SAND2015-4699C

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

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***Abstract* — Three balance of systems (BOS) connector designs common to industry were investigated as a means of assessing reliability from the perspective of arc fault risk. These connectors were aged in field and laboratory environments and performance data captured for future development of a reliability model. Comparison of connector resistance measured during damp heat, mixed flowing gas and field exposure in a light industrial environment indicated disparities in performance across the three designs. Performance was, in part, linked to materials of construction. A procedure was developed to evaluate new and aged connectors for arc fault risk and tested for one of the designs. Those connectors exposed to mixed flowing gas corrosion exhibited considerable Joule heating that may enhance arcing behavior, suggesting temperature monitoring as a potential method for arc fault prognostics. These findings, together with further characterization of connector aging, can provide operators of photovoltaic installations the information necessary to develop a data-driven approach to BOS connector maintenance as well as opportunities for arc fault prognostics.**

***Index Terms* — connector, reliability, corrosion, accelerated aging, electrical contact**

I. Introduction

Arc faults are a low-probability, high-consequence hazard in photovoltaic (PV) systems. The rate of arc faults 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.

Beyond the obvious, though possibly acceptable, costs of Ohmic power loss due to connector contact degradation, there is the potential cost burden due to arc fault hazards. Although series arc faults that result from BOS connectors are low-probability they can have highly damaging consequences, with visible events that are difficult to quantify if industry-wide public perception costs to PV are included. There have been instances where arc faults related to BOS connectors have been documented with its prevention being identified as a critical knowledge gap [4, 5].

Physically, there are situations where overheated wiring can lead to arcing events and conversely, where arcing can lead to overheating with subsequent combustion of connectors or wire insulation [1]. In most electrical and PV applications, series arc faults, which occur when the connection failure is in series with the load, are typically more common than parallel arc faults [6]. This type of fault can generally produce high current with a magnitude that depends on the faulted circuit. Research by Shea [1] on residential wire-related arc faults found that, even without defects, wiring can be subjected to high thermal stresses because of currents at or above the conductor or thermal insulation ratings. His results found conductor wire and insulation material ratings can be exceeded when conducting rated current and currents at 110% of the wire ratings. This type of thermal stress can increase wire aging, especially in the presence of humidity [7] and can accelerate material degradation that increases brittleness of connector insulating materials and crack formation of the conductor wires [5]. Further research by Armijo *et. al.* [8] also found that geometrical variations in wire electrodes can have a significant impact on facilitating and sustaining an arc. In their study they found that a 50% reduction in the geometry of current conducting electrodes resulted in a reduction as high as 45% in arc discharge ignition time.

In addition, current progress towards developing a degradation model for BOS connectors has been limited. To date, there has also not been research that relates any degradation model predictions to the likelihood of arc fault event. This work seeks to address this issue by utilizing accelerated test and field test results for future development of a degradation model for BOS connectors. In this investigation, laboratory and field aging of three connector designs common to industry was performed to determine the arc fault hazard potential against a pristine-condition control group. An arc fault generator and test methodology was developed and applied on new and aged connectors as a potential means of assessing arc fault risk of BOS connectors.

II. Approach and Methods

The work presented in this paper is part of a larger effort aimed at developing a degradation model for BOS connectors [9]. The primary objectives of the efforts represented here were to (1) generate connector aging data associated with field and accelerated tests for model development and input and (2) understand the effect of connector aging on arc fault risk. Motivating questions include: how do field and laboratory exposures compare in terms of performance degradation rate and damage modes? How does connector material construction and design affect aging performance? What is impact of connector contact degradation on arc fault risk?

A. Aging Tests

Three exposure environments were chosen to characterize the effects of various environmental stress factors on electrical contact resistance and materials degradation. Three common latching BOS connector designs, from three different manufacturers, were exposed in these environments. Two of these exposures were comprised of laboratory accelerated tests commonly used for robustness screening of photovoltaic components and electrical contacts- mixed flowing gas (MFG) and damp heat [10,11]. The damp heat test was conducted using conditions stated in IEC60068 for laboratory air at 85^{o} C/85% RH [11]. Grime simulants for coastal and desert environments were applied to a subset of samples exposed to the damp heat to examine the effect of contamination on contact performance [12,13]. Mixed flowing gas exposure was according to ASTM Method G, which involves exposure to a gas mixture of H_2S, Cl_2, NO_2 at ppb levels, 70% RH and 30 ^{o}C [10]. This test has been demonstrated to emulate and accelerate damage of in-service electrical contacts in sheltered light industrial atmospheric conditions [14]. The third exposure was carried out at an outdoor test site at Sandia National Labs in Albuquerque, which can be classified as a light industrial, high desert environment. Connectors were mounted on a boldly exposed polycarbonate panel at 45° relative to the ground and facing south. Four-wire resistance measurements were made across the connectors on an hourly basis during all tests using calibrated and multiplexed milliohm meters.

