Parametric Study of PV Arc-Fault Generation Methods and Analysis of Conducted DC Spectrum

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Abstract — **Many photovoltaic (PV) direct current (DC) arc-fault detectors use the frequency content of the PV system to detect arcs. The spectral content is influenced by the duration and power of the arc, surrounding insulation material geometry and chemistry, and electrode geometry. A parametric analysis was conducted in order to inform the Underwriters Laboratories (UL) 1699B ("Photovoltaic DC Arc-Fault Circuit Protection") Standards Technical Panel (STP) of improvements to arc-fault generation methods in the certification standard. These recommendations are designed to reduce the complexity of the experimental setup, improve testing repeatability, and quantify the uncertainty of the arc-fault radio frequency (RF) noise generated by different PV arcs in the field. In this investigation, we (a) discuss the differences in establishing and sustaining arc-faults for a number of different test configurations and (b) compare the variability in arc-fault spectral content for each respective test, and analyze the evolution of the RF signature over the duration of the fault; with the ultimate goal of determining the most repeatable, 'worst case' tests for adoption by UL.**

Index Terms — **arc-fault circuit interrupters, arc-fault detectors, photovoltaic systems, PV reliability, UL 1699B.**

I. Introduction

The time-domain measurements and spectral content during DC arc-fault generation has been studied extensively to determine methods for arc-fault detection [2-7] and to identify challenges associated with arc detection in PV systems, e.g., tripping multiple AFCIs due to crosstalk [8], differentiating series and parallel arc-faults [9-11], and determining the location of the arc-fault [12-13]. Most residential PV inverters manufactured today are equipped with arc-fault protection systems based on this research. In order to comply with the National Electrical Code (NEC) Requirement 690.11, a Nationally Recognized Testing Laboratory (NRTLs) must certify the product to Underwriters Laboratories (UL) 1699B [1]. Currently, UL 1699B is an Outline of Investigation for certifying photovoltaic (PV) direct current (DC) arc-fault circuit interrupters (AFCIs). In order to transition the Outline of Investigation into a certification standard, the Standards Technical Panel (STP)—made up of stakeholders from industry, government, and academia—vote to adopt the Outline as a standard. Before this happens, the committee needs to define consensus methods for conducting the certification testing. However, there are a number of areas still under debate, including defining types and configurations of PV simulators allowed to perform arc-fault tests, expansion of the number and range of the unwanted tripping tests, and alternative methods for generating arc-faults. In this paper, we focus on technical questions surrounding arc-fault generation by performing a parametric study to determine appropriate arc-fault generation methods for the standard. The goal of this work was to identify repeatable arc-fault generation methods which establish sustainable arcs and determine arc-fault tests which are the most challenging to detect, i.e., produce the least conducted radio frequency (RF) noise on the DC system.

In UL 1699B, 300-900 W arc-faults are generated by inserting a tuff of fine (size 00) steel wool in a polycarbonate sleeve between two ¼ inch diameter copper electrodes. As described in Hastings' original work on arc generation and burn times [14], when the PV DC current passes through the steel wool, it vaporizes and establishes the arc-fault plasma discharge between the two electrodes. Through trial and error, the correct gap size can be preselected to provide an arc voltage drop which generates arcs within the ±10% target power level required by the outline. In this study, a PV simulator was programmed with I-V curves that generate constant power regardless of arc voltage. This technique was used to determine burn times for different polymers found in PV systems [15], and validate heat transfer models of arc-fault plasma [16]. During this process, ignition times and temperatures were measured with respect to input power levels to investigate material degradation and arc-fault limitations. Using this novel technique, a parametric study of different arc-fault generation methods was performed to determine the ease and repeatability of generating an arc-fault for different DC arc power levels, electrode geometries, and respective polymer sheath materials and geometries. Additionally, since many AFCIs use the RF noise for arc-fault detection, real-time Discrete Fourier Transforms were collected and saved for each test. These spectral signatures were analyzed to determine which arcing parameters establish the 'least detectable' arc-faults in PV systems.

