SAND2014-4445C

# Arc Fault Risk Assessment and Degradation Model Development for Photovoltaic Connectors

Benjamin B. Yang, Kenneth M. Armijo, Jay Johnson, Jason M. Taylor, N. Robert Sorensen

Sandia National Laboratories, Albuquerque, NM, 87185, USA

***Abstract* — This paper approaches balance of systems (BOS) connector reliability from the perspective of arc fault risk. A degradation model based on accelerated tests, field tests, and outdoor monitoring data is integrated with results from arc fault testing. The accelerated tests include thousands of hours of damp heat, atmospheric corrosion, and temperature cycling. Arc fault tests are performed on new and aged connectors to determine the relative effects of degradation. Together, the degradation model and arc fault risk assessment will provide operators of photovoltaic installations the information necessary to develop a data-driven plan for BOS connector maintenance.**

***Index Terms* — connectors, arc fault, reliability, accelerated testing**

## I. Introduction

As the reliability of more traditional photovoltaic (PV) modules become better characterized, the focus has gradually expanded to the balance of systems (BOS) components. Increasing emphasis is being placed on inverters, junction boxes, and interconnects [1]. Of these components, the reliability of BOS connectors has been relatively uncharacterized beyond qualification tests, which do not offer a prediction of lifetime. The annual potential power loss observed in one study due to increased contact resistance of a particular connector was estimated to be 140 Watt-hours per string [2]. These losses quickly add up over multiple connectors and strings.

Beyond the obvious but possibly acceptable costs of Ohmic power loss, there is the more subtle cost of arc fault risks. The series arc faults that result from BOS connectors are low-probability, high-damage and visible events with effects that are difficult to quantify if one is to factor in industry-wide publicity costs to PV. There have been instances where arc faults related to BOS connectors have been documented and its prevention has been identified as a critical knowledge gap [3], [4].

Currently, progress towards developing a degradation model for BOS connectors has been limited. There has also has not been any study that could relate such degradation model predictions to the likelihood of arc fault. This paper seeks to address both of these issues by utilizing accelerated test and field test results to develop a degradation model for BOS connectors. An arc fault generator is applied on new and aged connectors in order evaluate arc fault risk and establish a definition of failure to provide practical implications to the degradation model results.

## II. Approach and Methods

The experimental approach for this paper is summarized in the flowchart in Fig. 1. There are two primary project objectives: 1) to develop a degradation model for BOS connectors, and, 2) evaluate new and aged connectors for arc fault risk in order to complete the degradation model with a figure of merit for part failure. The degradation model alone will provide the PV industry with information necessary for a cost-benefit analysis on energy loss versus replacement costs for the connectors.

Current accelerated test results, however, suggest that it is more likely that the cost of a catastrophic arc fault event is likely to overshadow the penalty of resistive energy lost. Therefore, the connection between arc fault risk and degradation must be made in order to properly assess the cost effectiveness of BOS connector maintenance.

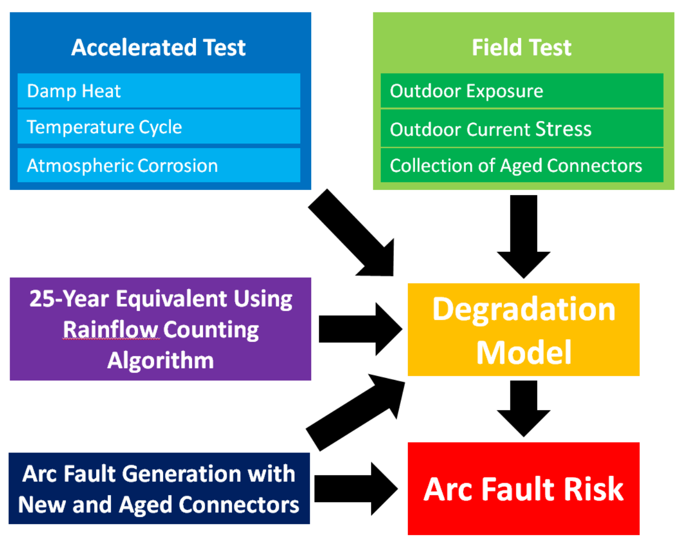


Fig. 1. Overview of the BOS connector arc fault research approach. Accelerated tests are used to generate measureable degradation in a reduced amount of time. These results are correlated with field data through the addition of field tests and a rainflow counting algorithm to develop a degradation model. Arc fault generation experiments with new and aged connectors are then used to determine the amount of degradation necessary for arc fault risk, which provides a failure criterion for the degradation model.

