Quantification of PV Module Discoloration using Visual Image Analysis

Preprint

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2017 IEEE 44th Photovoltaic Specialists Conference (PVSC)

2017
Quantification of PV Module Discoloration using Visual Image Analysis

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Abstract — Discoloration of encapsulant is one of the primary causes behind the decrease in power output of field aged PV modules. It would be beneficial to develop a method for quantifying the discoloration based on visual photography and establish a correlation with the power degradation. We hereby describe techniques for analyzing visual images to quantify the discoloration, with the ultimate aim of estimating the short circuit current degradation. Our analysis shows that it is possible to estimate the Yellowness Index of discolored areas in PV modules from the visual images, and it correlates well with the reduction in short circuit current density (calculated from quantum efficiency measurements).

Index Terms — Degradation, encapsulation, photovoltaic modules, silicon, reliability.

I. INTRODUCTION

Encapsulant discoloration is one of the major causes for degradation in PV module performance. It reduces the optical transmittance of solar radiation reaching the solar cells encapsulated inside the PV module thereby reducing the short circuit current and consequently the power output from the module [1]. Ethylene Vinyl Acetate (EVA) is the most commonly used encapsulant in PV modules, though it is well known that it degrades and discolors upon long term exposure to UV radiation (naturally present in sunlight) and high module operating temperatures [2]. Manufacturers add various additives like UV absorbers and anti-oxidants to mitigate these effects. The encapsulants can still degrade within a short period of field exposure, often due to improper manufacturing practices (like insufficient lamination time, or use of expired raw materials beyond their shelf life), or even due to improper mix of additives [2]. Field surveys in India have shown many such cases of early discoloration of the encapsulant within first 5 years of outdoor exposure [3][4]. The pressure for module price reduction from the marketplace is forcing many manufacturers to experiment with lower-priced materials which may be of lower grade, and this can lead to faster module discoloration as well. Hence, it becomes important to analyze the encapsulant discoloration in the field-aged PV modules, and understand its impact on the module performance. Visual images can serve as an important tool to quantify the discoloration in the modules, as evident from the works of Mayank Maloo [5] and Sushanth Gudla [6]. This paper gives details of our work in this direction, with the aim to establish an easy method to estimate the short circuit current degradation in discolored modules from the visual images, without interrupting the operation of PV power plant.

II. METHODOLOGY

Digital cameras capture color images by using red, green and blue filters in front of their sensors [7]. The popular JPEG image format also stores images in 3 separate channels (red, green and blue), and it is possible to read the pixel by pixel colour information from the image file as intensities of red, green and blue light. The crystalline silicon solar cells are predominantly dark blue in colour during manufacturing (the actual blue colour depends on the thickness of the anti-reflective coating deposited on the silicon solar cell). As the PV module ages in the field, the discoloration of the encapsulant leads to gradual yellowing, but usually the edges of the solar cells still remain blue in colour (in modules with breathable back-sheets) as the degraded encapsulant undergoes photo-bleaching upon exposure to oxygen diffusing from the edges of the cells [2]. Hence, comparing the color of the encapsulant over the cell, at the centre and the edge, can serve as a useful tool to quantify the discoloration in the module. Table I shows a set of colors starting from blue, and progressively going to full brown. The RGB information of these colors is also given, along with the percentage blue content in the color (which can be called the Blueness Index as defined below).

Blueness Index (BI) = \( \frac{B}{R+G+B} \times 100 \) \hspace{1cm} (1)

where, R, G and B are the intensities of the red, green and blue channels respectively, in the image.

Since our goal is to determine the extent of discoloration, we define a discoloration index as follows:

Discoloration Index (DI\(_{\text{BI}}\)) = \( 1 - \frac{\text{BI}_{\text{present}}}{\text{BI}_{\text{initial}}} \) \hspace{1cm} (2)

where,

\( \text{BI}_{\text{present}} \) = present value of Blueness Index

\( \text{BI}_{\text{initial}} \) = Initial value of Blueness Index

<table>
<thead>
<tr>
<th>TABLE I</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISCOLORATION INDEX BASED ON BLUE CONTENT</td>
</tr>
<tr>
<td>BI</td>
</tr>
<tr>
<td>DI(_{\text{BI}})</td>
</tr>
</tbody>
</table>
There is an alternative technique to quantify the extent of browning, on similar lines as the Yellowness Index which is widely used to quantify the yellowing of textiles, paints and plastics [8]. It is possible to calculate a Yellowness Index from RGB values, under certain assumptions. One of the important assumptions is regarding the illuminant, and the formula given below assumes the illuminant to be D65. The CIE standard D65 illuminant is meant to simulate the noon-time light from the northern sky, with colour temperature of 6500 K [9] and it is comparable to (though not exactly same as) the AM1.5G spectrum [10]. Since assumptions are involved and it is not a direct measurement using a colorimeter (having a standard D65 illuminant), we refer to this Yellowness Index calculated from the visual image as the Pseudo Yellowness Index (PYI).