II. Repeatable Arc-Fault Generation

In order to determine potential improvements to the arc-fault generation method provided in UL 1699B, a range of different arc-faults were established by varying the polymer sheath geometry/material, electrode geometry, and initiation method. The two initiation methods were manually separating the electrodes by hand ("pull-apart" method), and using steel wool between the electrodes, with the electrodes remaining

TABLE I
SUMMARY OF ARC-FAULT EXPERIMENTS WITH A PV SIMULATOR AND ARC-FAULT GENERATOR

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

stationary. In both cases, the electrode gap was fixed to a respective arc initiation position unless the arc self-extinguished due electrode oxidation or ingress of melted polymer into the plasma stream. When this occurred the gap spacing was lengthened to increase the voltage and re-establish the arc discharge [15]. The full list of arc-fault tests is shown in Table I. Each test was performed 5 times to determine the ease of initiating and sustaining an arc. However in some cases, the arc-fault stability was difficult to establish and these data were removed.

The following general observations were made after completing the experiments:

1. Cleaner electrodes (no copper dust or burring) were better for establishing sustainable arc-faults.
2. If the flat electrodes are not flush it is more difficult to sustain the arc.
3. At low power (100 W), smaller 1/8 inch electrodes are easier to establish arc-faults, but at 300 W, the 1/8 inch electrodes melt and/or weld together.
4. In certain cases the steel wool did not burn through and a sustained arc was not established. This was especially a challenge with the 100 W arcs.
5. Rounded electrode tips are superior for sustaining an arc compared to flat-surface electrodes.
6. Polycarbonate has less arc or flame retardant characteristics than Nylon 6,6 and PET.
7. Including a hole in the polymer allows oxygen to enter the plasma stream and provides a more sustainable plasma arc discharge.
8. The tests that included steel wool for initiation, added much more time and experimental complexity, and this configuration would often not facilitate an arc-fault for lower power levels.
9. There is a preliminary faint 'glowing' corona discharge that occurs prior to an arc-fault when using steel wool for initiation.

Based on these results the least-complex arc-fault tests to setup were those without a sheath or steel wool. The most repeatable tests—as defined by the fewest times the arc-fault needed to be re-established to reach polymer combustion—were the 1/8" flat electrodes. The least-complex configuration to establish an arc-fault was with either ¼" rounded-tip, or 1/8" flat electrodes, all without a polymer sheath.

III. SPECTRAL CONTENT ANALYSIS

During the arc-fault tests shown in Table I, current measurements were recorded at 5 MHz using a National Instruments (NI) PXI-5922 digitizer and Techtronix TCP303 current probe. After 2^{16} samples were collected, the Discrete Fourier Transform (DFT) was calculated using a NI LabVIEW program and saved locally. Many AFCIs perform a similar mathematical operation to detect the arc-fault on the PV system. These devices monitor multiple frequencies and trip when there is elevated noise content in the majority or all of these frequencies. Therefore, arc-faults which produce small magnitudes of respective signature noise are less likely to be detected. These arc-faults are of particular interest to the Standards Technical Panel because they indicate real world scenarios where AFCIs may fail to detect the arc and a fire could be established.

As shown in Fig. 1 (A)-(E), the spectral content of the DC system is plotted over the duration of the arc-fault. The spectrum was calculated using a DFT with a Hanning window, at a rate of approximately 0.28 sec/DFT measurement due to the processing capabilities of the NI system. The data shown in Fig. 1 (F-J) show the PV arc power, voltage, and current,

