SiliconPV 2023, 13th International Conference on Crystalline Silicon Photovoltaics
Module Characterization and Simulation
https://doi.org/10.52825/siliconpv.v1i.867

Published: 22 Feb. 2024

Investigation of Degradation in 20-Year-Field-Exposed PV Modules From India by Cross-Characterization Using Electroluminescence Imaging and Thermography

Arti Pareek[1][https://orcid.org/0009-0009-6138-0741], Roopmati Meena[1][https://orcid.org/0000-0001-6061-2912], and Rajesh Gupta[1][https://orcid.org/0000-0002-5579-8174]

[1]Department of Energy Science and Engineering, Indian Institute of Technology Bombay, India

Abstract. The reliability of photovoltaic (PV) modules is essential for ensuring a smooth operation over the anticipated timespan while operating outside. Examining the degradation in field-exposed photovoltaic (FEPV) modules will help to identify the possible degradation modes that can affect PV module performance and functioning. In this paper, to identify the major modes of degradation in Indian sub-tropical climate conditions, 20-year-old FEPV modules have been investigated by cross-characterization using dark lock-in thermography (DLIT) and electroluminescence (EL) imaging. Cross-characterization using EL and DLIT images has been helpful in investigation of various modes of degradations in FEPV modules in the presence of multiple degradations. Encapsulant and busbar ribbon interface degradations have been identified as the two main modes of degradation observed in Indian sub-tropical climate conditions. Minor degradations include finger interruptions and cell cracks. A major effect of degradation has been observed on the fill factor and short circuit current, which have decreased by up to 30% and 40%, respectively. The results presented in this paper can be used to understand degradation occurring in a sub-tropical climate and for the non-destructive analysis of degradations in the FEPV modules.

Keywords: Field Exposed Photovoltaic Module, Degradations, Electroluminescence Imaging, Dark Lock-in Thermography

1. Introduction

Photovoltaic (PV) module installations are rapidly growing worldwide due to their ability to offer an affordable and sustainable alternative to non-renewable energy sources. While PV modules are becoming increasingly economically viable, there is still a need for gaining more confidence in their long-term reliable operation, as they are expected to perform efficiently for more than 25 years in outdoor conditions [1]. The reliability of PV modules is critical to ensure a long lifespan in outdoor operating conditions as it is susceptible to various defects and degradations. PV module experiences various environmental stresses such as high temperature, ultraviolet (UV) radiation, humidity, wind, and rain in outdoor operating conditions. In the presence of such harsh environmental conditions, components of PV modules undergo various modes of degradation such as encapsulant delamination and discoloration, cell cracks, corrosion and failure of interconnecting electric circuits, and cracking of backsheet [1]. The performance of a PV module depends on the type of degradation modes and their severity which is affected by the operating climatic conditions. In order to ascertain the dominant degradation modes and reliability issues occurring under different climatic conditions, the investigation of field-exposed photovoltaic (FEPV) modules would be helpful. Generally, electroluminescence

(EL) imaging and dark lock-in thermography (DLIT) are primarily used as non-destructive characterization techniques [3]. The working principles of both the techniques are different therefore simultaneous use, provides more insight about the degradations in FEPV nodules. EL imaging provides spatial voltage distribution while DLIT image gives the thermal profile of a PV module.

India is currently ranked fourth in the world for producing electricity using PV modules and has a potential future for PV module installation [2]. However, the hot climatic conditions of India may affect PV module operation in the long run, which can cause issues in the module's performance and reliability. Thus, it is important to investigate the degradations that may occur in the FEPV modules during their lifespan under Indian climatic conditions.

In this paper, an investigation of FEPV modules has been performed on 20-year-old modules degraded under India's sub-tropical climate conditions. The investigation has been performed by cross-characterization using DLIT and EL imaging techniques.

2. Methodology

In this work, crystalline silicon FEPV modules from India have been systematically investigated to identify the different modes of degradations that occurred in 20 years under sub-tropical climatic conditions. A schematic of the method that has been followed in this work is shown in Figure 1.

