Automated Data Collection for Determining Statistical Distributions of Module Power Undergoing Potential-Induced Degradation

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Automated Data Collection for Determining Statistical Distributions of Module Power Undergoing Potential-Induced Degradation

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We propose a method for increasing the frequency of data collection and reducing the time and cost of accelerated lifetime testing of photovoltaic modules undergoing potential-induced degradation. This consists of *in-situ* measurements of dark current-voltage curves of the modules at elevated stress temperature, their use to determine the maximum power at 25°C standard test conditions, and distribution statistics for determining degradation rates as a function of stress level. The semicontinuous data obtained by this method clearly show degradation curves of the maximum power, including an incubation phase, rates and extent of degradation, precise time to failure, and partial recovery. Stress tests were performed on crystalline silicon modules at 85% relative humidity and 60°, 72°, and 85°C. Activation energy for the mean time to failure (1% relative) of 0.85 eV was determined and a mean time to failure of 8,000 h at 25°C and 85% relative humidity is predicted. No clear trend in maximum degradation as a function of stress temperature was observed.

Introduction

Photovoltaic (PV) module manufacturers, who are applying multi-decade warranties on their products, and customers seeking to predict return on investment find it impractical to perform lifetime tests on modules at normal operating conditions because of the long times required. Acceleration is applied, for example, when a manufacturer would like to project the median time to failure in the field under a certain operating environment. This may be achieved by experimentally determining the activation energy for the time to failure for the degradation mode and PV module design of interest. The data can be used to estimate the mean time to failure of the PV module at some arbitrary operating condition or used in modeling the degradation in the climate of deployment. However, application of statistical methods to accelerated lifetime testing of PV modules has been impeded by the expense of cumbersome module transfers and by transients in stress levels from moving modules between the environmental chamber to the solar simulator or flash tester to quantify degradation. Non-contiguous points along the degradation curves also make it difficult to clarify the shape of the curve.

Potential-induced degradation (PID) is of recent interest because it has been discovered to be a source of relatively rapid and significant degradation in some PV modules in the field [1]. In conventional n^+/p front-junction cells, PID has been associated with sodium migration toward the cell [2]—specifically, sodium at stacking faults [3].

We previously showed the utility of dark current-voltage (*I-V*) curves measured by intermittently lowering the module temperature from the elevated stress temperature to 25°C for determining the extent of module power loss by PID at standard test conditions (STC) or under low light conditions [4,5]. With these results, an Arrhenius plot was used to determine the activation energy of the mean time to failure for lifetime prediction at a use temperature [4]. We subsequently developed the methodology for calculating the STC power of the module undergoing PID using dark *I-V* curves measured at elevated stress temperatures and equipment to automate the data taking [6]. This eliminates the temperature and relative humidity (RH) transients associated with the return of the chamber to 25°C for dark *I-V* curve measurements and allows for significantly more frequent dark *I-V* curve measurements on a great number of modules.

We receive inspiration from the study of optoelectronic devices such as lasers and light-emitting diodes, whereby a photodetector is placed in front of the device for continuous monitoring of degradation as a function of temperature and time [7] to move away from the labor-intensive procedures that give discontinuous data. In this paper, we first review the concept of superposition for accurate determination of the STC fraction power degraded using 25°C dark *I-V* curves and those measured at elevated stress temperature. With these methods, STC power is evaluated for replicas of a module type undergoing PID at several stress temperatures. STC power is monitored semicontinuously using dark *I*-V curves measured at the stress temperature. This permits us to precisely understand and determine the statistical distribution of the time to failure of the modules, without temperature transients and interruptions for 25°C measurements.

An Arrhenius analysis is applied to fit the time-to-failure results as a function of temperature, and an activation energy is calculated. Finally, extrapolation of time to failure to a use condition is demonstrated.

