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Characterization of Fire Hazards of Aged Photovoltaic Balance-of-System Connectors

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Abstract — While unmitigated arc faults of balance of systems (BOS) photovoltaic connectors are a well-known hazard, the associated risk remains unquantified. Successful risk characterization requires moving beyond qualification testing to attain predictive capability of connector aging and quantify aging effects on arc fault risk. This paper presents a suite of techniques for understanding and mitigating the arc fault risk of BOS connectors. Signal analysis of connector current and optical emission spectroscopy are utilized to study and potentially predict arc faults. A thermal-based mitigation approach is also demonstrated. These tools can advance knowledge in both connector aging and arc fault physics.

***Index Terms* — connector, arc fault, reliability, corrosion, accelerated test, fast Fourier transform, optical emission spectroscopy**

I. Introduction

Arc faults are a low-probability but high-consequence hazard in photovoltaic (PV) systems. The rate of arc faults, however, is expected to increase as the worldwide installed capacity of photovoltaic systems continues to grow. In the US alone, there have been a number of high profile fires caused by arcing in PV systems [1, 2]. Some of these incidents have been traced to balance of systems (BOS) connectors, with risk and prevention being identified as a critical area to address [3]. The reliability of BOS connectors has been relatively uncharacterized beyond qualification tests.

This paper presents the development of an experimental platform for characterizing arc fault risk of BOS connectors and improving the scientific understanding of how degradation affects the underlying arc mechanisms. Techniques covered include fast Fourier transform (FFT) analysis, optical emission spectroscopy and a thermal-based prognostic approach. The complete set of developed tools will advance the state of the art in arc fault prognostics as well as BOS connector lifetime characterization and prediction. Utilizing this platform, work is underway to develop a lifetime prediction model based on the physical properties and behavior of field and accelerated-aged connectors.

II. Experimental Methods

A PV simulator at Sandia National Laboratories was developed to represent constant power I-V curves from a set of 1024 points. From experimental observations, the arc power was nearly constant for any given curve regardless of the electrode gap spacing. As a safety precaution, the PV simulator power was provided to the arc-fault generator through a power resistor. Additionally, the curves programmed into the PV simulator were limited to 600 V and 15 A. For this investigation, a 300 W constant power curve was evaluated [4, 5]. As shown in Fig. 1, the experimental setup consists of an arc-fault generator, with current and voltage probes, as well as k-type thermocouples, which were placed on each respective connector electrode set. The connectors — one moveable (anode) and one stationary (cathode) — were separated using a lateral adjustment of the moveable electrode to the desired gap spacing.

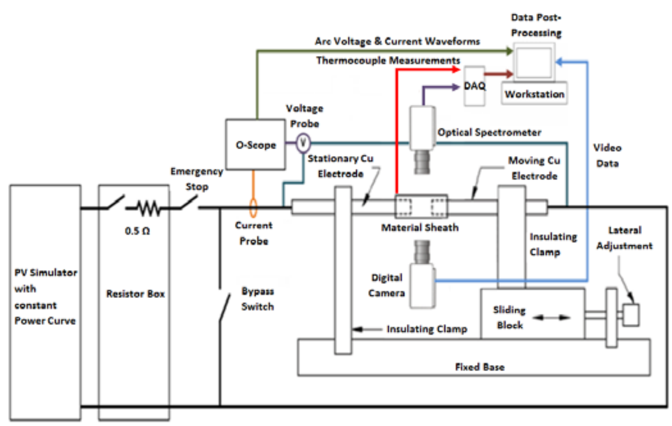

Fig. 1. Schematic of the arc fault generator and associated instrumentation. The arc fault test bed is powered by a PV simulator to produced realistic responses to the arc produced. Analysis methods instrumented in the arc fault generator include voltage, current, fast Fourier transform signal processing of the current signal, thermal measurements, optical emission spectroscopy, and smoke detection.

