Co-located Accelerated Testing of Module Level Power Electronics and Associated PV Panels

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Co-located Accelerated Testing of Module Level Power Electronics and Associated PV Panels

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Abstract — In order to study the relative degradation between co-located PV modules and microinverters in an ACPV configuration, four 260 Watt PV modules and four 250 W microinverters purchased on the open market have been co-located in a thermal chamber set at a static temperature (69°C). Instantaneous electrical/thermal measurements have been taken on the microinverters with periodic dark IV measurements on the modules. After over 10,000 hours of testing, no failures or observable degradation have been seen in either the module or microinverter. Using average measured field-temperature data with Military Handbook analysis, this indicates an approximate field use of 44 years of operation lifetime for PV modules, and 13 years of operation for microinverters with reliability of 66.87% with a lower one-sided confidence level of 80%.

Index Terms — materials reliability, photovoltaic systems, solar panels, power electronics, DC-AC power converters.

I. INTRODUCTION

Over the past several years, there has been a distinct movement for module level power electronics (MLPE) integration into the module to become an integrated ACPV system that exports AC power directly from the module. Although there are currently no MLPE units which are incorporated directly into the module back sheet or framing, there are now several manufacturers which are offering a module and MLPE system directly to the consumer. Since these MLPE units are sold paired with PV panels, customers are demanding unit lifetimes and warranties similar to that of PV modules (~25 years). This type of unit is an intermediate step towards full incorporation of the power conversion into module production and will likely increase in the coming years. Unfortunately, the reliability of these types of integrated PV-MLPE systems have never been reported publicly by any independent testing organization and it is an open question whether the module or the power conversion device will be the first to fail.

In the previous work, we have applied a variety of accelerated testing protocols to a wide variety MLPE topologies (DCOs and MIIs were included) and manufacturers (five included) [1]. In situ power measurements as well as periodic efficiency measurements over the length of experimental tests compared to module data in the open literature indicate that MLPEs demonstrate less degradation than modules under similar testing conditions.

This work has expanded on those comparisons by testing four microinverter/module units co-located and co-monitored in the same thermal chamber. These units have been tested at a static temperature of 69°C for over 10,000 hours (tests are still ongoing) to monitor relative degradation rates as well as time-to-failure (TTF) between the two components of the ACPV system.

II. EXPERIMENTAL SETUP

In order to study the relative degradation between co-located PV modules and microinverters in an ACPV configuration, four 260 Watt PV modules and four 250 W microinverters purchased on the open market have been co-located in a thermal chamber set at a static temperature. The setup for long-term ACPV testing is shown in Fig. 1. Rated power (Voc=42 V Isc=8.3 A FF=0.723) from a Sorenson PV simulator is applied to the microinverters while they are continuously monitored with a data acquisition system with one second sampling rate. Dark IV curves are carried out periodically on the modules to detect gradual degradation in the modules with a Keithley 2751 power supply.

![Fig. 1. ACPV Test Setup](image)

The ambient thermal chamber setpoint is set to be just below the derating temperature of all the microinverter units. This temperature (ambient temperature ~69°C) is maintained by the chamber to within a degree during normal operation. This results in a temperature spread of ~5°C between the four inverters in the chamber from 74 to 69°C as monitored on the backplane of the devices.

A number of data channels are used for monitoring the electrical performance of the microinverters. In addition to temperature, input/output voltages and currents are monitored and used to calculate relevant operational parameters. The available measured and calculated parameters include AC/DC voltage/current/power, apparent power/power factor, efficiency, and unit/ambient temperature.
The modules in the chamber are being monitored through dark IV traces applied periodically using a Keithley 2651A high current power supply. This power supply is capable of applying up to 40 V and 50 A in a pulsed mode. To take the IV curve, a sweep of 100 voltage pulses (3 ms on, 50 ms off, 6% duty) from 0 to 35.2 V (datasheet Voc of the panel under STC) is applied to the module and the current draw on the supply is monitored. The measured data is an average of 10 collected readings at a given voltage.