Method

The principle of superposition [8] is used to transform the first-quadrant dark *I-V* curve to the fourth quadrant to obtain a quasi light *I-V* curve by subtracting the photocurrent of the module. To determine STC module power, we used the module short-circuit current I_{sc} as the photocurrent. This has been observed to be relatively constant for modules undergoing PID [1]. The maximum power point (Pmax) is then evaluated on the translated *I-V* curve, as is conventionally done for curves obtained with solar simulators. This value determined from the dark *I-V* data can be compared to the measured power obtained with a solar simulator at the end of the stress test, to show the success of the dark *I-V* analysis at determining Pmax.

For simplicity of analyzing data, degradation of modules is expressed normalized to its initial power ($P\text{max}/P\text{max}_0$). This ratio is abbreviated as R in the case when the measurements are performed at 25°C. Because we analyze the degradation in terms of the fraction $P\text{max}/P\text{max}_0$, there is only mild sensitivity to the I_{sc} that is used to translate the dark *I-V* curves for both numerator and denominator in the analysis. The photocurrent parameter may be adjusted to have the Pmax results from the dark *I-V* curves match that of the solar simulator; however, the I_{sc}-translated dark *I-V* curves generally yield accurate Pmax results for modules undergoing PID [4,6]. Solar simulator testing of the module is performed at the start and end of the stress test at 25°C, and dark *I-V* curves and R values derived thereof may be taken at 25°C during the course of PID testing to obtain a degradation curve [6]. In this case, the module temperature must be intermittently returned to 25°C when performing PID stress testing at elevated temperatures. This has the disadvantage of causing interruptions in the testing, stress-level transients that can degrade the integrity of the data, and as a result, fewer data points along the degradation curve are usually obtained.

In the interest of maintaining the module under test at an elevated stress temperature without interruption, the relative degradation at the stress temperature T, $\text{Pmax}_T/\text{Pmax}_{T\,0}$ (the ratio is abbreviated R_T) can be similarly obtained from the I_{sc}-translated dark *I-V* curves measured at temperature [6]. $P\text{max}_{T\,0}$ is taken from the initial I_{sc}-translated curve at the first instant the module reaches the stress temperature. The ratio R_T is repeatedly calculated from the dark *I-V* curves using the superposition principle over the course of the degradation at temperature T to obtain a semicontinuous degradation curve. If R (degradation data obtained at 25°C) is also measured, an offset is observed between the normalized module power at the stress temperature and that at 25°C (R_T and R, respectively) and its change over time resulting from PID can be seen [6]. To carry out stress at the constant elevated temperature, we seek to only use the initial and final 25°C dark *I-V* and/or solar simulator data to compute the STC degradation curve. The extent of the offset between R_T and R was found to expand linearly as a function of the extent of degradation in the range of 0% to 32% relative [6]. Therefore, the entire STC degradation curve can be calculated from R_T values obtained over the course of PID with measurement of the offset at the end of the stress test—$R_{T\,F}$ and R_F are taken at the test temperature and 25°C, respectively. The linear scaling factor M represents the offset between R and R_T, normalized to the fraction degraded, $1\text{-}R_T$, as determined at the end of the test (denoted by the subscript F), and it can be calculated as $(R_F\text{-}R_{T\,F})/(1\text{-}R_{T\,F})$. This results in a negative number in this analysis. Then, the normalized 25°C (STC) power, R_{25}, is recalculated for each R_T measured as in Fig. 1 according to $R_{25} = R_T\text{-}M(R_T\text{-}1)$.

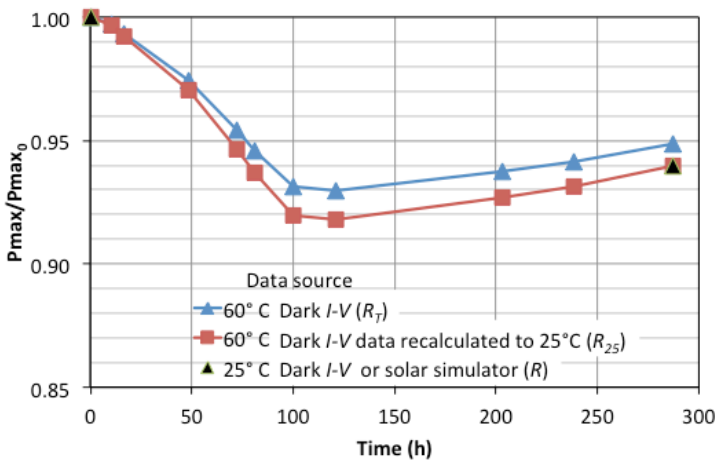

Fig. 1. Evolution of dark *I-V*-derived 25°C (STC) power (normalized to initial power) obtained from dark *I-V* curves taken at the 60°C stress temperature. Initial and final 25°C solar simulator results are also shown.