PYI is calculated by converting the RGB values to the CIE XYZ colour space (formulae given in [11]) and then using the ASTM E313-15 formula for Yellowness Index [12], as given below in Eq. (3). A pre-factor equal to 0.25 is added to this ASTM equation based on the observation that the Yellowness Index obtained from digital image analysis (using the ASTM formula) is about 4 times of the value measured using the colorimeter instrument.

\[
\text{PYI} = 0.25 \times \frac{1.3013X - 1.1498Z}{Y} \times 100 \quad (3)
\]

A discoloration index can again be calculated based on the change in the Yellowness Index of the colour:

\[
\text{DI}_{\text{PYI}} = \frac{\text{PYI}_{\text{present}} - \text{PYI}_{\text{initial}}}{\text{PYI}_{\text{range}}} \quad (4)
\]

where,
- \(\text{PYI}_{\text{present}}\) = present value of Pseudo Yellowness Index
- \(\text{PYI}_{\text{initial}}\) = initial value of Pseudo Yellowness Index
- \(\text{PYI}_{\text{range}}\) = difference in PYI between the worst possible browning and the initial (blue) colour.

\(\text{PYI}_{\text{range}}\) is the normalizing factor which ensures that the discoloration index lies between 0 and 1 (with the worst possible browning denoted by 1). Table II gives the PYI and the discoloration index \(\text{DI}_{\text{PYI}}\) values for the same set of colors as in Table I. It can be noted that for PYI values less than -15, the colour is perceived by our eyes as blue and significant browning appears in images with PYI values greater than zero.

### TABLE II

<table>
<thead>
<tr>
<th>R,G,B</th>
<th>79, 129, 188</th>
<th>86, 117, 153</th>
<th>93, 112, 134</th>
<th>101, 105, 116</th>
<th>107, 100, 81</th>
<th>115, 95, 61</th>
<th>123, 90, 44</th>
<th>137, 84, 24</th>
<th>144, 77, 6</th>
<th>151, 72, 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYI</td>
<td>-57.0</td>
<td>-43.0</td>
<td>-29.3</td>
<td>-14.3</td>
<td>-1.6</td>
<td>9.8</td>
<td>19.7</td>
<td>26.5</td>
<td>32.0</td>
<td>36.8</td>
</tr>
<tr>
<td>(\text{DI}_{\text{PYI}})</td>
<td>0</td>
<td>0.15</td>
<td>0.29</td>
<td>0.44</td>
<td>0.57</td>
<td>0.69</td>
<td>0.79</td>
<td>0.86</td>
<td>0.92</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Three PV modules are chosen for this study, such that there is a progressive increase in the extent of discoloration. These modules had been exposed to outdoor environment for more than 10 years. A 12 Mega Pixel digital camera (SONY Cybershot) and a 13 Mega Pixel mobile phone camera (ASUS Zenfone Max) have been used for taking digital photographs of these PV modules. Software has been developed in Octave (which is an open source alternative to Matlab) to compute the Blueness Index and the Pseudo Yellowness Index for a JPEG image, pixel by pixel, and store as a 2 dimensional matrix. These values are shown for points along the centre-line for a solar cell in Fig. 1(a) & 1(b) (overlaid on the image of the cell). This solar cell is located above the name plate in the PV module (which seems to be the cause for the asymmetrical discoloration). Fig. 1(c) shows the false color image formed from the Yellowness Index values, and it is clear that this false color image mimics the discoloration in the actual visual image of the solar cell. In the false colour image, green is used for PYI values less than -15 (so corresponds to the blue areas of the solar cell), and the colour progresses to yellow and then red for higher values of PYI.