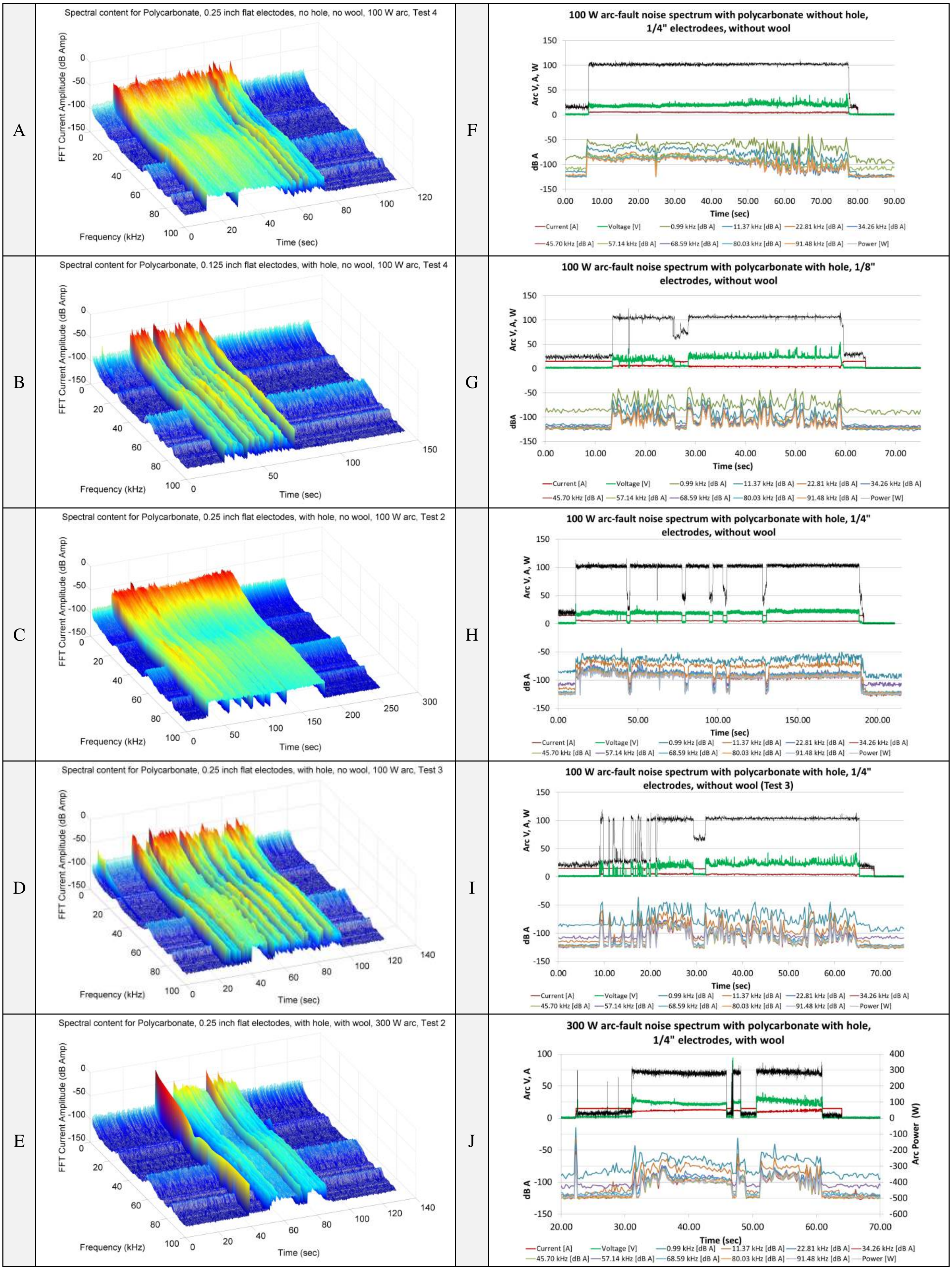

Fig. 1. (A)-(E) FFT measurements for different arc-faults and (F)-(J) arc power, voltage, and current plotted with selected frequencies.

