Degradation of Power Output of Photovoltaic Modules Due to Accelerated Ageing

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Abstract

This research work focusses on a type of indoor accelerated stress test (AST) which is an extension of the damp-heat (DH) test proposed by the international electrotechnical commission in IEC-61215-2, to reproduce the field failures by applying environmental stresses (temperature (T), relative humidity (RH)) to photovoltaic (PV) mini-modules as well as to compare whether the calculated activation energy associated with such degradation modes is consistent with the range of values reported in literature. In addition, the effect of curing time during PV module lamination on the durability of the PV-modules will be evaluated for crystalline silicon (c-Si) PV mini-modules produced from the same materials.

Keywords: accelerated ageing, damp heat test, failure modes, degradation, activation energy.

1. Introduction

The long-term reliability and durability of installed photovoltaic (PV) modules are critical in ensuring the cost-effectiveness and commercial success of solar PV systems [1]. Hence, the need for upfront testing of materials, components, and overall systems has increased in order to improve the design and manufacturing processes of PV modules before being installed in the field [2]. However, directly observing the time-to-failure or predicting the long-term performance of PV modules in the field is difficult as most PV modules are designed to operate without failure for decades in normal use conditions. Therefore, an alternative indoor methodology based on accelerated stress tests (AST) is required to evaluate the PV module by hastening the performance degradation, so that the required reliability or durability information can be obtained quickly.

As reported in [3], during standard qualification tests of c-Si PV modules, damp-heat (DH) and thermal cycling (TC) tests are the main stresses used, because they emulate degradation modes that are seen to cause the highest number of failures in operational modules. The focus of this research project is to investigate the effect of accelerated environmental stresses on c-Si PV mini-modules by extending one of the standard qualification tests in IEC-61215-2 [4](DH test at 85%RH/85°C), to reproduce the field failures and calculate the minimum activation energy (E_a) required for the reaction to happen, the power of humidity factor ***n*** as well as the time parameter ***a*** which is related to the materials natural lifetime of the parameters of the Pan and Peck models detailed in sections 2.1.1 and 2.1.2 respectively.

Dixon [5] in his findings reported that the values of the activation energy for polymeric materials are in the range of [0.6, 2.0] eV. In addition, the reliability distribution function versus E_a given by Laronde *et al.* [7] as well as the explanation given by Whitaker [8] indicates that a higher values E_a corresponds to an improved reliability of a product.

Furthermore, Whitaker [8] found that the nominal values of the power of the humidity acceleration factor ***n*** (which is a humidity constant) from fitted data are in the range [2.5, 3.0].

This test is a baseline for the next phase that will include a light source as a combinatory stress factor in addition to temperature and humidity.

2. Statistical Modelling

There are existing models that describe the combined effect of temperature and humidity on the power output of PV modules. The model used in this work is the starting point in the development of a new model to include also the effect of light exposure, which will be the primary focus of the next phase of the research.

2.1. Temperature and Humidity as Acceleration Factors

2.1.1. Pan Model

Based on the recommendation of the Jet propulsion laboratory, Pan proposed a degradation model (Equation (1)) of the power output of a PV module as follows [9]:

$$D(t) = 1 - \exp(-b * t^a) \quad \textbf{(1)}$$

Where D is the power output degradation compared to the initial output given by:

$$D = 1 - P_{\max\_t}/P_{\max\_0} \quad \textbf{(2)}$$

t is the time of the accelerated indoor test in hours and ***a*** and ***b*** are parameters of the degradation model associated with the material natural lifetime and an acceleration factor that increases and decreases the product lifetime as a result of environmental stresses, respectively [9]. Parameter ***b*** is itself a function of stress factors and when the stress factors are temperature and humidity it may be expressed by the Peck model (Equation (3)) [2], [10], [11], [12].

2.1.2. Peck Model

The acceleration factor ***b*** for the degradation of the maximum power output of PV modules that accounts for temperature (***T***) and relative humidity (***RH***) stresses is given by the Peck model and is expressed by Equation (3) [2], [10], [12]:

$$b_{Peck} = A * exp\left(\frac{-E_a}{k_b * T}\right) * (RH)^n \quad \textbf{(3)}$$

Where E_a is the activation energy of the degradation process in electronvolt (eV) that quantifies the minimum amount of energy needed to allow a certain chemical reaction to occur, ***T*** is the temperature in kelvin, k_b is Boltzmann's constant, the pre-exponential factor ***A*** and the power of humidity factor ***n*** are constants dependent on the failure modes.

3. Methodology

Four 6-cell crystalline-silicon (c-Si) PV module test samples with a module structure shown in Fig. 1 without a junction box and frame were prepared at CREST and tested to an extended DH test (at $85°C$ and 85% relative humidity) proposed in IEC-61215-2 [4]. Two of the mini-modules (modules 1 and 3) were laminated with long curing time (15 minutes), while the remaining two (modules 6 and 8) were laminated with the industrial standard curing time of 10 minutes.

