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Nondestructive characterization of encapsulant discoloration effects in crystalline-silicon PV modules

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ABSTRACT

Encapsulant discoloration is a common type of degradation in photovoltaic (PV) modules, which significantly affects its performance and reliability under field conditions. This paper presents the nondestructive characterization techniques for investigation of encapsulant discoloration in crystalline-silicon PV modules. These characterization techniques have been channelized and applied to investigate various aspects of discoloration effects on 20 years old field-exposed PV modules. Dark lock-in thermography (DLIT) has been exploited for investigation of temperature variation and defects caused by uneven discoloration over the cells, while electroluminescence (EL) imaging has been proposed for relative quantification of extent of discoloration in a PV module. The spatially-resolved images obtained from both the techniques provided the qualitative and quantitative information about the optical and electrical effects of discoloration in a module, which is not possible by the conventional visual inspection method alone. The electrical methods including proposed differential current analysis, *I–V* measurement and insulation resistance test have also been used to aid this investigation. The results obtained from these techniques show that the power degradation due to discoloration was attributed to significant reduction in fill factor by non-uniform discoloration and increase in series resistance of cell contacts, and to some extent by its direct effect of light reduction. Electrical mismatch appeared to play an important role in accelerating the encapsulant discoloration in the module. These nondestructive characterization approaches can enable to inspect large number of PV modules in their actual encapsulated form by fast and efficient manner.

1. Introduction

The investigation of field-aged photovoltaic (PV) modules is attracting significant attention these days due to rapid deployment of large-scale PV systems. Wafer based crystalline-silicon (c-Si) PV technology modules contribute to the largest share in the solar installation worldwide. A c-Si PV module generally comprises of a front glass, a solar cell assembly sandwiched between polymeric encapsulant and a backsheet. Encapsulant is one of the important layers in the structure of a PV module that provides the structural support, optical coupling, electrical isolation and mechanical protection to solar cells from external environmental stressors (moisture, dust, hail etc.). Ethyl vinyl acetate (EVA) is the dominant encapsulant for PV applications due to its low cost and high thermal stability [1,2]. However, it suffers from discoloration degradation in the modules, especially in hot and humid climatic zones [3]. Fig. 1 depicts the causes of discoloration and its adverse effects on the module performance and reliability. Discoloration is caused by the photo-thermal degradation of EVA encapsulant under high UV light exposure and high temperature, which results in the appearance of color over the solar cells [1,4,5]. It primarily decreases light transmission to the solar cells, which directly reduces the short-circuit current (I_{sc}) of the module and decreases the module efficiency. There are some indirect effects of discoloration, which also contribute in efficiency reduction. EVA degradation leads to the production of acetic acid and other volatile gases, which get trapped within the module at different interfaces, causing the delamination or bubbles formation that reduces the performance and reliability [6,7]. The acetic acid attacks the metallic contacts of solar cells and causes corrosion, which increases its series resistance (R_s) and ultimately reduces the power yield [8]. The acetic acid also acts as self-catalyst that enhances the reaction pathways of the polymer degradation. The discoloration is generally non-uniform over the module, resulting in additional power loss due to mismatch within a cell as well as module. All

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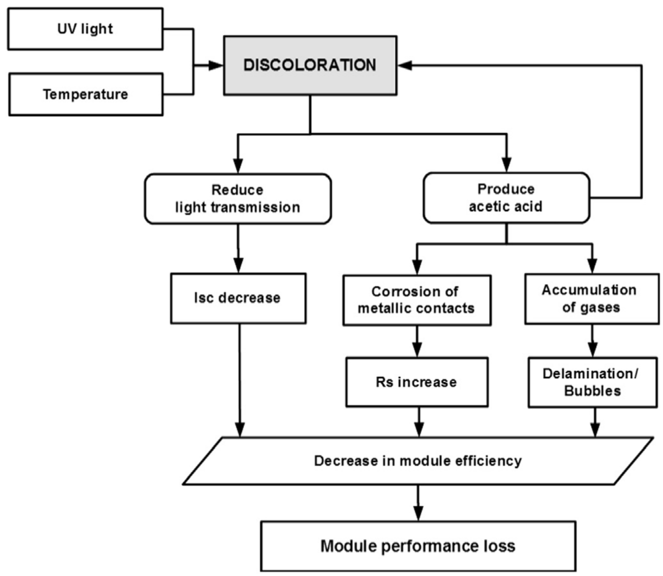

Fig. 1. Causes and effects of encapsulant discoloration in the PV module.

these articulate the need for investigation of encapsulant discoloration and its different aspects that affects the performance and long-term reliability of PV modules.