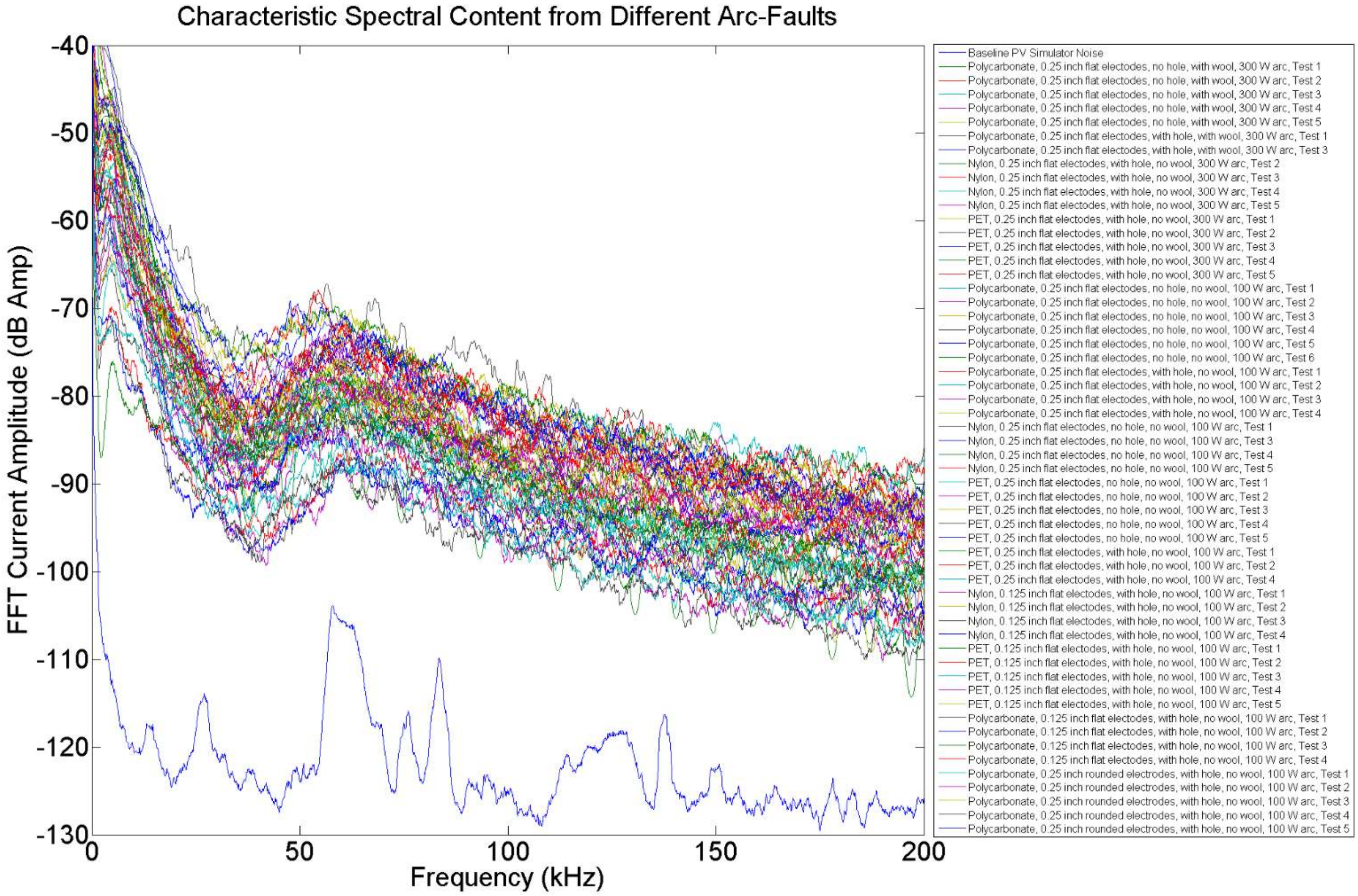

Fig. 2. Spectral content for the arc-fault tests. Some signatures were removed for transient effects during arc initiation, e.g., Fig. 1 (E) and (J).

