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Evaluating the Durability of Balance of Systems Components Using Combined-Accelerated Stress Testing

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***Abstract*—The degradation of photovoltaic (PV) balance of systems (BoS) components is not well-studied, but the consequences include offline modules, strings, and inverters; system shutdown; arc faults; and fires. A utility provider experienced a ~30% failure rate in their power transfer chain, originally attributed to branch connectors. Field-failed specimen assemblies were therefore examined, consisting of cable connector, branch connector, and discrete fuse components. In this study, unused field-vintage specimens are examined using combined-accelerated stress testing (C-AST) to clarify the most influential environmental stressors as well as the effect of external mechanical perturbation. A benchtop prototype fixture was used to develop the perturbation capability for the C-AST chamber. The benchtop experiments were also used to develop the in-situ data acquisition of specimen current, voltage, and temperature. A significant increase in operating temperature (~100°C from ~40°C) and a different failure mode were observed promptly once periodic mechanical perturbation was applied. The current at failure was decreased from 35 A (with failure in the fuses) to 15 A (failure at the male/female metal pin connection). After initial examination using X-ray computed tomography, the external plastic was machined away from failed specimens to allow for failure analysis, including the extraction of the internal convolute springs for morphological examination (optical and electron microscopy).**

Keywords—balance of systems, branch connector, C-AST, durability, DuraMAT, fuse, reliability, SEM, XCT

I. BACKGROUND

Balance of systems (BoS) components in photovoltaic (PV) systems include: cable connectors, cables, branch connectors, fuses (discrete), and fuse blocks. To date, the durability of BoS components has received limited research. After inverters, PV-specific studies have focused mostly on connectors, e.g., through steady-state or single-factor accelerated testing [1]. The industry generally speaks of a quantifiable replacement rate that may approach the order of ~1% of strings per year, whereas owners and operators may choose to extend system life beyond typical PV modules' 25-year warranties. Consequences of BoS degradation and failure include offline modules, strings, and inverters; system shutdown; arc faults; and fires [2].

Standards for connectors include IEC 62852 [3] and UL 6703 [4]. Focusing primarily on safety, these standards apply a variety of functionality metrics (e.g., current capacity, electrical insulation, and mechanical insertion force) and accelerated test methods (e.g., separate current-, temperature-, and humidity-cycling tests as well as mechanical bending). Component durability is typically examined using tailored methods designed to address historically observed degradation modes. In contrast, combined accelerated stress testing (C-AST) has recently been developed to examine PV modules [5]. In C-AST, multiple stressors (including UV-VIS radiation, temperature, moisture, electrical current, and external mechanical perturbation) are applied simultaneously in a developed time sequence, rather than in steady state. C-AST is intended to screen for degradation and failure modes, based solely on the extremes of the PV application in challenging environments. While C-AST was initially developed for PV modules, it may also be applied to PV materials and components.

This study explores an event where a utility provider experienced a ~30% failure rate in their power transfer chain at multiple PV installations in Arizona and New Jersey, originally attributed to branch connectors. "Failure" refers to overheating, softening, and physical distortion—with overt temperature rises observed in thermographic imaging. The worst consequences included broken circuits, electrical arcs, and local combustion. Here, in collaboration with the utility provider, we sought to further diagnose and advise on the BoS components. This study was also used to develop accelerated BoS test capability.

II. INTRODUCTION

In this study, C-AST was adapted for the examination of PV branch connectors. The PV installations featured branch connectors fixed to the system using long leads (up to ~1 meter) of cable, allowing a variety of inadvertent mechanical motions. To study the mechanical motion possible in the installations, a custom fixture was used to develop the capability to apply periodic external multi-axial mechanical perturbation during weathering. While the chamber version is presently in study, a benchtop prototype was used to compare static and dynamic (externally actuated) specimen assemblies. The key activities of the C-AST BoS project include:

- Development of accelerated testing, in-situ data acquisition, and subsequent read point characterization methods for the use of C-AST with BoS components.
- Demonstration of the ability to distinguish known bad components using C-AST and identify their corresponding degradation modes.
- Identification of the significance of external mechanical perturbation in C-AST, relative to testing with no external actuation.

III. EXPERIMENTAL

A. *Specimens*

Because the number and contribution of damage-susceptible components was unknown, the adjoining system components were examined together as an assembly consisting of: two cable connectors (specimen ends), two branch connectors, and two fuses (specimen middle). Components of a similar vintage to the utility system components were purchased from an electronics vendor to aid development of the test capability. Unaged spare field specimens were obtained from the utility provider for use in C-AST. Field-failed specimens were obtained from the utility provider to compare to the assemblies subject to accelerated testing. Upon the utility provider's request, component make and models will be kept confidential.