From these IV curves, the relevant module parameters (FF, Rs, and Rs) are derived. Fill Factor is determined by the ratio of the maximum sourced power to the product of the datasheet Voc and Isc values. Rs and Rs are determined by fitting 10 data points of the IV curve around V=0 and V=Voc, respectively, and taking the inverse of the slope.

### III. RESULTS

#### A. Microinverters

This setup has currently been collecting data for over 10,000 hours and continues to collect data in an automated manner. Data will be collected until all the units fail in order to derive a time to failure for the components under these conditions.

Efficiency measurements of the inverters are shown in Fig. 2. The inverter efficiencies range from 96-98.5%. Although efficiency does vary over time (most likely due to small errors in voltage/current measurements propagating to efficiency calculations). No long-term degradation in unit efficiency has been evident at this point in testing and all units are operating at rated power as expected. Abrupt, periodic changes in efficiency of the inverters are shown in the figure. Upon further investigation, these steep drops in efficiency are due to data dropouts in data acquisition equipment are not due to changes in operation of the inverters.

**Fig. 2. Monitored Microinverter efficiency in ACPV test showing efficiency measurements with periodic data dropouts**

#### A. PV Modules

As can be seen from Fig. 3, after 10,000 hours at an ambient chamber temperature of 69°C, the FF, Rs, and Rs values of the panels do not show any observable long-term degradation. These values are currently being monitored for degradation along with the microinverter operation and will continue until unit failure.

**Fig. 3. Derived module parameters over time from measured Dark IV curves showing module Fill Factor (solid circles), series resistance (dashed lines), and shunt resistance (solid triangles) over time.**

### IV. TIME TO FAILURE ANALYSIS

When reliability is estimated from experimental data, the estimated reliability is a distribution which can be calculated by dividing number of samples failed at a particular time by the total of samples in a population. This historical usage data is accurate and useful, but time-consuming, difficult to collect, and difficult to control for variables in device operation.

In evaluation of expected lifetime of a device which has not seen service in the field, reliability and lifetime are not known a priori, but must be estimated based on testing (either via accelerated stress or normal stresses). In a test-to-fixed life approach, a given number of products with unknown failure distribution and lifetime but known usage conditions are tested to a fixed time, with zero failures allowed. These zero failure reliability tests allow for manufacturers to test for a product’s minimum reliability for a given duration of operation for a desired reliability and confidence limit. These tests are utilized extensively in industry as they can be achieved for a fixed chamber time with a limited number of samples, thus limiting the costs.

However, in tests with a fixed censoring time and small sample sizes, it is possible to have zero failures at one or more levels of stress at the end of the test. Although no failures have occurred and typical methods of calculating failure distributions cannot be applied, the lack of any failures itself gives information regarding the population failure distribution.

During a test, the reliability of a device can be estimated using a binomial equation [2]:

\[
1 - CL = \sum_{i=0}^{r} \binom{n}{i} (1 - R)^i R^{n-i}
\]
Where $R$ is the system reliability, $CL$ is the confidence level, $n$ is the sample size and $r$ is the number of failures.

If the number of failures is zero, (1) simplifies to:

$$1 - CL = R^n$$

(2)

Therefore, reliability of a device is a function of the confidence level and vice versa. TABLE I shows pair-wise confidence level and reliability values for $n=6$ and zero failures observed:

<table>
<thead>
<tr>
<th>CL</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.7953</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7401</td>
</tr>
<tr>
<td>0.8</td>
<td>0.6687</td>
</tr>
<tr>
<td>0.9</td>
<td>0.5623</td>
</tr>
<tr>
<td>0.95</td>
<td>0.4729</td>
</tr>
<tr>
<td>0.99</td>
<td>0.3162</td>
</tr>
</tbody>
</table>

This table indicates that for a test of $x$ hours, it can be stated that the reliability of the devices at $x$ hours is 56.23% with a confidence level of 0.9, or 56.23% with a confidence level of 0.95. In other words, 56.23% of devices will have a lifetime of greater than $x$ hours with a confidence level of 0.95.

From the binomial formula in (1), it is apparent that there are an infinite number of combinations of $n$ and $r$ that can demonstrate the desired reliability for a given confidence level.

