

Reliability Model Development for Photovoltaic Connector Lifetime Prediction Capabilities

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Abstract — This paper describes a rigorous effort to build a reliability model for photovoltaic connectors. The model is based on eight different accelerated tests performed on over 300 connectors. The study also examines the effects of connector housing ingress protection rating, installer error, and extra stresses from attachment to a rigid surface. Post-stress connectors will be compared with those from the field to correlate the lab degradation rate with that of outdoor operation. The final model will allow operators to quantify losses due to connector degradation and determine the optimal timing to replace the connectors in their system.

Index Terms — connectors, reliability, accelerated testing, fretting, corrosion

I. INTRODUCTION

While there are extensive efforts to characterize the reliability of photovoltaic (PV) modules and the supporting power conversion systems, the degradation of connectors has received less attention. While the occasional open-circuit connector failure can be seen as a nuisance to owners and operators, hidden degradation in the form of increased contact resistance can potentially accumulate over a large number of connectors into a noticeable quantity of lost power output. 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 in per string [1]. These losses would quickly add up over multiple connectors and strings. The degradation mechanism and losses could be further aggravated in systems with higher currents or warmer climates. Despite this potentially significant source of unquantified power loss, there have been few rigorous studies with large sample sizes to characterize the degradation rates of PV connectors [2].

This paper will describe the findings from an extensive effort to build a reliability model for PV connectors from three popular manufacturers. The model will be based on results of eight different accelerated tests, each of which involve over 20 connectors from each manufacturer. In addition to the standard procedures of thermal cycling, humidity exposure, and humidity freeze, the accelerated test also explores the effects of atmospheric pollution through a corrosion chamber that can simulate Class II and Class III environments. An analysis of post-stress connectors compared to aged ones from the field will be used to connect accelerated test conditions to actual degradation rates in the field.

To the authors' knowledge, the rigor, sample size, and variety of accelerated test factors in this study exceed those currently in the literature for PV connectors. The goal of the reliability model resulting from this effort is to provide the foundation for PV system owners and operators to determine the optimal time to replace connectors based on their specific combination of climate, energy and labor costs.

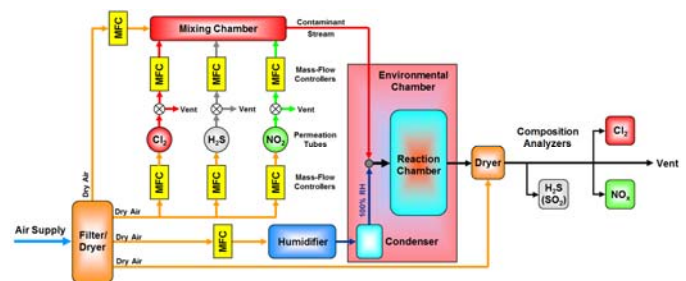


Fig. 1. Schematic of the mixed-flow gas chamber used to simulate corrosion.

II. TEST PLAN

The three known factors that contribute to the degradation and failures of photovoltaic connectors are [3]:

- Fretting due to relative movement of the contact interfaces. The relative movement can be caused by temperature expansion and contraction cycling or other outside environmental factors.
- Corrosion through the ingress of contamination to the interface.
- Gradual age-related change in the stiffness and morphology of the connector material.

The test plan in this study focuses on the first two factors, as they are believed to be the dominant sources of degradation.

Table I provides a summary of the accelerated test conditions. OD-1 will be used as a baseline to connect the accelerated test results with actual degradation rates that would be typical to a dry, high-altitude climate typical of the southwest region of the United States. A subset of the contacts will be exposed in an attempt to quantify the value added by the connector housing and estimate the additional degradation caused by incorrectly-built connectors.