B. *Test Fixture and Its Application*

A single specimen push-pull test fixture was developed in the preliminary benchtop experiments. During operation, a polymer collar was directed in the opposite direction of a polymer push-rod using a linked mechanism. A DC motor was used to displace the middle of the fuse within the specimen by 3 mm initially, which was later reduced to 1 mm in subsequent experiments. The DC motor was confirmed to operate at 16 rpm, faster than the hydraulic actuators in C-AST, i.e., with on and off durations on the order of seconds. Separate GENESYS+ GH20-75 (TDK-Lambda Corp.) power supplies gave direct current to separate static and dynamic (actuated) assemblies, starting at 20 A and 10 A, respectively, and initially incremented by 1 A each day.

C. *Data Acquisition and Subsequent Characterizations*

A 9174 chassis, equipped with 9220 analog-in and 9264 analog-out cards (all National Instruments Corp.) was used for current and voltage monitoring. Operating temperature was monitored with a 2700 system (Keithley Instruments LLC) using discrete T-type thermocouples (TCs). A separate TC was placed on each fuse and branch connector in each specimen assembly. Electrical and temperature data were obtained at 100 Hz and 0.5 Hz, respectively, and then analyzed in 1-minute bins. A T420 camera (FLIR Systems Inc.) was used for supplemental thermography imaging. An X3000 system (North Star Imaging Inc.) was used for X-ray computed tomography (XCT) to obtain the three-dimensional structures of the specimen assemblies (unaged and degraded). Brightfield microscopy was performed using a white-balanced VHX-5000 microscope (Keyence Corp).

IV. RESULTS AND DISCUSSION

A. *Benchtop Comparison of Static and Dynamic Specimens*

Fig. 1 compares assemblies tested simultaneously, including those: with external mechanical perturbation using the benchtop test fixture prototype ("dynamic"); and those without actuation ("static"). The dynamic specimen temperature of ~100°C is greater than the static specimen temperature of ~40°C despite the greater DC current to the static assembly. In successive experiments, dynamic specimens failed at 15 A at the fuse/branch connector connection. Localized arcing is suspected based on observations including smoke, heterogeneous melting of plastic, discolored metal pins, and increased fuse resistance. In successive experiments, static specimens failed at 35 A, with the greatest heating observed at the filament-based cartridge at the center of the discrete fuses. No additional visible indication was observed for failed static specimens, but an open circuit was verified for at least one of the fuses in each failed assembly. Temperature and current behavior like in Fig. 1 were observed in two successive static specimens, then two successive dynamic specimens, then two side-by-side static and dynamic benchtop experiments.

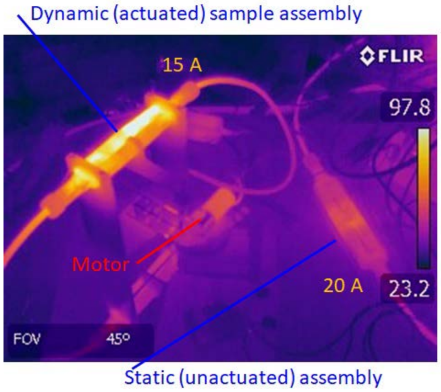

Fig. 1. Infrared image comparing sample assemblies in separate circuits. The maximum temperature of the dynamic sample (~100°C, for $\delta = 1$ mm) is greater than that of the static sample ($\delta = 0$ mm) with no external mechanical actuation (~40°C), despite a greater DC current to the static sample.

The temperature history for the dynamic specimen in Fig. 1 is shown in Fig. 2. The branch connectors (TC 106 and TC 108) and the adjoining discrete fuse (TC 107) both occasionally exceeded 100°C. While the second discrete fuse (TC 105) remained coldest overall, the rank order of the temperature for the other three components varied through the experiment. Supplemental infrared imaging, which included the TCs and the adjacent sample regions, identified localized temperatures exceeding 130°C. The specimen temperature in Fig. 2 is irregular, with spikes and broader peaks that do not always correspond to the electrical current increments. The voltage drop across the current-controlled specimen assembly was also irregular (not shown), with peaks occurring corresponding to the temperature spikes in Fig. 2. The TC data for the static assembly (not shown) is more monotonic, with the greatest temperature approaching 40°C in the fuses and 30°C in the branch connectors.