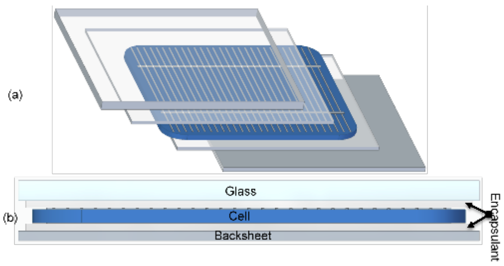

Fig. 1 Top view (a) and side view (b) of the structure of the test samples.

A 2.9 mm thick un-tempered low iron float glass, $460\ \mu m$ thick fast cure ethylene vinyl acetate encapsulant (FC1000011E/A), polycrystalline silicon cell, and a tri-layer backsheet consisting of PET/PET/primer layer (dyMat PYE3000) are the materials that have been used to produce all the mini-modules.

The performance parameters of the modules such as short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), current at the maximum power output (I_{mpp}), voltage at the maximum power output (V_{mpp}), series resistance (R_s), shunt resistance (R_{sh}), and maximum power output (P_{max}) were extracted from I-V measurements made using a $1000\ W/m^2$ Pasan 3B flash sun simulator at $25°C$ temperature as shown in Fig. 2a. In addition, electroluminescence (EL) imaging of the PV mini-modules (Fig. 2b) was performed at different times during the DH test (before, during and after ageing). Furthermore, visual inspection was used to inspect some of the failure modes. Finally, statistical models such as the Pan and Peck model were used to calculate the parameters of the models by fitting the measured data from the accelerated test.

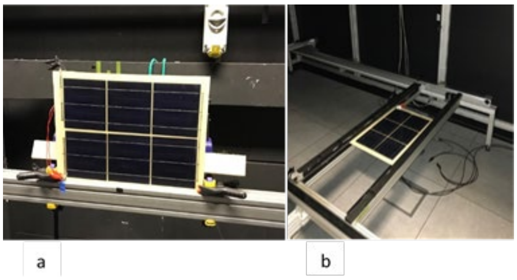

Fig. 2 Setup of I-V measurement (a) and EL imaging (b).

4. Results and Discussion

4.1. Visual Inspection

Some of the visually observed failure modes as a result of the DH test are discoloration, corrosion, and delamination as shown in Fig. 3 and Fig. 4.

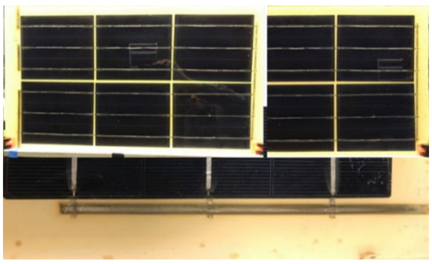

Fig. 3 Discoloration and corrosion of the PV mini-modules.

The discoloration of an EVA as a result of the damp heat exposure reduces the optical transmission of light reaching the active cell. In addition, the EVA also reacts with water vapor to produce acetic acid which leads to corrosion of the metallic parts of the PV modules. As a result of the corrosion and the detachment of the solder bonds, the series resistance of the PV modules has been increased by 215%, 184%, 222%, and 300% for modules 1, 3, 6, and 8 respectively.

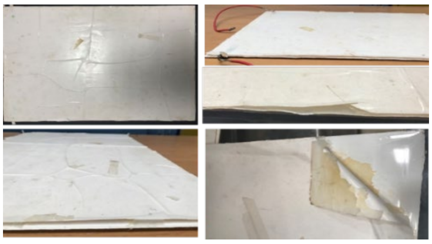

Fig. 4 The delamination of the backsheet as a result of the DH test.

The delamination of the PV modules as a result of the loss of adhesion between the layers leads to an acceleration of moisture ingress and the associated effects described above. Furthermore, if the delamination is between the cell and the front EVA layer this causes optical decoupling of the layers and leads to a reduction of light reaching the active cells, further reducing the power output.

4.2. Electroluminescence Imaging

As shown from the EL images in Fig. 5 failures due to the humidity corrosion due to water vapor ingress as a result of the loss of adhesion of the layers have been worst in the PV module cured for a standard time (module-8) which is with less crosslinking of EVA. The dark area observed in the EL images is evidence of series resistance increase.

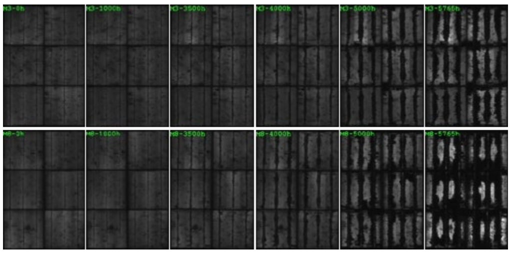

Fig. 5 The EL images of module-3 (top) and module-8 (bottom) at different periods of the DH test.

4.3. I-V Curves

Fig. 6 shows how the I-V curves of the mini-modules are affected over the duration of the test. It shows that the V_{oc} remains almost constant for all the modules. However, the I_{sc} of the PV mini-modules decreases over time and this could be related to the degradation of optical parameters such as discoloration of the PV mini-modules (encapsulation transparency loss), delamination (causes optical uncoupling of the layers), corrosion of the antireflection coating of the cells. The overall loss of I_{sc} of modules 1, 3, 6, and 8 is 16%, 10%, 13% and 24% respectively.