The zero-failure demonstration test requires a small sample size and is therefore widely used. However, this calculation does not take into account period of time elapsed, which for devices with long desired lifetime, can result in significant experimentation time, increasing the cost. For this reason, tests are typically done with higher stress level than devices will experience in the field. These increases levels of applicable stressors will induce failures in a shorter amount of time, decreasing the time of testing. For this reason, tests are typically done with higher stress level than devices will experience in the field. These increases levels of applicable stressors in devices are typically driven by thermal, thermal cycling, voltage, humidity, or mechanical stressors and there exist a wide variety of ALTs and stress models to equate time at elevated stress-level with time in the field. For thermally driven failure mechanisms, the Arrhenius life-stress model is most often used. This model is typically given as:

$$L(T) = Ce^{\frac{E_a}{kT}}$$

(3)

Where: $L$ represents a quantifiable life measure (such as mean life), $C$ is a constant, $E_a$ is the activation energy and $k$ is Boltzmann’s constant ($8.617385 \times 10^{-5}$ eV/K).

For Silicon and Silicon-based systems (such as most power handling devices), the activation energy is typically assumed to be 0.7 eV. For example, the Military Handbook [3] for reliability prediction of electronic equipment uses an activation energy of 0.7 eV for the failure of electronic components and systems. While this is technically only true for bulk semiconductor device failure, it is common in the industry to assume that systems, as a whole, have an activation energy of 0.7 eV. This approximation is much more appropriate for static temperatures than cyclic temperature profiles, as the most common failure mode for cyclic temperatures are not bulk semiconductor related (e.g. device packaging, connectors).

With an appropriate approximation of the activation energy of a failure mechanism, the Arrhenius equation can be used to extrapolate lifetime of one device operated at one temperature ($T_1$) based on information of that same device operated at a different temperature ($T_2$):

$$L(T_1) = L(T_2)e^{\frac{E_a}{k} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

(4)

The proportionality factor, $e^{\frac{E_a}{k} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$ is also known as the acceleration factor. By applying a test to a device at a high temperature, information can be constructed about the lifetime of the device at some low operational temperature.

The Arrhenius relationship can be linearized and plotted on a Life vs. Stress plot, also called the Arrhenius plot. The relationship is linearized by taking the natural logarithm of both sides in the Arrhenius equation or:

$$\ln(L(T_1)) = \ln(L(T_2)) - \frac{E_a}{k} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

(5)

To estimate the usage case lifetime of ACPV units, $L(T_1)$, indicated by the zero-failure demonstration results in this work, it is necessary to understand the thermal environment for ACPV units in the field. For this purpose, data was collected on microinverter and module thermal environment.

Sandia has been carrying out long-term monitoring of modules in fielded operation in Albuquerque, NM. A 7kW fielded array with crystalline silicon modules has been instrumented for multiple years with one second resolution data of electrical and thermal behavior. The data collected can be used to inform the work done here to provide context for how accelerated testing time correlates to useful life for the module. A field-measured, normalized histogram for one year of data of the measured temperatures (during daylight hours) of a module is shown in Fig. 4. A Gaussian fit to the module data shows good agreement with the data. The best fit for the temperature
distribution has a median temperature of 35.98°C (309.13 K) with a standard deviation of 16.4°C.

Fig. 4. Module temperature histogram for 1 year of temperature data.

Microinverter thermal data was obtained from literature [4]. This data included thermal measurements of a microinverter in Phoenix, AZ over one year. This data included thermal readings for daylight as well as nighttime hours. Inclusion of nighttime hours in the measurement creates a bimodal distribution to the temperature histogram. Since it is assumed that stress only accumulated during operation, only the daylight hours are of interest. Therefore, the second peak of the bimodal distribution (which is caused by daytime peak temperatures) was fit to a Gaussian. The best fit for the temperature distribution has a median temperature of 43.1°C (316.2 K) with a standard deviation of 9.63°C.

Using the proportionality factor in (4) and the mean of the field-use thermal profiles, the acceleration factor of the test conditions for the testing presented here (69°C) can be calculated to be 12.63 for the PV module and 6.99 for the microinverter. For a more conservative estimate, the mean and one standard deviation can be used to estimate the field-use temperature. This would give acceleration factors of 2.74 for the module and 3.27 for the microinverter.