B. Materials Analysis

Both as-received and aged connector pins and sockets were cross-sectioned and examined using optical and electron microscopy. Regarding the latter, analysis was performed using a Zeiss Supra 55VP field emission SEM under high vacuum, 20 kV accelerating voltage, and a working distance of 10 mm in both secondary and backscattered electron modes. A Bruker SDD EDS detector and software were utilized for compositional analysis.

C. Arc Fault Tests

The arc fault behavior of select as-received and aged connector pins and socket sets was characterized using an arc fault generator, similar in description and function to that used by Johnson and Armijo [15]. A PV simulator running a constant power 300W I-V curve was used as the power source. Voltage, current and connector surface temperature were captured at a rate of 2 Hz during these tests using methods and equipment described elsewhere [9].

In these experiments, power was run across a set of connectors under test while simultaneously separating a fully mated connector at 0.09 mm/s using a motorized linear stage until a sustained arc occurred. As demonstrated in previous work, resistance across the connector pin and socket rises during separation due to a gradual decrease in contact area [9]. If a decreased amount of translation is necessary to produce a sustainable arc, then the resistance increases and the connector disturbance needed to cause an arc-fault event also increases. The separation distance prior to the first detected spark as well as that required for a sustainable arc was examined as a means to infer the relative risk of arcing between contacts in a connector. The intermittent and sustained arcing events were visually observed and position noted during the experiments. The separation velocity utilized was found to provide sufficient time for a sustained arc to develop as a result of separation.

IV. Results

A. Aging Tests

Resistance measurements taken across connectors during the damp heat, MFG and outdoor field exposures are given in Figs. 1-3. Fig. 1 exhibits resistance measurements taken during damp heat exposure of 27 connectors. Average resistance increased on the order of 0.1 mΩ across all connector and contamination types between 350 h and 10,000 h. From this figure, it is evident that a portion of the Type 1 connectors contaminated with coastal and desert grime exhibited the largest increase in resistance of ~ 1 mΩ. Fig. 2 exhibits resistance measured across 99 connectors exposed to the MFG environment. Relative to the damp heat test, resistance increases were rather minimal, with the exception of one Type 1 connector that indicated gradual degradation that accelerated after the 4000 hour mark. The results for outdoor exposure of 55 connectors are given in Fig. 3. These data are noisier than the laboratory exposures due to diurnal and seasonal temperature variance. Comparison of average resistance measurements across all connectors during similar temperature regimes (2000 and 10,000 hours) indicated that values increased on the order of 1 mΩ, excluding 1 Type 3 connector and 9 Type 2 connectors. These connectors exceptionally exhibited the greatest change in resistance, up to 100 mΩ, amongst connectors across all three exposure tests.

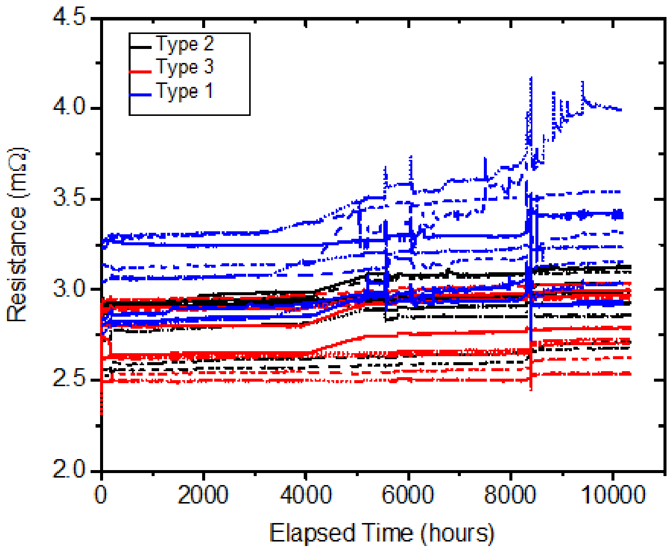

Fig. 1. Resistance measured during over 10,000 hours of damp heat testing. Connectors contaminated with coastal grime simulant are represented as dotted lines; those with desert contaminant simulant are dashed lines and those without contamination are solid lines.