with the DC noise from multiple frequencies between 0-200 kHz. The frequency data can be considered as cross-sections of the data displayed in Fig. 1 (A)-(E). During an arc-fault, conducted noise changes based on the stability of the ionization (plasma) stream between the electrodes, the pressure of the plasma (which changes based on surrounding materials and geometry) and the chemical composition of the plasma (determined based on the presence of oxygen and the chemical composition of the ionized atmosphere). These factors cause noise from the arc-fault to evolve. As the arc-fault burns (Fig. 1 (A) and (F)), the noise content of the fault is reduced, indicating the arc-fault is burning more cleanly. However, since arc-fault detectors must trip within 2 seconds or less for all arc-fault power levels [1], the most critical period of time is at the beginning of the arc discharge. In all tests, the arc-fault quickly produces AC noise once the arc is established. The change to arc power at the beginning of tests in Fig. 1 (I) and (J) show the difficulty in initiating certain arc-fault tests. In the 100 W arc-fault tests with steel wool, individual strands of wool burn for a long period of time as the gap size is increased. Eventually, the conduction path through the wool mesh is destroyed and the arc is established. In the case of 300 W arcs, the steel wool vaporized more easily and the gap size was not adjusted to initiate arcing.

In order to provide recommendations to the UL STP regarding difficulty of detecting different arc-faults, Sandia analyzed arc-fault noise created during the first second of each arc-fault test. The DFT data was smoothed using a 40 sample (~230 Hz) sliding window average. Then the epoch (time index) of the largest increase in arc noise across the spectrum for the test duration was determined. The noise created at this epoch determined the start of the arc-fault noise and is plotted in Fig. 2. All the tests produced noise ~15 dB above the baseline PV simulator noise (blue line), but there was roughly 20 dB range for the test spectra between 0-200 kHz. This indicates some of the arc-faults are more difficult to detect within the required UL 1699B trip times. To determine which factors suppressed arc-fault noise, a range of dissections of the arc-fault noise were plotted in Fig. 3. In the plots the gray region represents the range of arc-fault noise from all the tests, with the colored plots indicating the arcing noise for the parameter of interest. The plots confirm operator anecdotal experiences that more violent arcing is correlated to increase spectral content:

1. Rounded electrodes tend to produce less arc-fault noise because the arc-fault is consistently, and 'cleanly,' established at the radial center of the electrodes.