The degradation model requires inputs from four different resources. Firstly, accelerated tests are performed in a laboratory setting to induce degradation and characterize the effects of various stress factors. These accelerated tests are necessary due to the slow degradation of BOS connectors that are in the field. In addition, it will result in an improved understanding on the effects of various stress factors, which enables the degradation model to be adjusted for different environments without the aid of custom outdoor tests for each condition. The laboratory portion of the study consists of three accelerated tests: damp heat (85°C/85% relative humidity), temperature cycling (-45°C to 110°C), and atmospheric corrosion. The atmospheric corrosion test utilizes a mixed flow gas corrosion test chamber that can generate Class II and Class III environments [5]. These corrosion tests cover most environments applicable to PV systems by simulating light or moderate industrial environments.

The accelerated test results will be evaluated against field test data from connectors in outdoor environments. A test bench has been established in a high-desert environment to subject BOS connectors to an outdoor setting. In addition, connectors are being fabricated to endure current stress in the same outdoor location. Due to the expected slow degradation of these connectors, the field data will be supplemented by connectors collected from existing installations that are of a known age. In addition, year-round temperature data collected from the field as well as measurements from the arc generation setup will also be used to help translate the lab results to long-term expected lifetimes.

In addition to quantifying the rate of degradation, the model results must be converted into risk of arc fault. An arc fault generator developed and implemented at Sandia National Laboratories powered by a PV simulator was used to generate arcing events in both new and aged connectors. A layout of the arc fault generator is shown in Fig. 2. The likelihood of arcing will be based on objective parameters from the experiment, such as separation distance and temperature measurements.

## III. BOS Connector Accelerated Test Results

This section summarizes the existing results of BOS connectors that have been subjected to thousands of hours of testing. Current results include data from damp heat, atmospheric corrosion, and outdoor temperature.

A sample of nine BOS connectors after over 6000 hours of damp heat testing at 85°C/85% relative humidity is shown in Fig 3. While there have been minor increases in resistance, all of the measurements remain below 5 mΩ. Observable variation in resistance begin to develop, especially after 4000 hours, with changes on the time scale of hours. The cause and arc fault implications of these connectors will be studied at the conclusion of this test, which is currently ongoing. In addition to damp heat, this study also seeks to examine the degradation effect of grime contamination on the contacts. Laboratory-created, reproducible grime simulating coastal and desert environments have been applied to a subset of the samples [6], [7]. Currently, the grime-contaminated connectors are indistinguishable from the control samples.

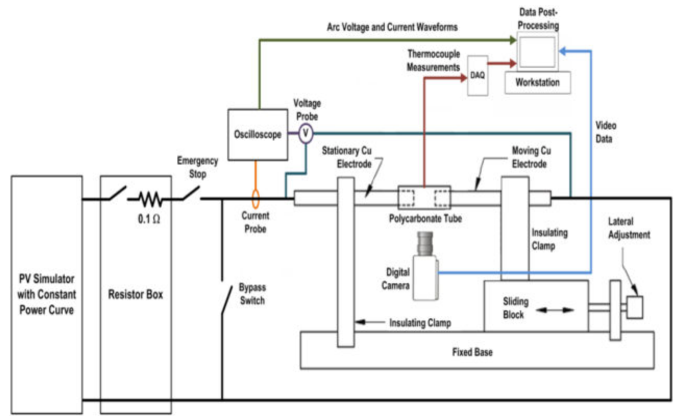


Fig. 2. Diagram of the arc fault generation experiment that was applied to new connectors as well as connectors that have been exposed to accelerated tests or field conditions. The effect of degradation on the necessary separation to induce arc fault were used to quantify arc fault risk and define the failure criteria for the degradation model.

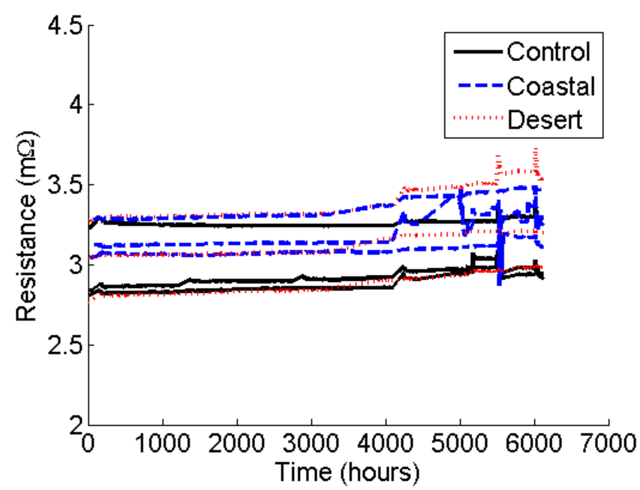


Fig. 3. Resistance over time for over 6000 hours of damp heat test. Three sets of connectors are shown here: 1) control set, 2) samples with grime simulating a coastal environment applied to the contacts, and 3) samples with grime simulating a desert environment applied to the contacts. The resistance has remained below 5 mΩ throughout the duration of the damp heat test. Variation begins to develop after 4000 hours. The cause of this instability and its implication to arc fault risk are under study.