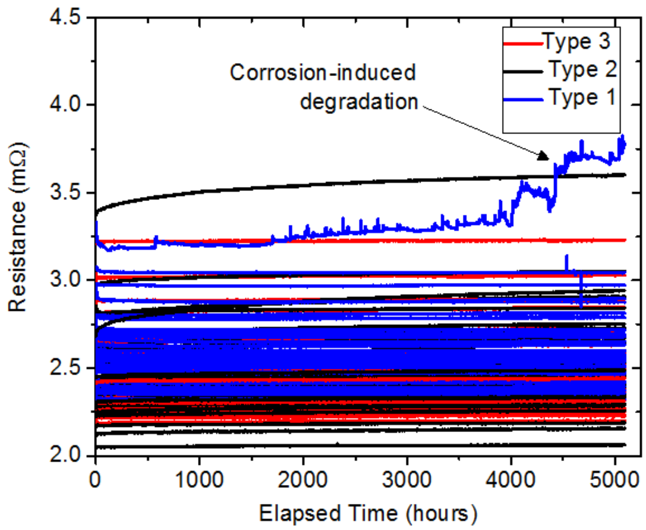

Fig. 2. Resistance measured across 99 connectors in a MFG corrosion chamber over the course of 5000 hours. Corrosion-induced degradation of one connector out of the sample is readily visible.

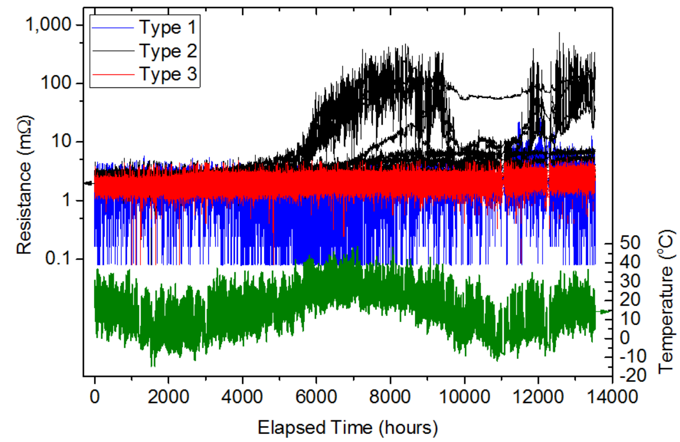

Fig. 3. Resistance (upper) and temperature (lower) measured on connectors boldly exposed to a high-desert light industrial outdoor environment.

B. Materials Analysis

The materials of construction of pins and sockets for the three connector types are listed in Table 1. This information was derived from SEM/EDS analysis of cross-sections of as-received components. It is notable that Types 2 and 3 are similar in materials make-up.

TABLE I
CONNECTOR CONTACT MATERIALS OF CONSTRUCTION

Type	Base Alloy	Underplate, Nominal Thickness (μm)	Overlayer, Nominal Thickness (μm)
1	Cu-Zn-Pb	Cu, 1	Ag, 3-4
2	Cu	--	Sn, < 1 -8
3	Cu	Ni, 1	Sn, 5-9

Post-mortem analysis was carried out on connector pins that were boldly exposed (no housing) to the MFG environment to ascertain extent of corrosion damage. In general, the tin-plated Type 2 and 3 connectors qualitatively suffered less corrosion than the silver-plated Type 1 connectors. Micrographs in Fig. 4 exemplify this. Type 2 and 3 connectors exhibited sparse and localized attack of the underlying base metal in areas of thinner plating or porosity, as exemplified in Fig. 4(c). This is in contrast to the relatively uniform and nearly complete mineralization of the silver plating (a) and attack of underlying base metal (b) of the Type 1 connectors. The thickness of the mineralized silver layer on one cross-section averaged 7±4 μm. Work is underway to carry out similar analyses of connectors exposed to damp heat, thermal-cycling, and outdoor exposure to draw comparison between laboratory degradation tests and field-exposed connectors. Development of an accelerated test that accounts for corrosion as a materials degradation pathway is dependent on emulating damage distributions and corrosion product properties realized on in-service connectors.