Comparison of arc behavior of three common models of as-received connectors was performed. Prior to testing, the connectors were aligned and secured within the respective vices of the arc-fault generator, where they were initially fully mated. The connectors were then incrementally separated, with DC current, voltage, fast Fourier transform (FFT) analysis, connector temperature, and optical emission spectroscopy data collected. Prior to separation, the connectors were calibrated with respect to the exact disconnection point using a handheld multimeter. During each test, PV power was applied until the sample combusted by a sustained arc. A UL-listed smoke detector was also installed just above connectors, with high-speed video recordings collected to determine the first instance of smoke and subsequent combustion of the connector materials.

During the arc-fault tests, current measurements were recorded at 5 MHz using a National Instruments (NI) PXI-5922 digitizer and Techtronix TCP303 current probe. After every 2^{16} samples, the Discrete Fourier Transform (DFT) was calculated using a NI LabVIEW program, similar to the work performed by Johnson and Armijo [5]. This work assessed noise sensitivities from arc-faults since conductors that produce small magnitudes of respective signature noise are less likely to be detected.

Finally, to understand the plasma discharge process with connectors while predicting material degradation mechanisms, optical emission spectroscopy (OES) was used to measure the plasma electron temperature. For this study, optical spectra of the arc plasma were acquired using an Ocean Optics S2000 fiber spectrometer, which consisted of an integrated linear silicon CCD array and miniaturized optical bench. The spectrometer had a resolution of 0.33 nm, and a spectral measurement range of 340-1019 nm. The plasma spectra were optically coupled to the spectrometer using a diffusive cosine corrector free-space to fiber adapter. The position of the detector was adjusted relative to the arc to avoid saturation. A spectrum integration time of 100 ms was used, with a series of over 100 spectra captured per arc discharge to examine change in emission and plasma conditions as a function of time.

III. Results and Discussion

FFT analysis of the measured current successfully identified the micro arcs that occur prior to a sustained arc fault. Fig. 2 shows an example of FFT spectrums taken during an arc fault characterization of a BOS connector. The micro arcs create measurable perturbation that can be utilized for precursor detection applications.

Additional exploration is underway to relate the frequency characteristics of connectors to their degradation state using complimentary materials analysis techniques, Fig. 3. Additional characterization with age data can potentially enable the use of FFT analysis to determine remaining connector lifetime.

Measured peaks from the OES data were compared with literature values and matched to known materials in connector composition [6], Fig. 4. The OES spectrum of copper electrodes (labeled "Cu"), two types of tin-plated BOS connectors (labeled "A" and "B," respectively), and a tin-plated brass connector (labeled "C"). A comparison of the spectrum characteristics successfully differentiates the tin-plated brass sample from the base copper counterparts in the study. With further development, OES can be used to: (1) identify materials that are prone to participate in the arc fault event, and (2) measure the temperature of the arc plasma. This knowledge can be used to design connectors that are resistant to arc fault, develop thermal approaches to arc fault prevention and suppression. Furthermore, OES is a technique that enables high-throughput screening and quality control for connectors regarding arc fault risk.

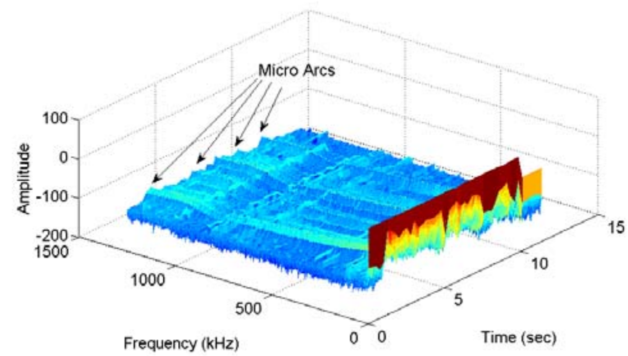

Fig. 2. Fast Fourier transform measurements taken as a function of time during arc fault tests. The micro arcs that precede the hazardous sustained arc manifest as changes in the FFT spectrum. This technique can be used for in-situ detection of impending arc faults as well as a potential technique to monitor degradation.

