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Degradation in Field-aged Crystalline Silicon Photovoltaic Modules and Diagnosis using Electroluminescence Imaging

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Abstract

Degradation phenomena observed in field-aged crystalline silicon photovoltaic modules include EVA browning, delamination between the glass-encapsulant and the cell-encapsulant interfaces, degradation of the anti-reflective coating, corrosion of busbars and contacts, cracks, humidity ingress, etc. The type and severity of the defects observed vary significantly between cells, modules and installations as affected by a number of both internal and external parameters. This study presents mild to severe degradation effects observed in crystalline silicon PV modules operating outdoors for different periods of time and investigated through non-destructive testing techniques including I-V characterisation, UV fluorescence, IR thermography and Electroluminescence (EL) Imaging. The identification and diagnosis of defects and further correlation to the electrical degradation of the module is achieved through the complementary contribution of these techniques. Severe electrical degradation and mismatch between the cells are identified through IR thermography and EL imaging. Diagnosis of rather uniformly degraded modules is enhanced through EL Imaging by which shunts, higher resistance regions, cracks, broken metallization are identified, while the module may appear to operate reliably. Signs of early degradation are further diagnosed through UV fluorescence and EL Imaging, allowing to monitor the evolution of defects and evaluate module reliability.

Keywords: PV degradation, Diagnostics, IR thermography, UV fluorescence, Electroluminescence imaging

INTRODUCTION

Crystalline silicon photovoltaic (PV) modules operating in the field for several years are often seen to exhibit degradation effects that may differ significantly between cells, modules and installations as these may be attributed to both internal factors and external conditions, leading to different electrical performance. A review on PV degradation rates reported in the literature from field testing gave a skewed distribution with mean degradation 0.8%/year and median 0.5%/year [1]. Diagnosis of PV degradation from an early stage is particularly important for the prognosis of further future faults, estimation of module lifetime and corrective measures to be taken. Non-destructive testing techniques that may also be used on-site for the identification and diagnosis of defects in PV modules provide a clear advantage. Several PV diagnostic techniques have been employed in the literature including I-V characterisation, IR thermography, Electro-luminescence, Photoluminescence, UV fluorescence and others such as in [2-8].

This paper presents mild to severe PV degradation examined through I-V characterisation, IR thermography, UV fluorescence and Electroluminescence (EL) imaging techniques. The latter provides a sensitive tool for the detection of even mild PV degradation and rather uniformly degraded modules which present more challenging cases.

PV DEGRADATION AND DIAGNOSTICS

Depending on the duration of PV outdoor exposure, the climatic conditions at the site, module and mounting technologies, and other factors, PV degradation may range from mild to severe defects. These may include browning of the ethylene-vinyl-acetate (EVA) encapsulant, degradation of the anti-reflective (AR) coating, delamination in the glass-encapsulant or the cell-encapsulant interface, cracks in the cells, bubbles, corrosion, burn marks, etc.

Non-destructive Diagnostic Techniques

Visual inspection is a simple procedure for the detection of most defects, from early signs of delamination and AR degradation. EVA browning may be detected by illuminating the module with UV light at 375nm [2,9]. In Figure 1 the pattern of EVA browning in a 15 year old sc-Si PV module is revealed through UV light illumination.

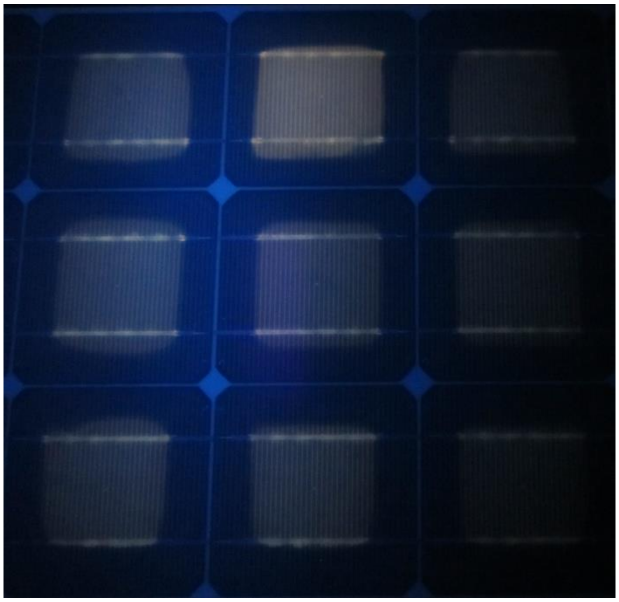

Figure 1: sc-Si PV module illuminated with UV light at 375nm revealing EVA browning in its cells.

Defects that give rise to hot spots, such as resistive bus-bars and contacts, often due to corrosion, are located using IR thermography. The IR image of a 20 year old sc-Si PV module that had experienced degradation through induced shading for a prolonged period [8] is shown in Figure 2. The IR thermography was captured with an IR camera with spectral range 7.5 to 14μm. The cell affected by extensive EVA browning exhibits temperature difference of more than 30ºC from the neighbouring cells of the module. Temperature differences in this range cause large mismatch and further severe degradation of the affected cell and module.