Finally, time-to-failure statistics are modeled using an Arrhenius relationship, $t_f = A \cdot \exp(E_a/kT)$, which is used to calculate a pre-exponential A and activation energy E_a, which can then be used to predict mean time to failure at some use temperature T.

Experiment

This experiment is carried out with an apparatus previously described [4,6]. It consists of an environmental chamber at 85% RH run sequentially with five modules each at 60°, 72°, and 85°C. A high-voltage power supply applied -1,000 V system voltage to the shorted module leads after the modules reached temperature and humidity equilibrium. The module frames were grounded. Modules were maintained to tolerance limits of ±2°C and ±5% RH over the course of the stress test. A 10 A power supply was used to drive forward-bias current through the modules to measure dark *I-V* curves; a switching network was used to switch modules intermittently from high-voltage bias for the dark *I-V* curve trace in 4 h intervals, and a computer controlled the sequencing of the measurements and conditions.

Conventional 60-cell multicrystalline front-junction n+/p cells were used. They were commercial modules from the same production lot with near-sequential serial numbers.

Results and discussion

The relative degradation in STC power is shown in Fig. 2 as a function of time for three temperatures with five replicas tested at each temperature using the method described above. No special outliers or early failures were detected; however, effects of an interruption of the data recording due to equipment problems can be seen in the 60°C data, the longest of the tests. Mean scaling factors M (with standard deviations) were -0.22 (0.13), -0.52 (0.09), and -0.56 (0.24) for the 60°, 72°, and 85°C conditions, respectively.

Several phases of the degradation curve can be seen most clearly in the 60°C condition: a period of relative stability or incubation, followed by degradation in power, a point of maximum power loss, and then a period of recovery. Interestingly, the higher stress temperatures do not show differing maximum degradation compared to the lowest. The maximum degree of degradation appears to be independent of the test temperature, so the higher temperature (85°C), with its benefit of greater acceleration, is equally suitable for revealing the maximum amount of degradation in these PV modules. Some variation in the degradation between modules stress tested at each temperature is seen, which may result from distribution in sensitivity of the cells within the modules.

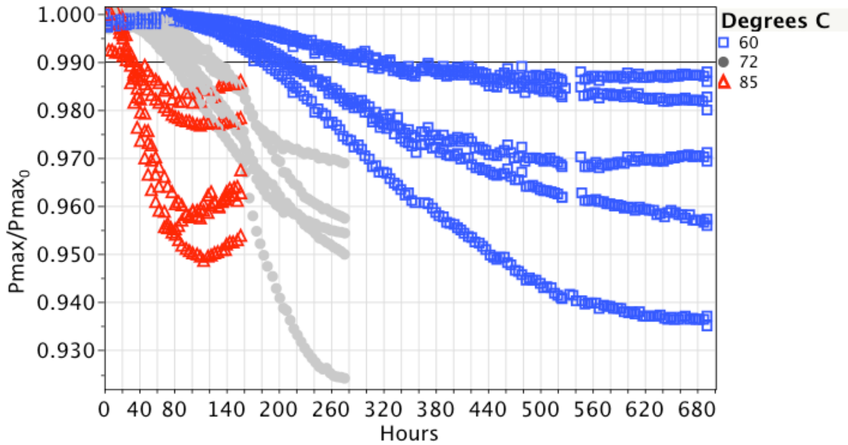

Fig. 2. Normalized STC power of PV modules undergoing PID at 85% RH, -1000 V bias, and at three temperatures indicated on the plot. The data were obtained semicontinuously at the stress temperature.