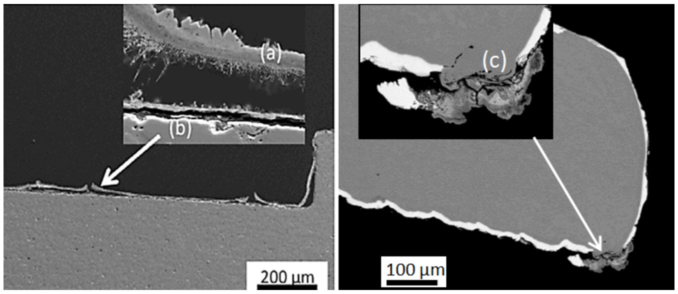

Fig. 4. SEM images of Type 1 (left panel) and Type 2 (right panel) connector pin cross-sections after MFG corrosion chamber exposure. The Type 1 connectors exhibited mineralized silver plating (a) that had delaminated from the base metal (b). The Type 2 connectors exhibited small areas of localized attack (c) on otherwise relatively intact plating.

C. Arc Fault Tests

The arc fault behavior of a Type 1 set of 10 new and 6 connector pins that were boldly exposed (no housing) to the MFG test environment was explored using the arc generator. Fig. 5 is a plot of the resistance and temperature measured as a function of position for these connectors. The position at -8 mm is the fully mated connector and 0 mm is indicative of the last point of Ohmic contact of the pin and socket upon separation as determined by a digital multimeter prior to each experiment. The average resistance of the fully mated aged connectors was 30 mΩ higher than that of the new connectors. The impact of this higher resistance is apparent in the temperature measurements that are near 100 °C for most of the aged connectors prior to separation. The onset of arcing is reflected in spikes in the temperature and resistance trends near the 0 mm position. Once sustained arcing was achieved during the separations, the power was cut off, which is seen as decreasing temperature after the spikes.

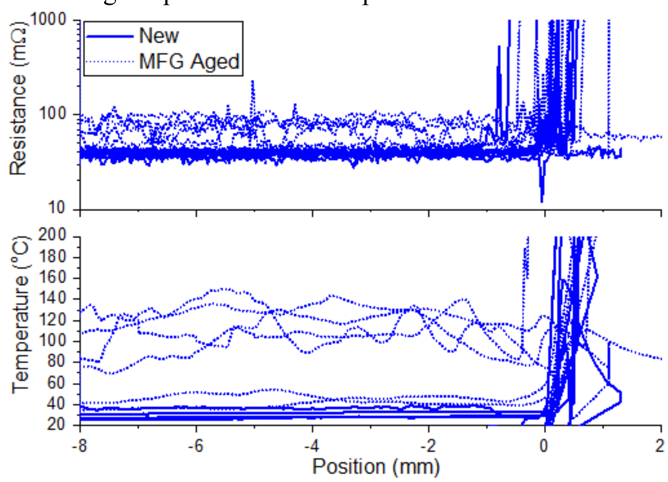

Fig. 5. Measured resistance (top) and temperature (bottom) as a function of separation distance during arc fault pull-apart experiments on Type 1 connectors. The position at -8 mm is the fully mated connectors and 0 mm represents the point of separation where ohmic contact was last detectable between the pin and socket by a multimeter. Positive position values indicate separation distance from this point.

Comparison of the separation positions at which the first intermittent arc and a sustained arc were observed during each experiment is given in Fig. 6. There appears to be no significant difference between new and aged connectors with regard to the positions at which arcs occurred. Similarly, examination of the position at which resistance spiked during the experiments revealed no clear differentiation between the new and aged connectors.

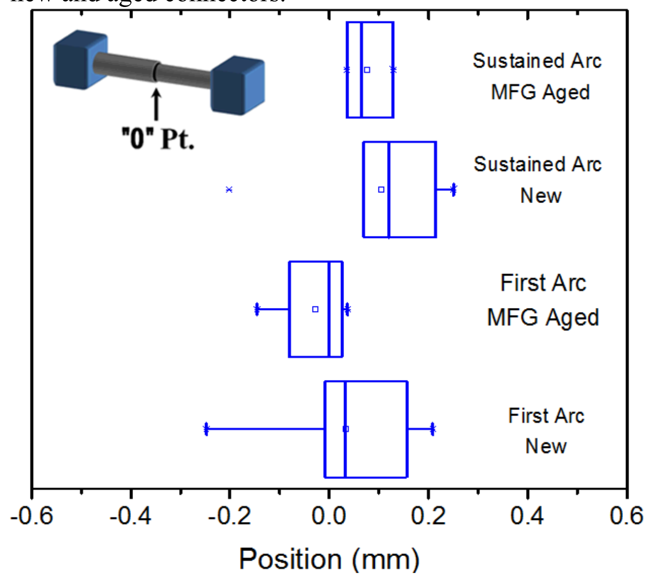

Fig. 6. Distribution of positions at which the first intermittent and sustained arcs were observed during arc fault experiments on Type 1 connectors. The position of 0 mm represents the point of separation where Ohmic contact was last detectable between the pin and socket by a multimeter. Positive position values indicate separation distance from this point.