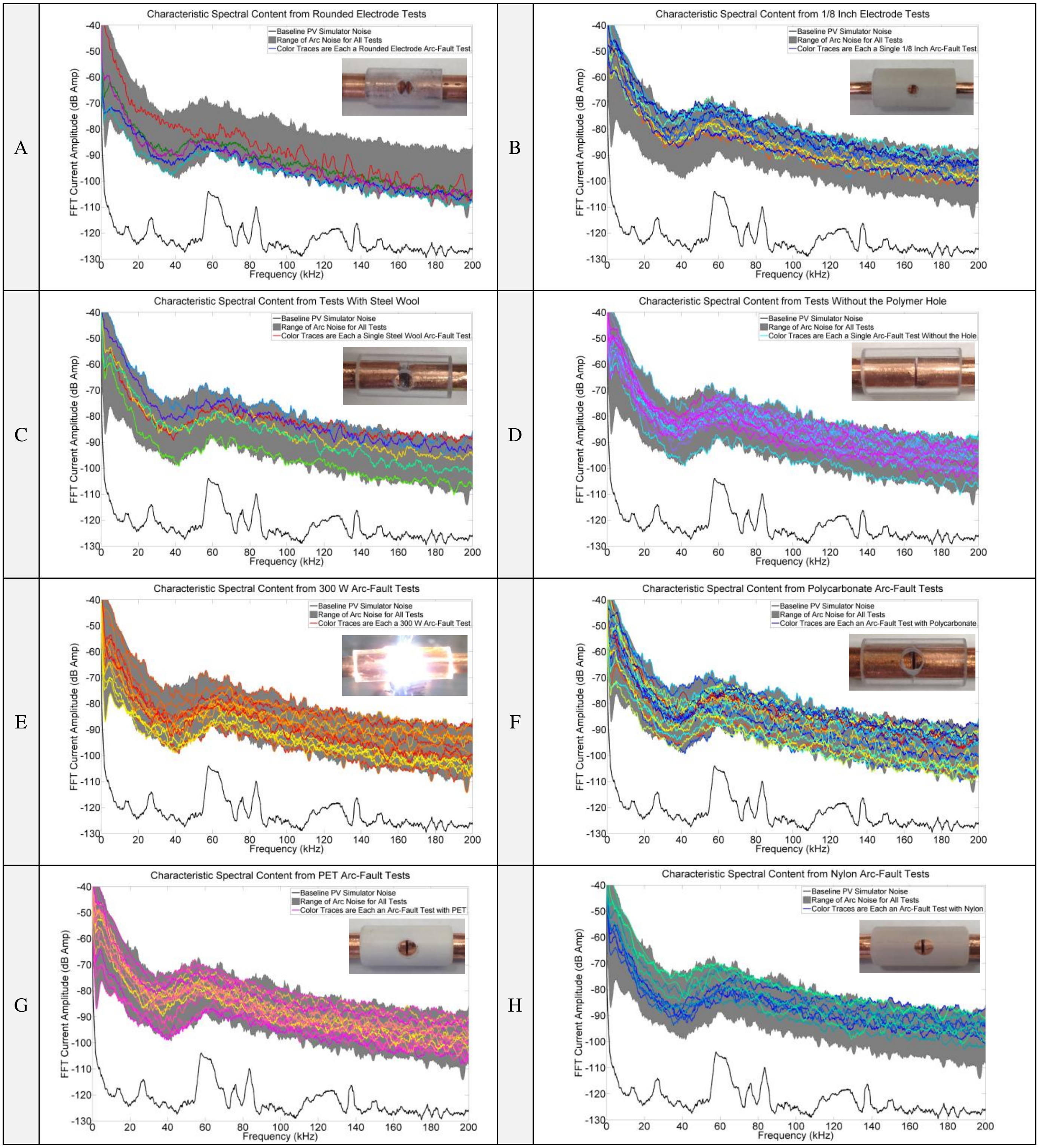

Fig. 3. The spectral content for categories of arc-fault tests with the baseline noise (black trace) and the range of current arc-fault noise for all tests shown in gray. The plots indicate which arcing tests are easier or harder for frequency-based arc-fault detectors to detect by comparing the range of noise signatures to (A) arc-fault noise from rounded electrodes, (B) 1/8 inch copper electrodes, (C) tests with steel wool, (D) polymer sheaths without a hole, (E) 300 W arc-faults, (F) arc-faults with polycarbonate sheaths, (G) arc-faults with PET sheaths, (H) arc-faults with nylon sheaths. In cases where the noise is toward the top of the spectral band, the arc-fault produces more frequency content, and the arc-fault can be more easily detected; but in cases where the arc-fault noise signatures are near the bottom of the spectral band, these arc-faults are more difficult to detect. Note for subplot (E), a more detailed analysis of 100 vs. 300 W signatures for nylon indicated no difference in noise signatures from 0-200 kHz.

2. Smaller electrodes produce high noise signatures due to increased off-gassing rates [15] and oxygen depletion due to a lower plasma cavity volume, which increases arc-power instabilities.
3. There is a large range of noise produced with the steel wool tests but the wool tended to produce noise toward the upper limit of the tests.
4. The presence of a hole in the polymer produced slightly cleaner burning arc-faults, possibly because of the increased presence of oxygen.
5. Higher power arc-faults tend to create more stable, cleaner burning, less noisy arc-faults.
6. Arc-faults with Nylon 6,6 created more noise than the polycarbonate and PET tests.

IV. CONCLUSIONS

A parametric study of various geometries, materials, and powers was conducted to determine repeatable arc-fault certification tests for adoption by the UL 1699B Standards Technical Panel. Based on these experiments, it was recommended:

1. A low power (100 W) arc-fault test be added to the standard because it represents a fire hazard, and if current/voltage were used in addition to the frequency content, these arcs may go undetected. See [15].
2. A 2 second trip time is a sufficient factor of safety for 100 W arc-faults. This test should allow for the "pull-apart" method of arc generation since it is very difficult to create a low power (100 W) arc-fault with steel wool. Note a more generous power tolerance on this test (± 30%) is necessary since arc-fault power cannot be controlled as accurately. More details in [15].
3. The use of a hole in polymer sheath should be allowed in the arc-fault tests to allow easier arc generation and reduce the total arcing noise in the system.
4. While the spectral content of the arc-faults was lower with rounded electrodes, this is unlikely in real PV systems and the setup time is greatly increase, so it is not recommended for addition into UL1699B.

