						
			100-200 W*	300 W^	L#	C#	L#	C#	Power Supply#	Tigo Optimizers$	Inverter E$	Inverter F$	Inverter G$	Inverter H$	Inverter I$	Charge Controller J$
A	Unrecognized	Stand-Alone AFD Product	✓	✓	Masked 234 W arc with 994 µH, ran indefinitely	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	Trip on startup period	Trip on startup and normal operation	Trip on inrush and startup period	Trip on inrush	Trip on startup and operation	✓
B	Unrecognized	Stand-Alone AFD Product	✓	✓	Masked 234 W arc with 994 µH, ran indefinitely	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	Trip on startup period	Trip on startup period	Trip on inrush and startup period	Trips when using power supply	Trip on startup and operation	✓
C	Recognized	Stand-Alone AFD Product	169 W (36 V, 4.7 A), 30+ seconds, pull apart	✓	Masked 234 W arc with 994 µH, ran indefinitely	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	✓	✓	✓	✓	Trip (only once)	✓
D	Unlisted	8-string Combiner Box with AFCI	169 W (36 V, 4.7 A), 30+ seconds, pull apart	298 W (42 V, 7.1 A), 20 sec, steel wool, Inv. I	Masked 234 W arc with 994 µH, ran indefinitely	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	✓	✓	✓	✓	Trip (only once)	✓
E**	Listed	3.8 kVA, 1ϕ, inverter with transformer	102 W (16 V, 6.4 A), 20+ seconds, pull apart	328 W (40 V, 8.2 A), 20 seconds, pull apart	Masked arc with 994 µH	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
F**	Listed	8.2 kVA, 1ϕ, TL inverter	✓	324 W (38.6 V, 8.4 A), 7 sec, steel wool	✓	✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
G	Listed	3.0 kVA, 1ϕ, inverter with transformer	✓	✓	Masked arc with 994 and 127 µH	Masked continuous arc with 1.5 µF	✓	✓	Would run only with inductors	✓	N/A	N/A	N/A	N/A	N/A	N/A
H	Listed	4.2 kVA, 1ϕ, TL inverter	✓	✓	Tripped when inductor installed	Tripped when capacitor installed	Tripped with 994, 127, and 82 µH	Tripped with 1.5 µF	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
I	Listed	5.5 kVA, 1ϕ, TL inverter	169 W (36 V, 4.7 A), 30+ seconds, pull apart	298 W (42 V, 7.1A), 20 sec, steel wool	N/A	N/A	N/A	N/A	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
J	Unlisted	14.4 kVA, 1ϕ charge controller	✓	N/A	N/A	N/A	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
Recommended for Manufacturer Testing			✓	✓	✓	✓	✓	✓	✓	✓	Test using as many inverters, converters, and charge controllers as possible for stand-alone devices.					
Recommended for UL 1699B Inclusion			✓	✓	Test with 1 mH unless otherwise specified by the mfr.	Test with 3 mF unless otherwise specified by the mfr.	Test with 1 mH unless otherwise specified by the mfr.	Test with 3 mF unless otherwise specified by the mfr.	✓	✓	Test using 1 single phase inverter, 1 three-phase inverter, 1 converter, and 1 charge controller for all stand-alone devices going to be UL 1699B recognition.					

^ Test currently in the UL 1699B Outline of Investigation.
* Tests added to the UL 1699B Outline of Investigation in November, 2014.
# Tests not included in the UL 1699B Outline of Investigation.
$ Only a single 1-phase or 3-phase inverter, converter, or charge controller is used as the load in the current version of Loading Condition I.
** These products are from the same manufacturer.

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Unwanted Tripping Experiments

ARC-FAULT CIRCUIT INTERRUPTER AND ARC-FAULT DETECTOR ARCING, MASKING, AND UNWANTED TRIPPING RESULTS (CONTINUED)

			Unwanted Tripping Tests																	
AFCI Product	UL 1699B Compliance	Product Specs	5. Loading Condition II – DC Disconnect ^	6. Loading Condition III – Irradiance Change*	7. Frequency Sweep with Coupling Transformer#	8. Inductive Coupling between Arrays				9. AC-DC Coupling				10. Broadband Noise Injection			11. Injected Inverter Signatures with Coupling Transformer		
						Inverters F, G, H#	Inverters F, G, I#	Inverters F, G, Charge Controller J#	Inverters E, G, H#	Paper Shredder #	Shop Vacuum #	Bench Grinder #	Relay on AC load#	50 ms#	100 ms#	150 ms#	Noise A#	Noise B#	Noise C#
A	Unrecognized	Stand-Alone AFD Product	✓	Tripped when 1/2 PV array is connected	Square wave tripped at 100 kHz, 133 kHz, 1-10 kHz; 73 & 76 kHz Trip with Inv. F			On J DC system		✓	✓	✓	Tripped with Power Supply	N/A	N/A	N/A	N/A	N/A	N/A
B	Unrecognized	Stand-Alone AFD Product	✓	✓	Square wave tripped at 1 and 2 kHz for many Inv.; Sine wave tripped 3-10 kHz			✓ On J DC system		✓	✓	✓	Tripped with Power Supply	N/A	N/A	N/A	N/A	N/A	N/A
C	Recognized	Stand-Alone AFD Product	✓	✓	Square wave tripped at 2kHz with Inv. E, 12-14 kHz trips with Inv. H			✓ On J DC system		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
D	Unlisted	8-string Combiner Box with AFCI	✓	✓	✓			✓ On J DC system		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
E**	Listed	3.8 kVA, 1ϕ, inverter with transformer	✓	Tripped when 1/2 PV array is disconnected or resistance added	✓				✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
F**	Listed	8.2 kVA, 1ϕ, TL inverter	✓	Tripped when 1/2 PV array is disconnected or resistance added	✓	✓	✓	✓		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
G	Listed	3.0 kVA, 1ϕ, inverter with transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
H	Listed	4.2 kVA, 1ϕ, TL inverter	✓	✓	✓	✓			✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
I	Listed	5.5 kVA, 1ϕ, TL inverter	✓	✓	N/A		✓			✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
J	Unlisted	14.4 kVA, 1ϕ charge controller	✓	✓	Square wave tripped at 1-2 kHz and 4 kHz			✓		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Recommended for Manufacturer Testing			✓	✓	✓	✓	✓	✓	✓	Test as many devices as possible.			✓	✓	✓	✓	✓	✓	✓
Recommended for UL 1699B Inclusion			✓	✓	✓ (With sine wave injection)	Test with same devices from Loading Condition I							✓	✓					

^ Test currently in the UL 1699B Outline of Investigation.
* Tests added to the UL 1699B Outline of Investigation in November, 2014.
# Tests not included in the UL 1699B Outline of Investigation.
** These products are from the same manufacturer.

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Conclusions/Recommendations

- Difficult to balance detection sensitivity with resistance to unwanted tripping.
- 9 detection, masking, and unwanted tripping experiments were conducted on 10 AFD/AFCI products.
  - 6 of the products passed UL 1699B and are UL-recognized or UL-listed.
  - AFCI/AFD issues with all products.
  - 1 inverter product did not experience unwanted tripping.
- Recommend manufacturers complete more comprehensive unwanted tripping experiments.
- Recommend UL 1699B STP adopt some of these experiments to improve products entering the market.

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Questions?

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