Reliability evaluation of a photovoltaic module using accelerated degradation model

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ABSTRACT

Many photovoltaic modules are installed all around the world. However, the reliability of this product is not enough really known. The electrical power decreases in time due mainly to corrosion, encapsulation discoloration and solder bond failure. The failure of a photovoltaic module is obtained when the electrical power degradation reaches a threshold value. Accelerated life tests are commonly used to estimate the reliability of the photovoltaic module. However, using accelerated life tests, few data on the failure of this product are obtained and the realization of this kind of tests is expensive. As a solution, an accelerated degradation test can be carried out using only one stress if parameters of the acceleration model are known. The Wiener process associated with the accelerated failure time model permits to carry out many simulations and to determine the failure time distribution when the threshold value is reached. So, the failure time distribution and the lifetime (mean and uncertainty) can be evaluated.

Keywords: Photovoltaic module, Reliability, Lifetime, Degradation, Wiener process, Accelerated degradation model, Accelerated life testing

1. INTRODUCTION

Many photovoltaic modules are installed all around the world. However, the reliability of this product is not enough really known. The reliability estimation of a photovoltaic module depends on the determination of lifetime distribution parameters. The accelerated failure time (AFT) model based on acceleration model (Arrhenius, Peck, Inverse power …) can be used to estimate the reliability.

Kurtz [1] studied the lifetime of a photovoltaic module versus several activation energy values (0.6, 1.1 and 2 eV) by considering an Arrhenius model. The author deduced the test time for a stress in temperature and the mean lifetime for several cities (Riyadh, Phoenix, Miami and Munich) is determined in nominal conditions. However, its study does not permit to take into account a confidence interval on results. In order to estimate the uncertainties, it is necessary to get enough failure times. Because accelerated life test (ALT) are long and expensive, we propose to use a degradation process, particularly the Wiener process, which permits to simulate several degradations versus time from one accelerated degradation test (ADT) in order to deduce more failure times. Thus a failure time distribution can be obtained and the mean lifetime with the confidence interval can be estimated. We present this method in this article.

According to literature [2,3,4], the main degradation mode of a photovoltaic module is corrosion. This mode is due to the influence of temperature and humidity [5]. In our study, these two parameters are taken into account.

This article presents the degradation process (Wiener process) with AFT model (Peck model). The lifetime (mean and interval confidence) of a photovoltaic module is calculated for several cities and for several parameters of Peck model using a damp heat test of literature [2].

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2. DEGRADATION PROCESS

The degradation of a component can be modeled by different processes, for example by Wiener or gamma processes. In our case, the Wiener process is chosen. The degradation is supposed to take place gradually over time in a sequence of tiny increments [6]. Increase degradations are noted $\Delta W(t_{ij})$ where $i=1…n$ is the degradation index and $j=1…q_i$ is the time index (Figure 1).

The Wiener process $W(t_{ij})$, $t_{ij}>0$ has the following properties [7]:

- $W(0)=0$
- increments $\Delta W(t_{ij}) = W(t_{ij}) - W(t_{ij-1})$

In the case of linear degradation, $\Delta W(t_{ij})$ follows a normal distribution with mean $m.\Delta t_{ij}$ and variance $\sigma^2\Delta t_{ij}$.

In the case of non-linear degradation, $\Delta W(t_{ij})$ follows a normal distribution with mean $(m(t_{ij}) - m(t_{ij-1}))$ and variance $\sigma^2\Delta t_{ij}$.

The Wiener process presented previously permits to simulate degradations in one condition from testing in this condition. To simulate degradation in another condition that test condition, it is possible using AFT model which is defined as:

$$W(t_{ij}|X) = W(r(X)t_{ij})$$

(1)

where $r(X)$ is the acceleration factor between known conditions $X^0$ ($r(X^0)=1$) and studied constant conditions $X$.