This acceleration factor is used along with (5) to determine the equivalent time in the field that yields commensurate stress as the accelerated test. Once this time is found, the appropriate reliability and confidence levels for the population can be found using (2). If the measured mean temperature for modules and microinverters is used, the 10,000 hours of testing results in an equivalent stress of 129,572.2 operational hours for the module and 69,891.1 operational hours for the microinverter. Operation-hours imply 24 hours daily operation, which is not applicable for solar PV systems. Assuming 8 hours/day operation, the same operation hours would translate into approximately 44.4 calendar-years for the PV module and 23.9 years for the microinverter.

Using a more conservative estimate for field-use temperature (one standard deviation above nominal) results in 38,078.0 operation-hours for PV module and 32,717.4 for the microinverter. This translates to 13 and 11.2 calendar-years for PV module and microinverter, respectively (see TABLE II).

Using confidence levels and reliability values from TABLE I, the microinverter’s reliability at 23.9 years is 66.87% with a lower one-sided confidence level of 80%. For a confidence level of 90%, the reliability of the microinverter at the same 23.9 years would be only 56.23% (i.e. with 90% confidence, at least 56.23% of a given population would survive 23.9 years). Using the more conservative estimate of field-use temperature (mean plus one standard deviation), the microinverter’s reliability at 11.2 years is 66.87% with a lower one-sided confidence level of 80%. For a confidence level of 90%, the reliability of the microinverter at the same 11.2 years would be only 56.23%.

Fig. 5 shows expected lifetime plot that superimposes probability density functions for the microinverters and modules for the projected mean operation temperature of 35.98°C (309.13 K) for the PV module and 43.1°C (316.28 K) for the microinverter. The more conservative lifetime estimate, which assumes a typical thermal environment for the PV module and microinverter is one standard deviation more than the mean values are also shown in Fig. 5.

Based on 10,000 hours of failure-free operation of the four microinverter/modules measured here and the measured thermal environment of these devices in field-use conditions, we can currently extrapolate approximately 44 years of operation lifetime for PV modules, and 13 years of operation for microinverters with reliability of 66.87% with a lower one-sided confidence level of 80%. Testing is still ongoing and longer test durations with zero failures increases the lifetime estimate. Therefore, these lifetimes represent a minimum estimate of reliability and lifetime for these devices.
V. SUMMARY

This work has applied static, high-temperature operating life tests to four microinverter/module units co-located and co-monitored in the same thermal chamber. These units have been tested at a static temperature of 69°C for over 10,000 hours (tests are still ongoing) in order to monitor relative degradation rates as well as time-to-failure between the two components of the ACPV system. Currently, the test has been operating for 10,000 hours with no observable degradation or failures in either the microinverter or module have been evident. Using monitored field-use data and Military Handbook approximations for the equivalent field-use stress of this test currently extrapolate unit lifetime to approximately 44 years of operation lifetime for PV modules, and 13 years of operation for microinverters with reliability of 66.87% with a lower one-sided confidence level of 80%.

From the thermal data, it is apparent that the microinverter will see a higher thermal environment from the PV module (due to the power handling of the unit and the limitation of thermal transportation via convection due to the location on the backside of the module). Assuming that the activation energies for thermal failure mechanisms are the same for the module and the microinverter, this means that the microinverter will have a shorter lifetime than the module. The ACPV system is assumed to be non-repairable, so that if any of the components fail, then the entire system fails. As such, the lifetime of the ACPV system will have the same lifetime as the shortest lifetime component; in this case, the microinverter.

It should be noted that in field-use, many competing stressors and failure mechanisms are present and may be the limiting component of product lifetime. Of these competing failure mechanisms, the one with the highest stress factor will cause end-of-life failure. While this work that provided a baseline lower limit on lifetime and reliability for the ACPV system with respect to pure thermal failure mechanism, it is completely possible that overall system lifetime will be determined in the field by other failure mechanisms (e.g. thermal cycling) which can limit lifetime to below the operation-years shown here.

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