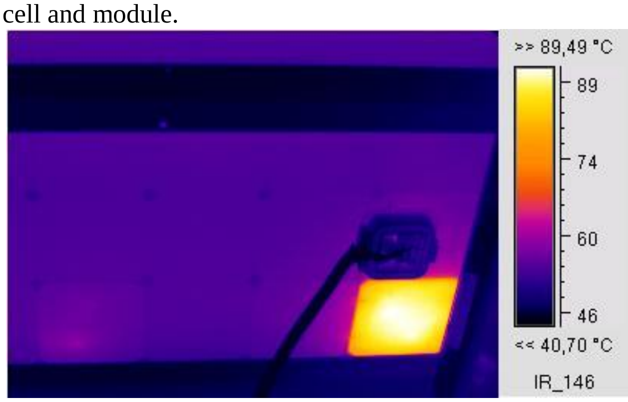

Figure 2: IR thermography taken from the back of a PV module during operation exhibiting a hot cell.

Electroluminescence imaging. Defects in the material of the cell, micro-cracks, broken metalization, shunts, inactive regions are detected via Electroluminescence imaging. EL imaging carried out in the dark with the PV module in forward-bias at near V_{oc} using a DC power supply, and is based on light emission around 1100nm as a result of the radiative recombination of carriers. The EL image captured with a SWIR InGaAs sensor with spectral range from 0.9 to 1.7μm of a PV module displaying early signs of ageing after several hundred hours of operation [4] gives evidence of a micro-crack in a cell and several broken fingers (Figure 3). The PV module exhibits 3.7% reduction in peak power P_m and 3.5% reduction in short circuit current I_{sc}. Extensive broken metalization and inactive regions are shown in the EL image of a 15 year old sc-Si PV module with mild signs of degradation in Figure 4.

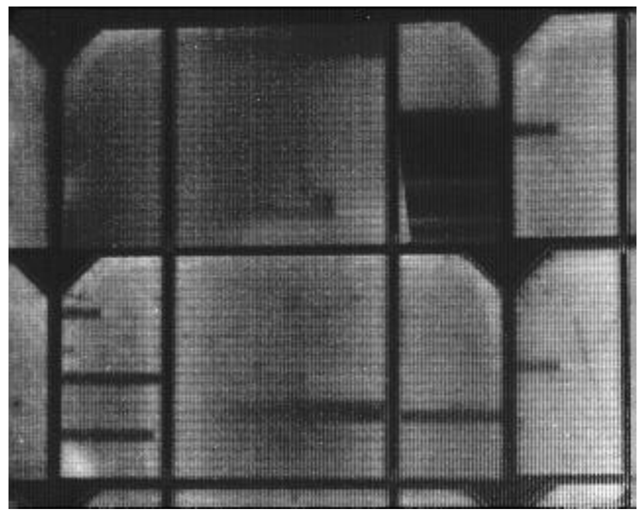

Figure 3: EL image of part of a PV module with several hundred hours of field operation.

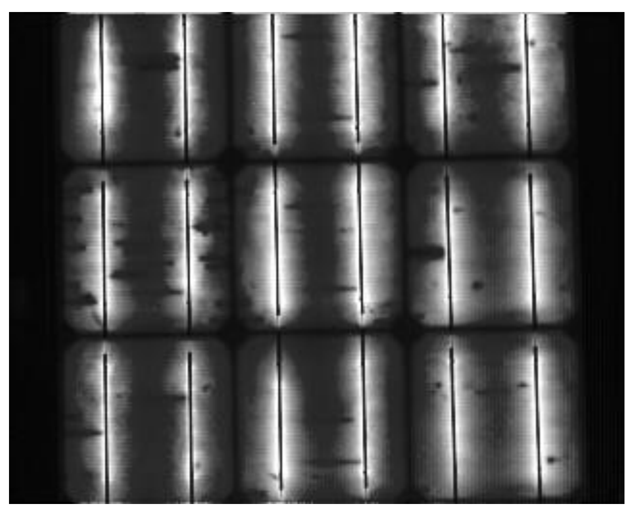

Figure 4: EL image of a sc-Si PV module operating in the field for 15 years.

The IR thermography of a 25 year old sc-Si PV module captured in the dark under forward-bias as seen in Figure 5 suggests a uniform degradation of the module. The module exhibits extensive EVA browning covering almost the entire cell surface of all cells in the module. The EL image of the module reveals several micro-cracks, shunts, in-active regions and non-uniform EL emision (Figure 6). I-V characterisation of the PV module resulted in 25.7% reduction in the STC normalised P_m, with a 16.7% reduction in the STC normalised I_{sc}. The reduction in current mainly attributed to the extensive EVA browning. However, the existence of shunts, several micr-cracks and in-active regions explains the further reduction with an average power degradation of 1%/year. This is realised by a reduced shunt resistance of 110 Ohm for the above module and a series resistance of 1.05 Ohm.