In the Wiener process, increments $\Delta W(t_{ij})$ follows a normal distribution $\mathcal{N}(m(r(X)t_{ij}) - m(r(X)t_{ij-1}), \sigma^2 r(X)\Delta t_{ij})$ and the probability density function is defined as:

$$f(x_i) = \frac{1}{\sigma \sqrt{2\pi \Delta t_{ij}}} \exp \left( - \frac{(x_i - (m(r(X)t_{ij}) - m(r(X)t_{ij-1})))^2}{2\sigma^2 r(X)\Delta t_{ij}} \right)$$

(2)

Mean and variance of $\Delta W(t_{ij})$ can be estimated by the maximum likelihood estimation which can be written as:

$$L(m, \sigma^2) = \prod_{i=1}^{n} \prod_{j=1}^{q_i} \frac{1}{\sigma \sqrt{2\pi r(X)\Delta t_{ij}}} \exp \left( - \frac{(\Delta W(t_{ij}) - (m(r(X)t_{ij}) - m(r(X)t_{ij-1})))^2}{2\sigma^2 r(X)\Delta t_{ij}} \right)$$

(3)
3. DEGRADATION OF PHOTOVOLTAIC MODULE

A photovoltaic module is a complex system which permits to transform the solar energy into electrical energy. It is composed of photovoltaic cells, encapsulant, bypass diodes, connectors, junction box, cables, a glass on the front of the module and a glass or polymer film on the back [8]. The current leaving the cables of a module is a current which depends mainly on the brightness of the sun that reaches the front (Figure 2).

A crystalline silicon photovoltaic module can be damaged by corrosion, encapsulant discoloration, broken cells, broken interconnects and solder bond failure [2,3,4,5].

The power degradation $D(t)$ corresponds to the power losses of a photovoltaic module versus the initial power. Using the Jet Propulsion Laboratory’s recommendation [9], the degradation model of photovoltaic module output power is given by:

$$D(t) = 1 - \exp(-bt^a)$$

where $a$ and $b$ are degradation parameters.

The main degradation mode for a crystalline silicon module is corrosion [2,3,4] which is due to the influence of temperature and humidity [5].

4. SIMULATIONS

Using the model of PV module power output degradation of relation (4), the mean increment $m(r(X)t_q)$ of Wiener process can be estimated by:

$$m(r(X)t_q) = 1 - \exp(-b_t^a r(X))$$

Wohlgemuth [2] carried out a damp heat test with a temperature of 85°C and a relative humidity of 85% (named 85/85 DH). The degradation versus time determined by the author for a polycrystalline silicon module is presented in Figure 3. Using its data and the relation (3) with an acceleration factor $r(X)=1$, all parameters of degradation model for a temperature of 85°C and a relative humidity of 85% are deduced. Thus: $a=4.2906$, $b=6.2643 \times 10^{-16}$ and $\sigma^2=4.588 \times 10^{-6}$. 
The acceleration model which permits taking into account the temperature and the relative humidity is the Peck model for which the acceleration factor \( r(X) \) is defined by the following relation:

\[
 r(X_1, X_2) = A \cdot X_1^n \cdot \exp \left( \frac{-E_a}{k \cdot X_2} \right) = r(X_1^0, X_2^0) \left( \frac{X_1}{X_1^0} \right)^n \cdot \exp \left[ -\frac{E_a}{k} \left( \frac{1}{X_2} - \frac{1}{X_2^0} \right) \right]
\]  

(6)

where \( X_1 \) and \( X_2 \) correspond, respectively, to the relative humidity and the module temperature, \( X_1^0 \) and \( X_2^0 \) correspond, respectively, to the relative humidity and temperature known, \( E_a \) is the effective activation energy of the degradation process, \( k \) is the Boltzmann’s constant, \( A \) and \( n \) are two constants which depend on the failure mode.

A literature review [10] indicates that the activation energy \( E_a \) of aged polymeric materials vary between 0.6 eV and 2.0 eV and often considered equal to 1.1 eV. Moreover, Crowe [11] informs us that the parameter \( n \) of the Peck model varies between 2.5 and 3, and generally equal to 3 for polymeric materials. These values are commonly used for the reliability evaluation of photovoltaic modules [1,12]. In the following section, we propose to study the influence of different values of activation energies \( E_a \) (0.6, 1.1 and 2.0 eV) and parameters \( n \) (2.5, 2.8 and 3) on the estimation of lifetime and reliability of a photovoltaic module.