![Fig. 1](attachment:image1.png)

(a) Pseudo Yellowness Index of a discolored solar cell (for pixels along the centre line)
(b) Blueness Index of the discolored solar cell (along centre-line)
(c) False color map based on the Pseudo Yellowness Index

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III. CORRELATIONS

The Pseudo Yellowness Index is compared with the actual Yellowness Index measured by a colorimeter (Xrite Ci64) and also with the quantum efficiency at different points of the solar cell (obtained by using Module QE machine QEX12M from PV Measurements). The PYI values were computed from digital images of the selected modules, which were taken between 12 noon to 1 PM at Arizona State University on a cloudless day. Fig. 2 shows the comparison with the Yellowness Index measurements, and it can be seen that there is a positive correlation (with correlation coefficient of 0.96). However, the correlation is better at higher degree of browning (refer 1st quadrant of Fig. 2) but not so good if there is no discoloration (refer 3rd quadrant). The Blueness index is also computed for these points. The correlation between the Blueness index and the measured Yellowness Index is also found to be linear, as shown in Fig. 3, but the scatter in the plot is much higher than in the case of Pseudo Yellowness Index. Hence we have used the Pseudo Yellowness Index for further analysis.

Quantum Efficiency (QE) was measured at different points along the centre-line of the discolored solar cell to understand the effect of the discoloration on the short circuit current generation. The various points are marked in Fig. 4(a), and the corresponding short circuit current density (computed from QE) are plotted in Fig. 4(b). The QE curves for these points are shown in Fig. 5. It can be seen that the QE in the wavelength range 400–700 nm reduced significantly in the discolored areas (with a negligible improvement for wavelengths greater than 700 nm). Consequently, the short circuit current density reduces towards the centre of the cell where the discoloration is higher than at the edges.

Fig. 2. Correlation of the computed Pseudo Yellowness Index with the measured Yellowness index at different points of solar cells from the three selected modules. (Number of sample points = 70)

Fig. 3. Correlation of the computed Blueness Index with the measured Yellowness index at different points of solar cells from the three selected modules. (Number of sample points = 70)

Fig. 4. (a) A solar cell in one of the selected PV modules, and (b) Short circuit current density (computed from QE) at various points of the solar cell (Number of sample points = 13)

Fig. 6(a) shows the plot of QE versus the PYI, for 500 nm and 600 nm wavelengths. The relation is linear, with different slopes at different wavelengths. Based on the PYI, the Discoloration Index is calculated using Eq. 4, in which \( \text{PYI}_{\text{range}} = 40 - \text{PYI}_{\text{initial}} \). The initial PYI value (PYI\(_{\text{initial}}\)) is assumed equal to the present PYI value at the edges of the cell (where photo-bleaching action has prevented the discoloration effect). The maximum possible PYI value seen in any solar cell in this study is ca. 40, so it is considered as the upper limit in this calculation to determine the maximum PYI range. The Quantum Efficiency also follows a linear relation with the Discoloration Index, as shown in Fig. 6(b).

\[
y = 0.8962x + 9.3793 \\
R^2 = 0.9243
\]

\[
y = -0.4031x + 25.999 \\
R^2 = 0.613
\]
The short circuit current loss (computed from the QE data) is plotted against the Discoloration Index in Fig. 7 and shows a strong correlation. Thus, it is possible to estimate the loss in short circuit current density based on the discoloration index.

**IV. CONCLUSIONS**

Analysis of visual images of PV modules can provide a quantitative indication of the discoloration extent. Our studies indicate that the Pseudo Yellowness Index (PYI) computed from visual image analysis can be used to estimate the actual Yellowness Index for discolored modules. The discoloration Index based on the PYI value has strong correlation with the quantum efficiency. The short circuit current reduction of a discolored cell is also correlated with the discoloration index. This will serve as a useful tool to estimate the decrease in the electrical performance through visual inspection of the modules.

**ACKNOWLEDGEMENT**

This research is based upon work supported in part by (a) the Solar Energy Research Institute for India and the U.S. (SERIUS) funded jointly by the U.S. Department of Energy subcontract DE AC36-08GO28308 (Office of Science, Office of Basic Energy Sciences, and Energy Efficiency and

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Fig. 5. Quantum Efficiency at different points of the solar cell

Fig. 6. (a) Quantum efficiency versus Pseudo Yellowness Index for different points on cell shown in Fig. 4, and (b) Quantum efficiency versus Discoloration Index for different points on the cell (Number of sample points = 13).

Fig. 7. Short circuit current density loss (computed from QE) versus Discoloration Index at various points of the solar cell.
Renewable Energy, Solar Energy Technology Program, with support from the Office of International Affairs) and the Government of India subcontract IUSSTF/JCERDC-SERIIUS/2012 dated 22nd Nov. 2012, and (b) the National Centre for Photovoltaic Research and Education funded by Ministry of New and Renewable Energy of the Government of India through the Project No. 31/17/2009-10/PVSC dated 29th September 2010.

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