IV. DISCUSSION

The three connector models examined in this work were generally resilient to the laboratory aging tests to which they were subjected. The Type 1 connectors explicitly exhibited the largest resistance increases during both tests, Figs. 1 and 2, but no larger than 3 mΩ. This would not be expected to cause significant joule heating to create an arc fault under PV array conditions.

The disparity in performance across the three connector types is attributed to variance in corrosion response related to materials of construction, Table 1. In contrast to the minimal corrosion seen on the tin-plated Type 2 and 3 connector pins when boldly exposed without their housing, the boldly exposed Type 1 pins exhibited severe corrosion, Fig. 4. Relative to tin, silver is vulnerable to corrosion in sulfur-rich environments representative of the MFG test and industrial atmospheres [16], so this could be expected. The results of these tests in combination with the arc fault experiments, Fig. 5, suggest that if the housing of the Type 1 connecters, which presumably shielded the contacts from the corrosive MFG atmosphere, were to be compromised in a sulfur-rich atmosphere for an appropriate amount of time, corrosion-induced joule heating could lead to arc fault conditions. Post-mortem analyses similar to those carried out for the MFG tests are necessary to relate the resistance trends in the damp heat tests to the realized degradation of the electrical contacts.

In contrast to the laboratory aging tests, a number of connectors exhibited considerably higher resistance increase at faster rates than invoked by the lab tests, Fig 3. The majority of these connectors were of Type 2 design. There are a number of potential degradation modes that could be responsible, including fretting corrosion of the plating due to differential thermal expansion and contraction. Tin, of which the Type 2 contacts are plated with, is particularly vulnerable to this degradation mode [17]. Alternatively, this behavior may have been due to a serial resistance increase at some location within the experimental setup external to the connectors themselves. Given measurements were taken using the 4-wire method, randomization carried out during test platform build and the prevalence of Type 2 connector degradation, it appears that this behavior is not an experimental artifact. This field data can provide value to the PV community by quantifying the seasonal variation in BOS connector contact resistance throughout the year. The measurements can provide margins to the subsequent arc fault risk assessment.

It is not clear in this work that the laboratory tests captured or accelerated contact resistance degradation to the degree and extent noted in the field environment. Further work is necessary to understand the differences between the outdoor and laboratory test results through post-mortem analyses of the exposed connectors and comparison of all tests. Field exposure in different environments, such as a heavy industrial area or coastal location, may produce a better correlation with the laboratory results presented here. Additional laboratory environmental conditions should be explored that are capable of both accelerating and emulating contact degradation observed on in-service connectors. In this regard, thermal cycling of both new and MFG-aged connectors is currently under examination.

The results for the connector arc fault revealed using a small sample size yielded no considerable difference between the separation distance needed to arc new and MFG-aged connectors, but several important conclusions can be drawn from these results. The results do show that arcs occur before the specified gap spacing of several millimeters indicated in the UL1699B standard for arc fault tests between two electrodes. In this work we found both intermittent and sustained arcing to occur within several hundred microns of contact separation, and in some cases before separation Fig. 5. This suggests that the UL standard spacing should be revisited for arc fault testing of connector pin and socket geometries. Additionally, visual observation of arcs as a function of position during connector separation is subjective with respect to the observer and may be a major source of the variance seen in the results. One means of reducing this uncertainty would be to determine the onset of an arc through FFT analysis of the current signal during the separation test [15].

V. Conclusion

This study is part of a larger effort to understand BOS connector degradation from the perspective of arc fault risk. Laboratory tests for future reliability model development found connectors to be resilient to corrosion degradation. An electrode separation method developed and utilized to evaluate the arc fault risk of connectors found no apparent difference in arc to separation between new and aged connectors. Further development of laboratory and field tests along with refinement means of assessing arc fault risk are necessary in order to allow PV operators to formulate a data-driven approach to BOS connector maintenance.

Acknowledgement

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly-owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

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