The operating temperature of a photovoltaic module varies along its life with the changing of seasons. If the acceleration factor is defined by the relation (6), it is possible to estimate an equivalent temperature \( T_{eq} \) which represents the degradation that would have taken place if the module had been aged for the same time, but at a constant temperature. The equivalent temperature \( T_{eq} \) can be calculated using the following relation [1]:

\[
 \exp \left( \frac{-E_a}{k \cdot T_{eq}} \right) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \exp \left( \frac{-E_a}{k \cdot T_{module}(t)} \right) \, dt
\]

(7)

where \( t \) is the time, \( T_{module}(t) \) is the time-dependent module temperature, and \( t_1 \) and \( t_2 \) are the beginning and ending times of integration.

Using the same methodology below, the equivalent relative humidity \( H_{eq} \) can be estimated as:

\[
 (H_{eq})^n = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} (H(t))^n \, dt
\]

(8)

where \( t \) is the time, \( H(t) \) is the time-dependent relative humidity, and \( t_1 \) and \( t_2 \) are the beginning and ending times of integration.

Using the PVMODREL toolbox that we developed in our laboratory [13], the module temperature \( T_{module}(t) \) and the relative humidity \( H(t) \) are simulated hour per hour during 50 years. In this study, we take into account four cities: Paris
(France), Oslo (Norway), Madrid (Spain) and Tamanrasset (Algeria). The equivalent temperature \(T_{eq}\) and the equivalent relative humidity \(H_{eq}\), obtained respectively versus \(E_a\) and \(n\) using relations (7) and (8), are presented in Figure 4.

![Figure 4. Equivalent temperature versus \(E_a\) (a) and equivalent relative humidity versus \(n\) (b) for the four cities studied.](image)

The Wiener process permits to determine the failure time distribution in the nominal condition of the photovoltaic module using parameters of Figure 4 and data of the accelerated degradation test of 85°C and 85%RH presented in Figure 3.

If we consider for instance that a photovoltaic module is installed in Paris with an activation energy \(E_a\) of 1.1 eV and a parameter \(n\) equal to 3, 1000 degradations are simulated using the Wiener process and presented in Figure 5.

![Figure 5. Simulated degradation of a photovoltaic module installed in Paris with \(E_a = 1.1\) and a parameter \(n = 3\).](image)

These degradations permit to estimate failure times when the degradation reaches a threshold value equal to 50%. In the example, the 1000 failure times follows an Inverse Gaussian distribution for which the probability density function is:

\[
f(t) = \frac{\lambda}{\sqrt{2\pi t^3}} \exp\left(-\frac{\lambda(t-\mu)^2}{2\mu^2 t}\right)
\]

where \(\mu\) is the mean and \(\lambda\) is the shape parameter of the distribution.

Using the 1000 failure times of the example, parameters are estimated thanks to the maximum likelihood method: \(\beta = 13.5\) and \(\eta = 3788336\) hours (= 432 years).
For the city of Paris, reliability functions versus one hand the three values of the activation energy $E_a (0.6, 1.1$ and $2.0)$ and versus in other hand the three values of the parameter $n (2.5, 2.8$ and $3.0)$ are presented in Figure 6. All functions permit to estimate the distribution parameters and the lifetime using the maximum likelihood method as well.

Figure 6. Reliability function versus the activation energy $E_a$ with $n = 2.8$ (a) and versus the parameter $n$ with $E_a = 1.1$ (b).

Figure 6(a) shows that the activation energy $E_a$ has a significant influence on the reliability estimation of the photovoltaic module and therefore on the lifetime estimation beyond 200,000 hours (22 years). Figure 6(b) shows that the reliability difference is much closed with changing the parameter $n$ of the Peck model.

The lifetime of a photovoltaic module using the three values of the activation energy $E_a (0.6, 1.1$ and $2.0)$ and the three values of the parameter $n (2.5, 2.8$ and $3.0)$ are presented in Table 1 for Paris, Table 2 for Oslo, Table 3 for Madrid and Table 4 for Tamanrasset. All uncertainties associated are estimated using a risk $\alpha$ of 10%. The uncertainties determined show that the expanded coefficient of variation is between 13.2% and 15.8%.