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REFERENCES

[1] Underwriters Laboratories 1699B, "Outline of Investigation for Photovoltaic (PV) DC Arc-Fault Circuit Protection, Issue 2, 14 Jan 2013.

[2] J. Johnson, B. Pahl, C.J. Luebke, T. Pier, T. Miller, J. Strauch, S. Kuszmaul and W. Bower, "Photovoltaic DC arc fault detector testing at Sandia National Laboratories," 37th IEEE PVSC, Seattle, WA, 19-24 June 2011.

[3] H. Häberlin and M. Real, "Arc Detector for Remote Detection of Dangerous Arcs on the DC Side of PV Plants", presented at the 22nd European Photovoltaic Solar Energy Conference, Milano, Italy, Sept. 2007.

[4] C. Strobl and P. Meckler, "Arc Faults in Photovoltaic Systems," 56th IEEE Holm Conference on. Electrical Contacts, pp.1-7, 4-7 Oct. 2010.

[5] F. Schimpf, L.E. Norum, "Recognition of electric arcing in the DC-wiring of photovoltaic systems," 31st International Telecommunications Energy Conference, pp.1-6, 18-22 Oct. 2009.

[6] Z. Wang, R.S. Balog, "Arc fault and flash detection in DC photovoltaic arrays using wavelets," IEEE 39th Photovoltaic Specialists Conference (PVSC), pp.1619-1624, 16-21 June 2013.

[7] X. Yao, L. Herrera, S. Ji, K. Zou, J. Wang, "Characteristic Study and Time-Domain Discrete-Wavelet-Transform Based Hybrid Detection of Series DC Arc Faults," IEEE Transactions on Power Electronics, vol. 29, no. 6, pp. 3103-3115, June 2014.

[8] J. Johnson, C. Oberhauser, M. Montoya, A. Fresquez, S. Gonzalez, and A. Patel, "Crosstalk nuisance trip testing of photovoltaic DC arc-fault detectors," 38th IEEE PVSC, Austin, TX, 5 June, 2012.

[9] J. Johnson, M. Montoya, S. McCalmont, G. Katzir, F. Fuks, J. Earle, A. Fresquez, S. Gonzalez, and J. Granata, "Differentiating series and parallel photovoltaic arc-faults," 38th IEEE PVSC, Austin, TX, 4 June, 2012.

[10] J. Flicker and J. Johnson, "Electrical simulations of series and parallel PV arc-faults," 39th IEEE PVSC, Tampa Bay, FL, 16-21 June, 2013.

[11] J. Johnson, B. Gudgel, A. Meares, and A. Fresquez, "Series and parallel arc-fault circuit interrupter tests," Sandia Technical Report, SAND2013-5916, July, 2013.

[12] T. Takashima, J. Yamaguchi, K. Otani, T. Oozeki, K. Kato, M. Ishida, "Experimental studies of fault location in PV module strings", Solar Energy Materials & Solar Cells, pp. 1079–1082, 2009.

[13] L. Schirone, F.P. Califano, U. Moschella, U. Rocca, "Fault finding in a 1 MW photovoltaic plant by reflectometry," Photovoltaic Energy Conversion, 1994.

[14] J.K. Hastings, M.A. Juds, C.J. Luebke, B. Pahl, "A study of ignition time for materials exposed to DC arcing in PV systems," 37th IEEE PVSC, pp. 3724-3729, 19-24 June 2011.

[15] K.M. Armijo and J. Johnson, "Characterizing fire danger from low power PV arc-faults", 40th Photovoltaics Specialists Conference, Denver, CO, 8-13 June 2014.

[16] K.M. Armijo, J. Johnson, M. Hibbs, A. Fresquez, "Quantifying Photovoltaic Fire Danger Reduction with Arc-Fault Circuit Interrupters," EU PVSEC, Amsterdam, Netherlands, 22-26 Sept, 2014.