The specimen temperatures shown in Fig. 1 and Fig. 2 readily identify the significance of external mechanical strain on the durability of branch connector/fuse assemblies. Not only is the temperature greatly increased by mechanical perturbation, but the hottest location also occurs in a different component within the specimen assembly. The measured temperature in Fig. 2 identifies that the specimen temperature loses stability within the first day of the experiment. The data in Fig. 2 is the average temperature through 1 minute; binning and averaging reduce its variation relative to the instantaneous temperature. Temperature spikes are observed even when the current is not incremented, identifying the stochastic effect of mechanical perturbation. The temperatures in Fig. 2 are representative of the specimen temperature, but do not give the maximum specimen temperature because the thermocouples are positioned near but not exactly on the hottest location in each component.

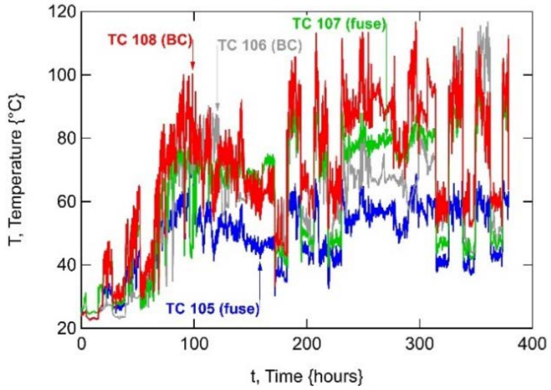

Fig. 2. Measured temperature for the dynamic sample assembly in Fig. 1. The thermocouples at the center of the discrete fuses ("fuse") are compared to those of the branch connectors ("BC"), as the current was initially incremented in steps and modulated occasionally to simulate the effect of light-level variation.

B. Assessing the Failure of Field and Accelerated Specimens

Failed specimens were examined iteratively: after testing, in their failed state; after milling the external plastic to reveal the internal metal components; and after extracting the convolute springs within the female metal pins. Fig. 3 compares specimens, field-failed (left) and after accelerated testing (right). An asymmetry is observed in (a), where the internal connection extends further on the right side (green arrow). Discoloration of the surface of the metal pins (originally silver in color) is seen in Fig. 3 (c) and (d). The Sn surface of the convolute springs is also discolored in Fig. 3 (e) and (f). Corrosion and bending of the members are observed along the length of the field-failed spring in Fig. 3 (e), whereas the spring from the dynamic specimen assembly is circumferentially deformed in Fig. 3 (f).

The failure analysis in Fig. 3 identifies a variety of degradation modes, including: oxidation (with discoloration from heating); inelastic deformation [longitudinally in Fig. 3 (e) and circumferentially in Fig. 3 (f)]; and additional corrosion in Fig. 3 (e). The most discolored metal pins and most affected convolute springs presumably reveal the hottest locations within the assembled components. More corrosion might be observed when the environmental stressors are applied during C-AST, going beyond the standard laboratory environment in the benchtop experiments in Fig. 3 (f).

V. SUMMARY

The C-AST method is being developed for use with BoS components. The use of external mechanical perturbation was found to quickly and greatly affect the results of benchtop experiments. Failure analysis diagnosed the hottest location, presumably the location of greatest degradation: the connection between male and female metal pins in both the benchtop (with mechanical perturbation) and field-failed specimens. The validation of the accelerated testing relative to the field installations in this study remains an ongoing effort in addition to the present examination of specimens using C-AST.

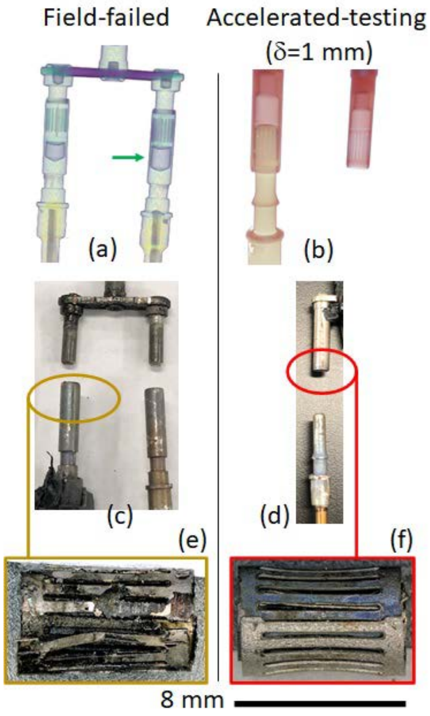

Fig. 3. Comparison of field-failed (left) and benchtop-failed (right, from Fig. 1 and Fig. 2) specimens, including: (a) and (b) X-ray computed tomography prior to removing the exterior plastic; (c) and (d) visual appearance of the interior metal components after removing the exterior plastic; and (e) and (f) optical micrographs of the convolute springs extracted from the failed connections.

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