### Table 1. Lifetime of a photovoltaic module for city of Paris (France) with $\alpha = 10\%$.

<table>
<thead>
<tr>
<th>$E_a$</th>
<th>0.6</th>
<th>1.1</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>(26.50 ± 3.71) years</td>
<td>(408.4 ± 58.6) years</td>
<td>(25174 ± 3737) years</td>
</tr>
<tr>
<td>2.8</td>
<td>(26.82 ± 3.95) years</td>
<td>(414.8 ± 58.9) years</td>
<td>(25481 ± 3646) years</td>
</tr>
<tr>
<td>3.0</td>
<td>(27.15 ± 3.59) years</td>
<td>(418.9 ± 58.0) years</td>
<td>(25785 ± 3739) years</td>
</tr>
</tbody>
</table>

### Table 2. Lifetime of a photovoltaic module for city of Oslo (Norway) with $\alpha = 10\%$.

<table>
<thead>
<tr>
<th>$E_a$</th>
<th>0.6</th>
<th>1.1</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>(44.42 ± 6.61) years</td>
<td>(891.3 ± 126.7) years</td>
<td>(91895 ± 12880) years</td>
</tr>
<tr>
<td>2.8</td>
<td>(45.65 ± 7.23) years</td>
<td>(916.4 ± 124.7) years</td>
<td>(94309 ± 13156) years</td>
</tr>
<tr>
<td>3.0</td>
<td>(46.34 ± 6.84) years</td>
<td>(931.7 ± 128.3) years</td>
<td>(95913 ± 13662) years</td>
</tr>
</tbody>
</table>

### Table 3. Lifetime of a photovoltaic module for city of Madrid (Spain) with $\alpha = 10\%$.

<table>
<thead>
<tr>
<th>$E_a$</th>
<th>0.6</th>
<th>1.1</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>(20.5 ± 2.92) years</td>
<td>(144.0 ± 21.9) years</td>
<td>(2095 ± 290) years</td>
</tr>
<tr>
<td>2.8</td>
<td>(21.83 ± 3.17) years</td>
<td>(153.3 ± 20.9) years</td>
<td>(2216 ± 311) years</td>
</tr>
<tr>
<td>3.0</td>
<td>(22.65 ± 3.21) years</td>
<td>(157.9 ± 21.9) years</td>
<td>(2309 ± 341) years</td>
</tr>
</tbody>
</table>
Table 4. Lifetime of a photovoltaic module for city of Tamanrasset (Algeria) with $\alpha = 10\%$.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$E_a$</th>
<th>Lifetime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>2.5</td>
<td>(103.05 ± 14.48)</td>
<td>(475.2 ± 64.9)</td>
</tr>
<tr>
<td>2.8</td>
<td>(116.68 ± 16.77)</td>
<td>(538.7 ± 81.7)</td>
</tr>
<tr>
<td>3.0</td>
<td>(142.39 ± 19.68)</td>
<td>(657.4 ± 97.3)</td>
</tr>
</tbody>
</table>

Tables 1 to 4 show the influence of the localization of a photovoltaic module on the lifetime estimation. For values of $E_a$ higher than 1.1 and whatever the value of the parameter $n$, the lifetime of a photovoltaic module placed in Oslo is better than the lifetime estimated in other cities. This is mainly due to low temperature as shown in Figure 4(a). The lifetime is better in Tamanrasset when $E_a$ is equal to 0.6 and whatever the parameter $n$. This is due to the low relative humidity given in Figure 4(b).

The photovoltaic module installed in Madrid has a lower lifetime than these other cities studied. This is due to a combination of high temperature and high relative humidity as shown in Figure 4.

5. CONCLUSION

The article proposes a methodology to estimate the uncertainty on the lifetime of a photovoltaic module using an accelerated degradation model. It permits to obtain a failure time distribution from a damp heat test given by the literature and the Wiener process. The advantage of this methodology is to overcome the lack of test data that can be obtained by classical accelerated life tests. Results associated with their uncertainties show that lifetime depends on the climate and the activation energy.

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REFERENCES