Fig 4 shows the contact resistance measured as a function of time for 99 connectors in a Class II atmospheric corrosion chamber. Gradual degradation in one connector from the sample began after the 4000 hour mark. As of 5000 hours of testing, however, the resistance remained below 5 mΩ.

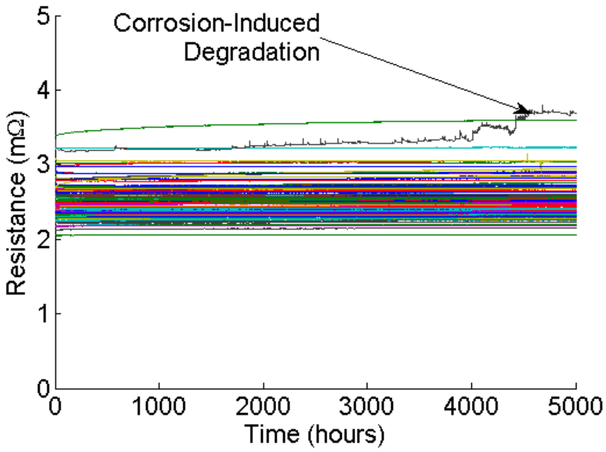


Fig. 4. Contact resistance as a function of time for 99 connectors in a class II corrosion chamber over the course of 5000 hours. Corrosion-induced degradation of one connector out of the sample is visible. Additional data through continued monitoring will provide estimates on the amount of time needed to reach the failure criteria defined by the arc-fault experiment.

An outdoor test bed was implemented to expose 51 connectors to high desert elements and explore their effects on their packaging and contacts. Over 2500 hours of testing has been completed with no catastrophic failure. Due to temperature fluctuations, the resistance measurements are noisier than the laboratory results in the previous figures.

It is likely that over one year of exposure is necessary before measurable degradation will occur in these samples. Compared to the accelerated tests, these samples are subjected to mild exposure. In addition, the noise introduced by the temperature variation will require a greater amount of degradation and data analysis before the changes can be detected.

In the meantime, this outdoor test can provide value to the PV community by quantifying the variation in BOS connector contact resistance throughout the year. The measurements will also provide margins to subsequent arc fault risk assessment.

## IV. BOS Connector Arc Fault Test Results

The degradation of BOS connectors are further contextualized by translating the results into arc fault risk. To accomplish this task, an experiment was built by running power from the arc fault generator in Fig. 2 across the connectors under test. In order to induce arc fault, the connector pins were gradually separated until arcing occurred. Real-time voltage and current measurements were acquired during translation and used to calculate the resistance.

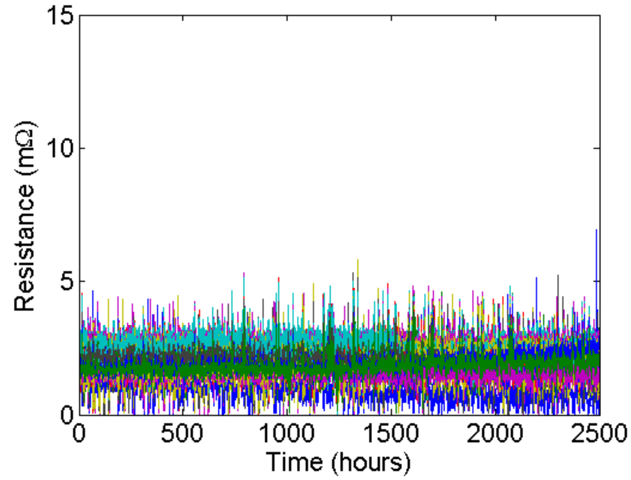


Fig. 5. Contact resistance data for connectors exposed to the elements in a high-desert outdoor environment. The measurements are noisier than the laboratory measurements due to temperature cycles. The results will be used to help infer connector lifetime from accelerated test results.