A 1% relative degradation level is chosen to determine the time to failure in each sample without censoring. Some samples do not degrade much more than this level, so failures would not be measured in some samples if the failure level were greater. The data with degradation up to this level and several data points beyond are taken to determine the points of failure (Fig. 3). Only the degradation segments of the curves were analyzed. Additional models will be required to model the incubation and recovery stages. A linear fit to the subset of data is achieved if the data are scaled to the power of two, as previously shown for other PID data [4]. The intersection of the degradation curve as a function of time with the failure level, 0.99 fraction power remaining, can easily be seen.

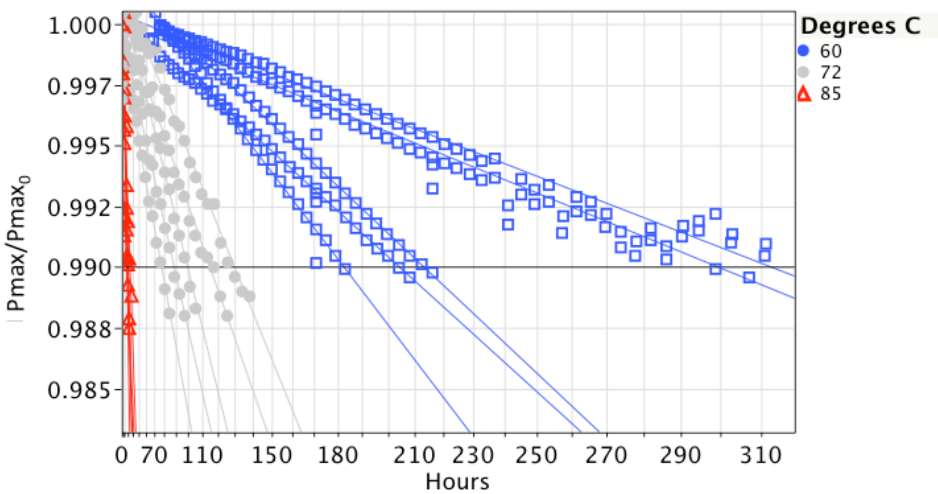

Fig. 3. Subset of the normalized STC power of PV modules undergoing PID at 85% RH, -1000 V bias, and at three temperatures indicated on the plot. The data are successfully fit linearly with the time (h) scaled to the power of two, and the intersection in time of the curves at the failure criterion of 0.99 relative power remaining can be seen.

The time-to-failure data were plotted on a lognormal cumulative failure probability plot as shown in Fig. 4. The data are reasonably well fit; however, the differing slopes based on the extent of data we have (five data points per temperature) suggest differing shape factors to the distribution as a function of stress level when viewed in this lognormal plot.

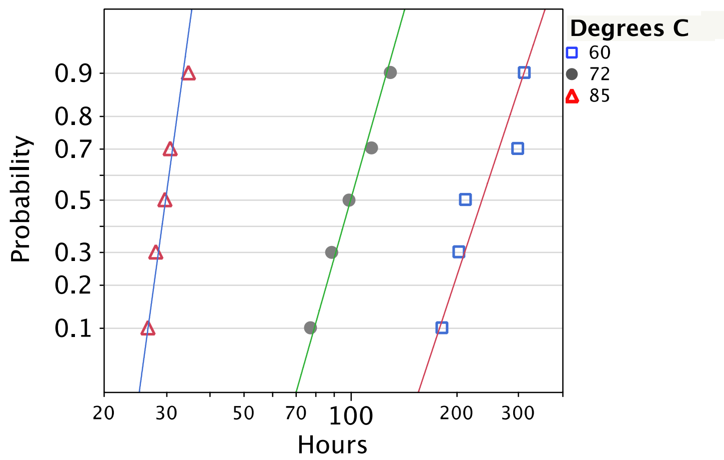

Fig. 4. Cumulative failure probability vs. time for three temperatures as shown on a lognormal plot.