The most common approach for evaluating this degradation is the visual inspection due to the appearance of color over the solar cells. The extent of degradation is correlated with the color of EVA, which extends from yellow to dark brown as degradation progresses. However, it is only a qualitative way to investigate discoloration, which can be perceived differently by different people. The conventional *I–V* testing is generally used for quantification of discoloration degradation. Earlier studies have shown a wide range of I_{sc} and P_{max} losses due to EVA discoloration in the modules after long exposure at different locations [9–11]. However, the measured electrical parameters give global degradation, which could represent the combined impact of several degradation mechanisms in the module. Several studies have also been conducted on the analysis and characterization of degraded EVA samples using different analytical methods such as UV–visible and IR spectroscopy, fluorescence analysis, gas chromatography, thermogravimetric analysis, solvent extraction etc. [8,12–15]. These techniques provide information about the chemical transformations of EVA polymer that affects its optical, mechanical and electrical properties after aging of the modules. Such studies were performed either by aging experiments on the laboratory-prepared EVA films or by extracting EVA from the module laminate in a destructive manner. These methods take considerably longer measurement time including sample preparation for the particular characterization. Removal of EVA from the module is another challenging part of analysis due to its good adhesion with other layers, which requires great expertise. Hence, these methods are not suitable for encapsulated PV modules as module will not remain in usable form after testing. Further, investigation on standalone EVA films could not give insight to the complete effects as that in its encapsulated form inside the module. These limitations urge the need of nondestructive techniques that can be applied for the investigation of encapsulant discoloration and its effects in the PV modules without destroying them.

Camera-based imaging techniques such as infrared (IR) thermography and electroluminescence (EL) imaging offer great advantages in achieving this requirement due to their salient features of fast, nondestructive, easily implementable and large area inspection feasibility. In the past several years, these techniques have gained wide attention for investigating various types of degradation and defects in the solar cells and modules [16–19]. Due to nondestructive nature and fast response of these techniques, the PV modules can be reused after being investigated as well as large number of modules can be inspected in a relatively shorter duration. Further, these characterization techniques have the scope to be implemented in the field conditions, if a suitable portable apparatus could be realized. In this paper, these nondestructive techniques along with some other electrical methods have been exploited and channelized for the investigation and quantification of encapsulant discoloration effects in the field-exposed PV modules.

2. Methodology

A systematic methodology approach has been adopted for the comprehensive investigation of encapsulant discoloration on some c-Si PV modules that were exposed to outdoor conditions for prolonged time. The degraded PV modules have been visually inspected to examine the discoloration of encapsulant layer and other physical deteriorations such as cracks, corrosion of conductive parts and burnt spots in the solar cells. *I–V* testing has been performed to determine the degradation in output power and other characteristic parameters of a module that are linked with discoloration. A nondestructive approach of differential current analysis based on partial shading has been proposed to measure the relative discoloration effect on individual cells in the module. Two spatial imaging techniques, LIT and EL, have been exploited for the qualitative and quantitative investigation of discoloration degradation in the module. LIT technique captures the temperature distribution over the solar cells highlighting the local non-uniformities, which assists in the detection and estimation of electrical mismatch losses in the module due to encapsulant discoloration. While EL imaging has been proposed for the spatial characterization and quantitative analysis of encapsulant discoloration in the module for the purpose of relative study. Insulation resistance test has also been conducted to study the impact of discoloration on the module's electrical insulation.

3. Experimental details

3.1. Samples

The study has been carried out on two special pairs of PV modules which were installed at National Institute of Solar Energy (NISE), India for around 20 years. These module pairs were consisted of two modules of 30 W each, in parallel configuration, under battery operated mode to power CFL street lighting system, as shown in Fig. 2. A remarkable fact about these pairs was that one of the modules in each pair was affected from discoloration (brown) whereas the other module was not showing any sign of discoloration, even though both modules were of same manufacturer and exposed under similar environmental conditions. These special module pairs were very interesting test case for isolating the degradation effects other than discoloration.

Fig. 3 shows the visual images of these two pair of modules, where the modules of one pair were named as M-01 (brown) and M-02 (non-brown), and the modules of another pair as M-03 (brown) and M-04 (non-brown) respectively. Each module had circular 36 mono c-Si cells in series and its structure was consisted of glass–EVA–Si solar cell–EVA–tedlar backsheet. The rated maximum power (P_{max}), short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the modules was 30 W, 2.4 A and 21 V respectively.