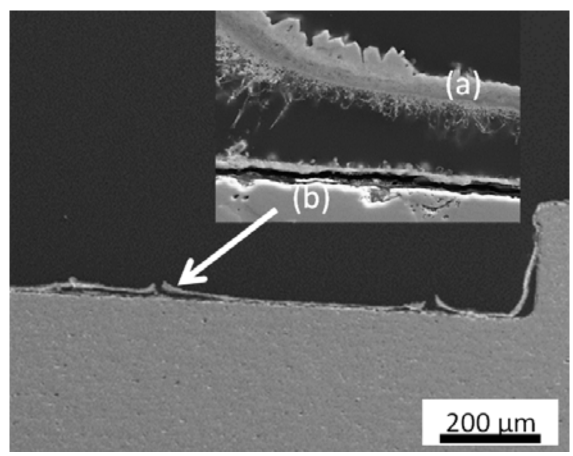

Fig. 3. Scanning electron microscopy image of a photovoltaic BOS connector pin after atmospheric corrosion accelerated testing. The magnified image shows the mineralized plated metal layer (a) delaminated from the base metal (b), which is a potential vulnerability leading to arc fault generation.

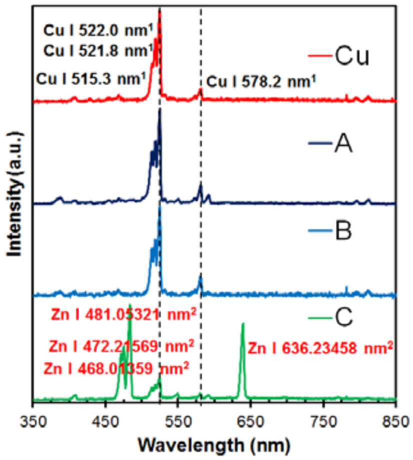

Fig. 4. Optical emission spectroscopy measurements from arc faults in copper electrodes and three types of connectors. The spectrum peaks have been matched to values from prior literature. The connectors A and B, which are copper-based, have characteristics similar to the copper electrode. Peaks associated with the presence of zinc in connector C, which is made of brass, is also detected.

A demonstration of a proposed thermal-based prognostic and prevention technology is described in Fig. 5. The approach utilizes the temperature increase that we observed prior to a sustained arc event. An optical fiber material is positioned in close proximity to the connector pin. By choosing a waveguide material that melts in the presence of this temperature increase, the impeding arcing event can be detected through continuous transmission monitoring.

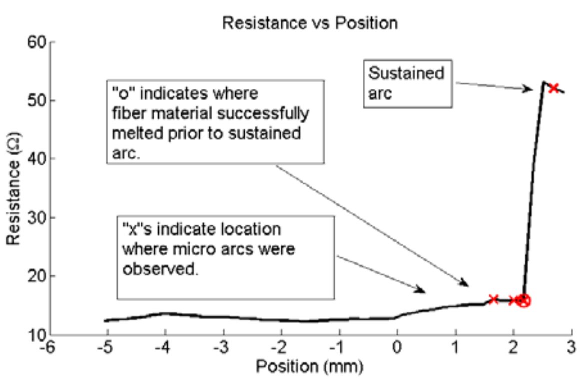

Fig. 5. Proof-of-concept demonstration of a prognostic technique for connector arc faults. Connector-pin separation was used to simulate the decreased conduction area that occurs due to corrosion. The optical fiber material under test successfully melted at the location marked with an "o," after the presence of micro arcs (labeled with "x"s) but before the point of a hazardous sustained arc.

IV. Conclusions

FFT has been demonstrated as a potential in-situ tool for identifying micro arcs that precede hazardous sustained arc fault events associated with complete separation. We are developing this approach to serve as an analysis tool for assessing the arc fault risk of BOS connectors due to degradation.

OES can be used to understand materials that are involved in the arc fault process. Peaks were successfully matched to literature values and materials identified matched information from manufacturer. We are actively developing methods to extract additional information from OES measurements, such as the electron plasma temperature and ionization potentials.

A thermal-based prognostic technique was proposed to detect situations of high arc fault risk. Other methods are also actively being explored.

Accelerated tests can be benchmarked with fielded connectors for arc fault risk through the arc fault characterization techniques in this paper. The combination of connector aging and arc fault characterization not only assess the ability of BOS connectors to meet the industry-standard 25-year lifetime but also quantify the connection between connector aging and arc fault risk.

V. Acknowledgements

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