TABLE I
SUMMARY OF CONNECTOR RELIABILITY TEST PLAN

Test ID	Test Condition	Configuration	Test Duration	Measurement(s)
OD-1	Normal Outdoor Exposure	<ul style="list-style-type: none"> • 20 complete (<i>e.g.</i> housed and unexposed) connectors • 20 exposed contacts • 20 previously-fielded connectors in operation 	1 year minimum	<ul style="list-style-type: none"> • Resistance • Temperature • Relative Humidity
AC-1	Class II Conditions	<ul style="list-style-type: none"> • 20 complete connectors • 20 exposed contacts with good crimps • 20 exposed contacts with poor crimps 	Minimum 1400 hours	<ul style="list-style-type: none"> • Resistance
AC-2	Class III Conditions	<ul style="list-style-type: none"> • 20 complete connectors • 20 exposed contacts with good crimps • 20 exposed contacts with poor crimps 	Minimum 1400 hours	<ul style="list-style-type: none"> • Resistance
RH-1	85°C / 85% RH	<ul style="list-style-type: none"> • 20 complete connectors • 10 previously-fielded connectors 	Minimum 1500 hours	<ul style="list-style-type: none"> • Resistance
RH-2	85°C / 40% RH	<ul style="list-style-type: none"> • 20 complete connectors 	Minimum 1500 hours	<ul style="list-style-type: none"> • Resistance
TC-1	Temperature cycle from -45°C to 110°C, leave loose	<ul style="list-style-type: none"> • 20 complete connectors • 10 previously-fielded connectors 	Minimum 500 cycles	<ul style="list-style-type: none"> • Resistance
TC-2	Temperature cycle from -45°C to 110°C, attached to rigid baseplate	<ul style="list-style-type: none"> • 20 complete connectors 	Minimum 500 cycles	<ul style="list-style-type: none"> • Resistance
HF-1	-40°C to 85°C / 85% RH. Leave loose	<ul style="list-style-type: none"> • 20 complete connectors • 10 previously-fielded connectors 	Minimum 100 cycles	<ul style="list-style-type: none"> • Resistance
HF-2	-40°C to 85°C / 85% RH. Attached to rigid baseplate	<ul style="list-style-type: none"> • 20 complete connectors 	Minimum 100 cycles	<ul style="list-style-type: none"> • Resistance

AC-1 and AC-2 focus on the effects of corrosion at the connector interface using a mixed flow gas corrosion test chamber. The test chamber components are summarized in a diagram in Fig. 1. These accelerated tests are performed using a mixed flow gas corrosion test chamber that can create Class II and Class III environments. Class II and Class III tests correspond to light or moderate industrial environments, which should include the most corrosive situations experienced by a majority of PV systems. There is also an additional set of connectors with “poor crimps” due to an insufficient amount of exposed wire being inserted into the sleeve. The results will seek to quantify the costs associated with this installation error.

Test ID RH-1 and RH-2 in Table 1 are designed to examine the effect of corrosion due to exposure to humidity only. Together, the tests AC-1, AC-2, RH-1, and RH-2 also involve sets of connectors that do not have housing and are completely exposed to the corrosive gasses. Furthermore,

some connectors have an ingress protection (IP) rating of IP67, while others have a rating of IP 68. A comparison of the different corrosion rates will quantify the value added by the increased IP rating.

Tests TC-1 and TC-2 accelerate the fretting degradation mechanism through thermal cycling. Tests HF-1 and HF-2 introduce fretting and other mechanical damage through humidity freeze cycles. In the case of TC-1 and HF-1, the connectors are left loosely hanging while those in TC-2 and HF-2 are connected to a rigid baseplate. The presence of the baseplate will increase the stress on the connector due to thermal cycling. Configurations where the cable and associated connectors are fastened against a surface of different material are becoming increasingly common, especially as building integrated photovoltaic (BIPV) designs increase in popularity. The effects of increased stress caused by temperature cycling of cables and connectors attached to a rigid surface have not been quantified before. A comparison

of the degradation rates between connectors that were loosely hanging and those that were attached to a rigid baseplate will provide insight on the necessity of developing new connector and cable types for BIPV systems.

A subset of the connectors involved in tests OD-1, RH-1, TC-1, and HF-1 will involve connectors that have already been used on the field. These connectors will be collected from existing photovoltaic arrays at Sandia National Laboratories, such as those in the Distributed Energy Technology Laboratory. An example of an aged connector in operation is shown in Fig. 3. Examination of these connectors before and after accelerated testing will provide data to translate the reliability findings of this study into degradation rates that are applicable to climates typical of the United States southwest.



Fig. 3. Example of an aged connector at the Distributed Energy Technology Laboratory at Sandia National Laboratories that can be later used to correlated acceleration factors with actual degradation rates in the field.

The heat generated under load by the connectors will be characterized before and after the accelerated tests. The contact resistance of all connectors will be monitored during

all tests and will be used as the primary performance metric. In addition, cross sections and other destructive failure analysis will be performed on a subset of connectors to better understand the degradation mechanisms and provide an accurate comparison between field connectors and those stressed in a laboratory setting.

III. CONCLUSIONS

This paper describes the first large-scale attempt to build a reliability model specifically for photovoltaic connectors. Data from three months of testing as well as initial reliability findings will be presented in the final version of this publication.

The results of this study will quantify the effect that connector degradation could have on the derating and diminished performance of PV systems. The final model will enable system operators to identify the optimal time to replace connectors based on the climate, energy and labor costs specific to their situation.

IV. ACKNOWLEDGEMENTS

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