The separation distance prior to the first detected spark as well as the translation necessary for a sustainable arc was used to infer the relative risk of arc fault between connectors. While the connector pins are separated, the resistance across the connector rises due to a gradual decrease in surface area. If a decreased amount of translation is necessary to produce a sustainable arc, then the resistance increase and connector disturbance needed to result in arc fault hazard in turn also increases.

Using this approach, we characterize a set of five new connector pins from three different manufacturers. The results are compared to an identical connector pin that has been exposed in a Class III corrosion chamber for a month without the protection of its casing. The position of the first spark and sustained arc fault between these connectors is compared. The use of resistance as a precursor to impending arc fault is also explored.

Fig. 6. shows a plot of the resistance as a function of position from Manufacturer A. The five dark lines refer to individual samples that have not been through corrosion. The dashed red line represents the measurement of the contact pin that had experienced prolonged exposure in the corrosion chamber. The position is translated relative to each other such that 0 mm refers to the last point of Ohmic contact detectable by a digital multimeter. The blue circle represents the location of the first detected arc and the blue “x” indicates where a sustained arc began to occur.

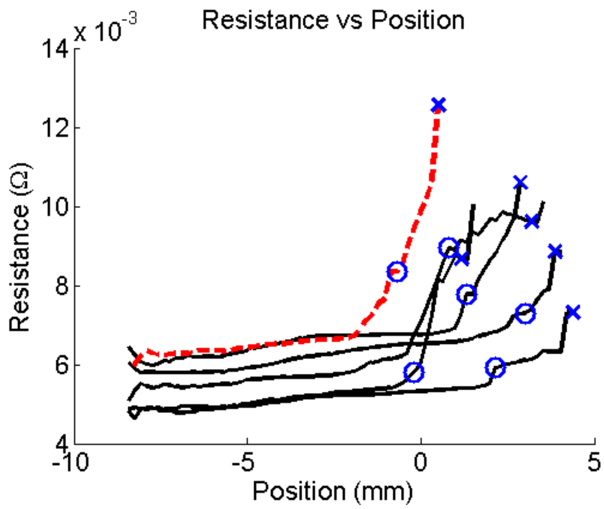


Fig. 6. Measured resistance plotted as a function of translational stage position during arc fault experiment for manufacturer A. The measurements are shifted such that 0 mm on the x-axis represents the location of where Ohmic contact was last detectable by a multimeter prior to the experiment. The five dark solid lines represent five new connector pins that were tested. These results are compared with the dashed red line, which shows the measurements from a connector pin that has been through exposure in a Class III corrosion chamber. The blue circles indicate the location of the first detected arc. The blue "x" shows the location where a sustained arc began to occur.

The measurements in Fig. 6 indicate that the initial contact resistance of Manufacturer A connectors were not significantly affected by the time spent in the corrosion chamber. Compared to the control part, however, the degraded connector experienced its first arc and also sustained arc with less separation than the control samples. Furthermore, there is an earlier increase in resistance prior to the first point of arc fault and a shorter distance separating the first arc from the point where a sustained arc fault was detected.

Fig. 7 shows a similar set of measurements using connector pins from Manufacturer B. Despite having the same material composition as Manufacturer A, The initial resistance of the connector from Manufacturer B was adversely affected by the corrosion chamber. Aside from this initial shift of increased resistance, however, the degraded connector pin began arcing at a similar location to the control samples. Therefore, it could be argued that despite increased Ohmic losses, the arc fault risk due to corrosion is not significantly altered for connectors from this manufacturer. The difference between the results in Fig. 6 and Fig. 7 possibly due to geometric design or relative layer thicknesses and remains a subject of further study.

Fig. 8 shows results of the same experiment performed on connectors from Manufacturer C. Manufacturer C differs from the other two brands in this study due to its physical design as well as a silver-plated coating. The silver-plated coating, in particular, makes the connectors particularly susceptible to the corrosion chamber effects. The initial resistance was nearly an order of magnitude higher than the control samples, and the resistance measurements throughout the experiment were less stable. The change in resistance as a function of position also decreased prior to the point of arc fault. Despite the dramatic increase in resistance compared to the control sample, the arc fault risk of connector C did not increase significantly.