The time to failure for each sample in each temperature category is plotted on an Arrhenius scale to determine the activation energy corresponding to the time to failure (Fig. 5). The points in each temperature category are shown with the computed lognormal distribution using the distribution shown in Fig. 4. The Arrhenius fitting curve and 95% confidence intervals are shown to either side of it. The curve is extended to 25°C, along with a computed lognormal distribution, to estimate the time to failure at that temperature.

The data set shows an activation energy of 0.85 eV. This result may be influenced by factors such as module materials and design and the failure criterion chosen. A previous, more limited study yielded E_a = 0.726 eV. The study had a different failure criterion on differing modules performed by reducing chamber temperature from the stress temperature to 25°C to obtain the STC power degradation curves. The approximately 8,000 h mean time to failure shown for the 25°C, 85%RH, and -1,000 V case must be considered with the understanding that the actual use conditions are not constant. These accelerated tests were performed in the dark. Illumination, especially the ultraviolet (UV) component, is found to mitigate PID to an extent [9]. If the humidity factor is removed (such as on a sunny day with low humidity), a stress factor is removed—specifically, the leakage current from the module face to ground is significantly interrupted, in which case modules have been shown to recover to an extent by thermal activation [1]. On the other hand, for some periods, relative humidity can be higher than 85%.

The technique shown here can be used to evaluate the activation energy for time to failure of various module types on a relative basis; but additional real-world factors may be introduced, such as illumination and PID degradation inclusive of recovery phenomena. This technique may also be extended in the future to analyze mean time to failure for other degradation modes.

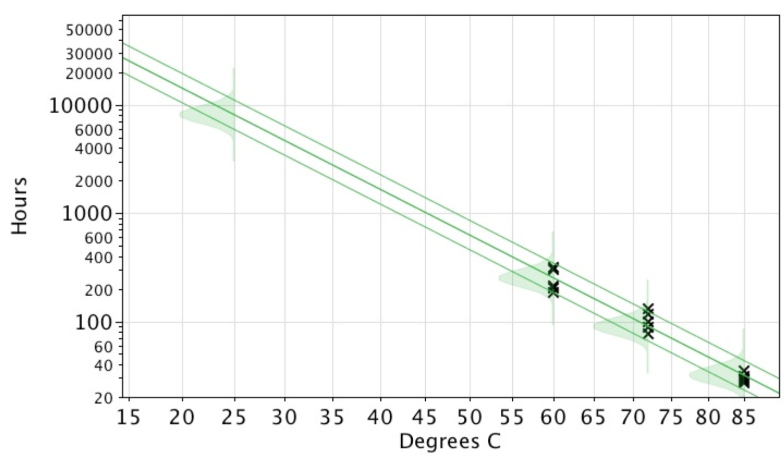

Fig. 5. Three-point Arrhenius fit to the lifetime data with activation energy 0.85 eV. 95% confidence intervals are shown to either side of the Arrhenius fit. Lognormal distributions are shown around the data points and the analysis is extended to a hypothetical 25°C use condition as an example.

Summary and conclusions

We demonstrated the application of failure distribution statistics to PV modules undergoing PID in an environmental chamber, facilitated by the development of an automated *in-situ* monitoring technique consisting of analysis of the dark *I-V* curves taken at the stress temperature. Semicontinuous degradation curves were obtained and lognormal statistics were applied to draw cumulative failure probability and activation energy plots. Activation energy for time to failure was determined to be 0.85 eV. We found that the maximum amount of degradation was independent of the stress temperature applied.

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$R = P_{\deg}(t_k) = P_{\max}(t_k)/P_{\max}(t_0)$
$R_T = P_{\deg}(t_k, T) = P_{\max}(t_k, T)/P_{\max}(t_0, T)$
$R_{25} = P_{\deg}(t_k, 25°C) = P_{deg}(t_k, T) - M^*[P_{deg}(t_k, T)-1]$
$R_F = P_{\deg}(t_n, 25°C)$
$R_{T\,F} = P_{\deg}(t_n, T)$
$M = [P_{\deg}(t_n, 25°C) - P_{\deg}(t_n, T)]/(1 - P_{deg}(t_n, T)]$

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