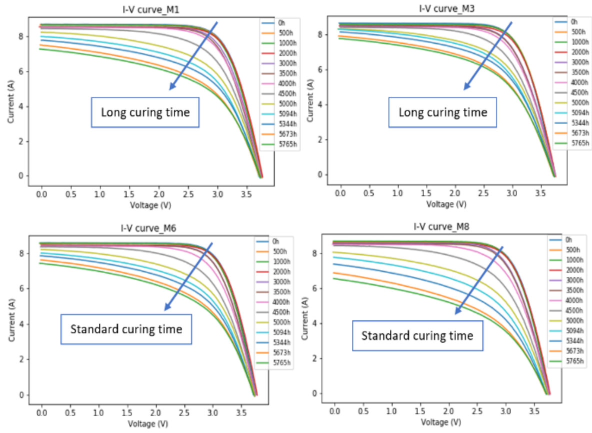

Fig. 6 I-V curves of M1, M3, M6, and M8 at different periods of the DH test.

4.4. Model Fitting

The model has been fitted to the measured data of the degradation of the power output using a nonlinear optimisation method to minimise the sum of squared deviations of the measured and modelled data. The following values (shown in Table 1) have been found for the parameters:

Parameters	$M_1(L)$	$M_3(L)$	$M_6(S)$	$M_8(S)$
$E_a(eV)$	1.59	1.42	1.52	1.65
A	4.90	4.91	4.90	4.89
n	2.58	2.65	2.62	2.55
a	4.36	3.65	4.10	4.66
$\sum \Delta^2$ (%)	0.25	0.11	0.22	0.21

Table 1 Value of the parameters from the fitted measured data.

As shown in Table 1, the values of the activation energy (E_a) found is consistent with the range of values of the E_a which is [0.6, 2.0] eV reported by Dixon [5] for polymeric materials and with values of E_a proposed by Kurtz *et al.* [6] to study thermal degradation of PV modules and by Laronde *et al.* [7] to estimate the lifetime and reliability of a PV modules. The inconsistence in the values of the parameters found for modules cured with the same lamination time could be due to the introduction of failures during the manufacturing of the PV modules. Furthermore, the values of n found are in agreement with the nominal values of ***n*** found from fitted data by Whitaker which is [2.5, 3.0] [8].

Based on the value of the parameters found by fitting the graph of the measured data of the DH test, the normalized maximum power output has been extrapolated and is shown in Fig. 7 and the DH test will be extended in the next phase of the test to compare whether or not the extrapolated model agreed with the actual measured data.

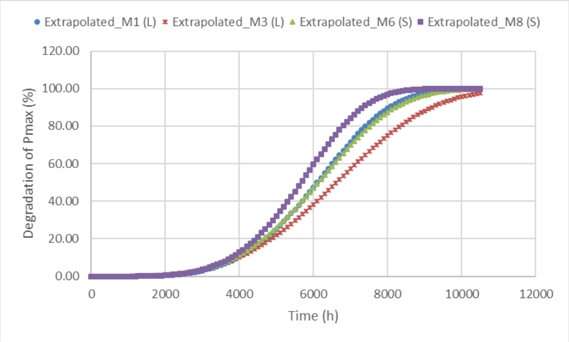

Fig. 7 The extrapolated normalized power output degradation of M1, M3, M6, and M8.

As shown in Fig. 7, the PV modules with higher activation energy have a short lifetime (low reliability) comparing to the one with lower activation energy. This looks it contradicts with the reliability distribution function versus E_a given by Laronde *et al.* [7] as well as to the explantion given by Whitaker which is a higher values E_a corresponds to improved reliability of a product. Even though it needs further study, the possible reason for this could be the reliability of the PV modules in the case of the DH test are highly influenced by the value of the time parameter ***a*** which is a parameter related to the material natural lifetime rather than the humidity power constant (***n***) and the activation energy (E_a) of the humidity and temperature factors respectively.

5. Conclusion

From the measured data of the parameters of the PV mini-modules, a decrease in the I_{sc} observed in all modules with an overall loss of 16%, 10%, 13% and 24% of the I_{sc} of modules 1, 3, 6, and 8 is respectively.

Long curing time ensures a higher crosslinking degree of the EVA resulted in a lower diffusion of water vapor during the DH test. Consequently, on average, modules laminated with long curing time perform better than the mini-modules laminated with the industrial standard curing time.

In addition, E_a, ***a***, and ***n*** have a high effect whereas the pre-exponential factor ***A*** has a low effect on the degradation of the power output. Furthermore, all parameters except E_a, have an inversely proportional effect on the degradation of the power output. Furthermore, the reliability of the PV modules under the DH test is highly influenced by the value of the time parameter ***a*** rather than the power constant ***n*** and the activation energy (E_a) of the humidity and temperature factors respectively.

Based on the calculated values of the parameters of the Pan and Peck models both the temperature acceleration factor as well as the humidity acceleration factor will be calculated to predict the lifetime of the PV modules in the real operating environment.

6. Acknowledgement

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