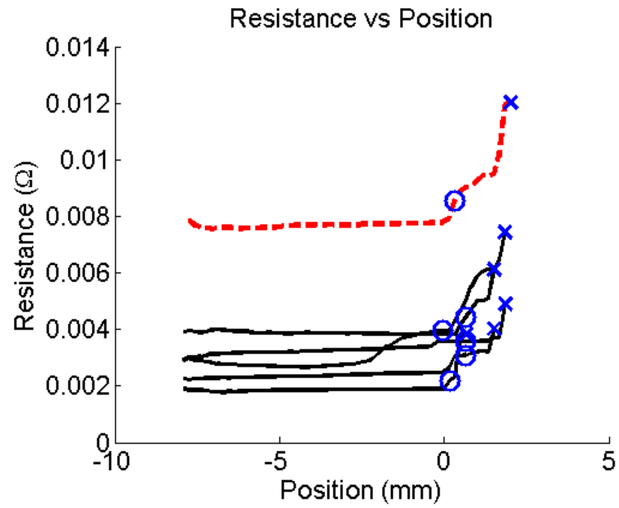


Fig.7. Measured resistance plotted as a function of translational stage position during arc fault experiment for manufacturer B. The five dark solid lines represent five new connector pins and the dashed red line represents a corroded connector. The blue circles indicate the location of the first detected arc. The blue "x" shows the location where a sustained arc began to occur.

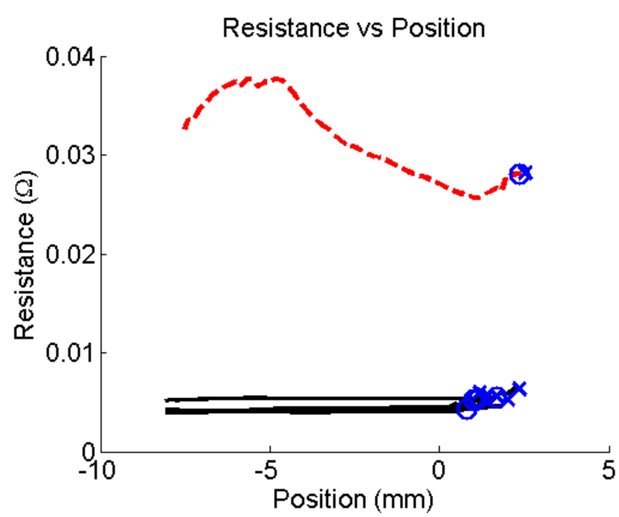


Fig. 8. Measured resistance plotted as a function of translational stage position during arc fault experiment for manufacturer C. The five dark solid lines represent five new connector pins and the dashed red line represents a corroded connector. The blue circles indicate the location of the first detected arc. The blue "x" shows the location where a sustained arc began to occur.

In summary, the effect of corrosion-chamber-induced degradation on Ohmic resistance and arc fault risk was evaluated for connector pins from three different manufacturers. Manufacturer A and B had the same bulk material composition but different designs. While Manufacturer A did not experience an initial resistance increase from the corrosion chamber, it had a higher arc fault risk. While the resistance of Manufacturer B was adversely affected by the corrosion chamber, its arc fault risk was comparable to Manufacturer A. Manufacturer C experienced a significant increase in resistance due to the corrosion chamber, potentially for reasons associated with its silver-plated coating. Its arc fault risk, however, was comparable to the control samples. Furthermore, increases in resistance was observed prior to arc fault in connectors from manufacturers A and C, which can potentially be used for arc fault prevention prognostics.

## V. Conclusion

This project studies BOS connector degradation from the perspective of arc fault risks. A degradation model is being developed to predict lifetimes based on accelerated tests and field measurements. Aged and fresh connectors are evaluated for arc fault risk through the use of an arc fault generator. Through further study, the combined the results will allow PV operators to formulate a data-driven approach to BOS connector maintenance.


## V. Acknowledgements

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.


## References


[1] J. H. Wohlgemuth, “Reliability of PV systems,” pp. 704802–704802, Aug. 2008.

[2] Photon International, “Good connections: market survey on PV connectors,” pp. 122-154, January, 2010.

[3] Juris Kalejs, Jeff Gadomski, and Zach Nobel, “Connector Issues in Reliability,” NREL PV Module Reliability Workshop, 2013.

[4] Kurtis Ming, “Hundreds of NorCal Solar Homes Could Catch Fire,” CBS13 News, November 4, 2013.

[5] W. H. Abbott, “The Development and Performance Characteristics of Mixed flowing Gas Test Environment”, IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol. 11, no. 1, pp. 22, 1988.

[6] W. Einfeld, R. M. Boucher, M. S. Tezak, M. C. Wilson, and G. S. Brown, "Evaluation of surface sampling method performance for Bacillus Spores on clean and dirty outdoor surfaces," SAND2011-4085, 2011.

[7] P. D. Burton and B. H. King, “Application and Characterization of an Artificial Grime for Photovoltaic Soiling Studies,” IEEE Journal of Photovoltaics, vol. 4, no. 1, pp. 299–303, Jan. 2014.