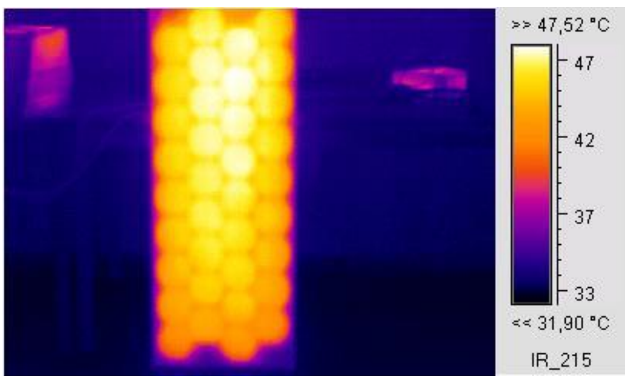

Figure 5: IR thermography of a PV module in the dark under forward-bias.

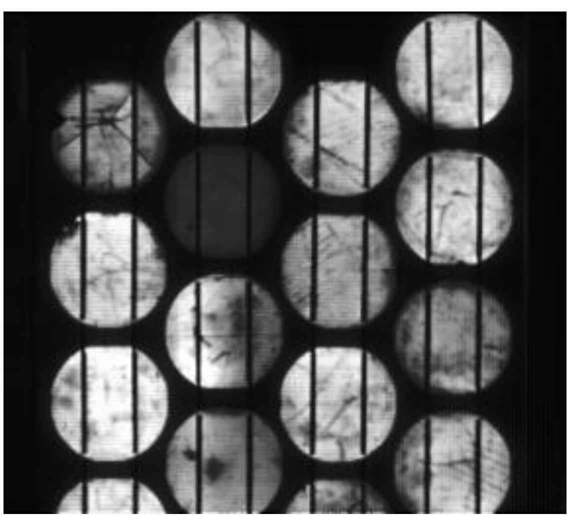

Figure 6: EL image of sc-Si PV module exhibiting micro-cracks, in-active regions and inhomogeneous EL emission.

The shunt resistance $R_{sh}=R_{sho}$ determined from the slope at the short circuit point and the series resistance R_{so} estimated from the slope of the I-V at open circuit point with R_s determined through R_{so} using the 5 parameter method [10].

Degradation of modules exhibiting more severe defects including highly resistive bus-bars, contacts and corrosion display highly deformed I-V characteristic with reduction in power output mainly attributed to reduction in the FF.

A severely degraded sc-Si PV module with a defected cell exhibiting EVA browning and corrosion on the bus-bar and contact is detected in the EL image in Figure 7, along with other defects including interrupted gridlines, shunts and micro-cracks in the neighbouring cells. The corrosion on the bus-bar appears in the IR thermography with an extreme hot spot exhibiting temperature 40°C higher than the average temperature of the module (Figure 8).

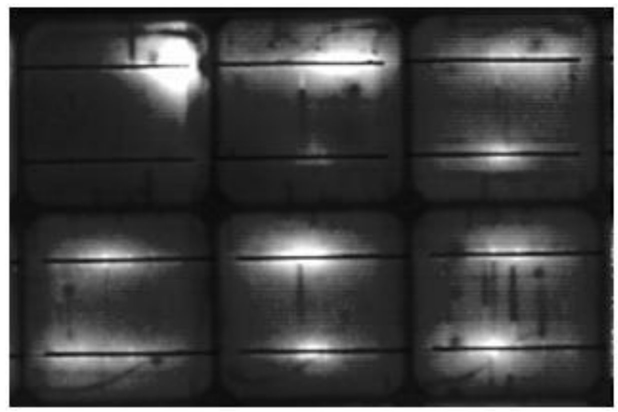

Figure 7: EL image of a severely degraded sc-Si PV module.

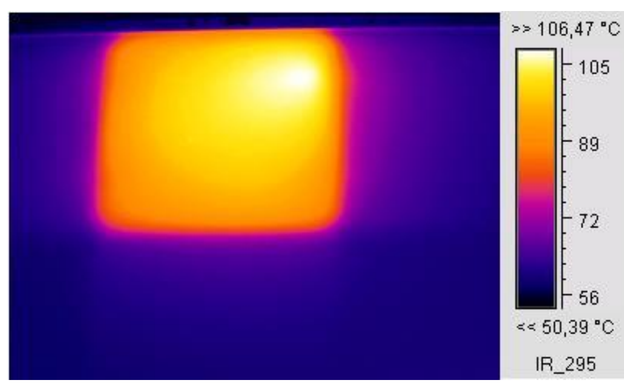

Figure 8: IR thermography revealing extreme hot spot in the severely degraded cell appearing in the top left part of the sc-Si PV module in Figure 7.

CONCLUSIONS

Non-destructive tests using UV fluorescence, IR thermography, and EL imaging for the diagnosis of PV degradation were presented. While the results given by these techniques correlate to some degree, they further provide complementary information for the diagnosis of defects. As shown, EL imaging provides further insights to the diagnosis of PV degradation even in mild cases and further cases where a uniform degradation is evident in the IR thermography and I-V curve analysis. The I-V characteristic is further used for the quantitative analysis of PV degradation. These techniques may further be used complementary to determine the expansion of defects in space and time, assisting in monitoring their evolution and evaluating module lifetime.

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