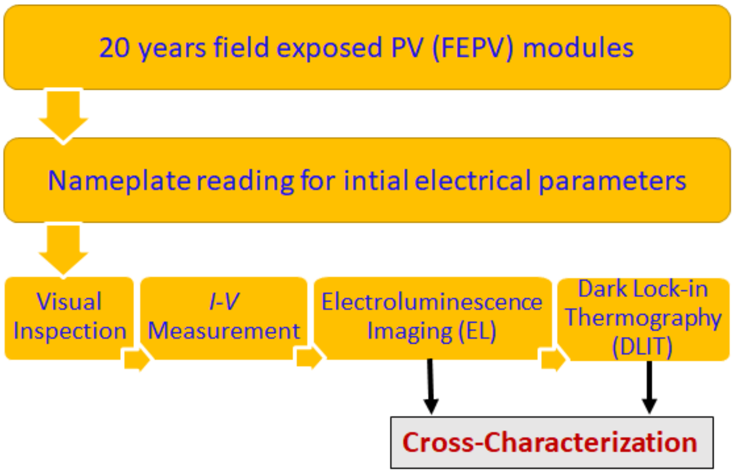


Figure 1. Schematic of the method followed to investigate FEPV modules.

The modules used for the study have been obtained from Mumbai city of India through preliminary analysis using visual inspection to examine discoloration and delamination of the encapsulant layer, visible cracks, and visible signs of corrosion. Herein, five FEPV modules have been selected for testing purpose. The impact of module degradations on module performance has been investigated by the change in electrical parameters. Nameplate reading has been used as the pre-electrical parameters of PV modules before degradation, while the post-degradation electrical parameters have been obtained by I-V measurements under standard test conditions (25 °C, AM 1.5 G, and 1000 W/m^2). Specifications of the module with rated electrical parameters are given in Table 1.

Table 1. Specifications of FEPV module with rated electrical parameters.

Number of Cells in Module	Cell Size	V_{oc}	I_{sc}	P_{mpp}	FF
36	156 x 156 mm^2	22 V	4 A	60 W	68.2

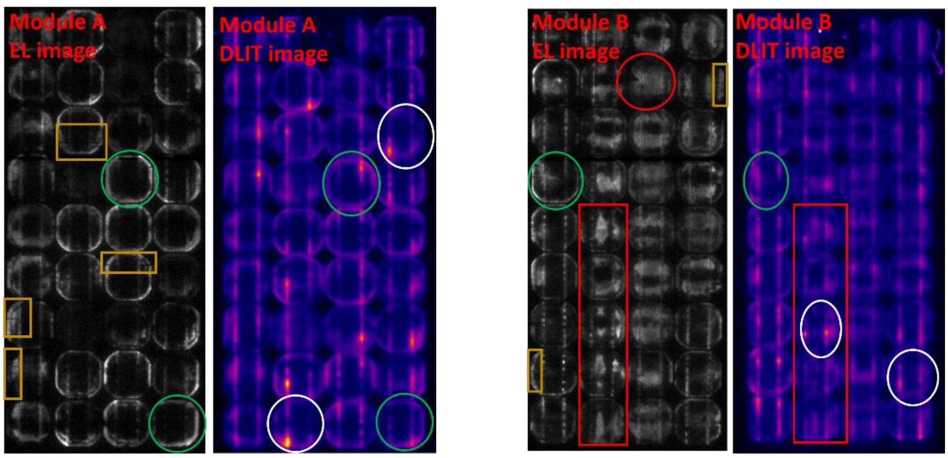
EL imaging has been used for non-destructive spatial investigation of FEPV modules, where various degradation modes appear as dark regions. In this imaging method, the module has been supplied a constant current equal to short circuit current (I_{sc}), and EL radiation emitted by the cells, passing through encapsulant and glass have been measured by a charge-coupled device detector EL camera. The sensitivity of the camera was in the range of 900-1100 nm. In the presence of multiple degradations, the EL image cannot differentiate amongst different modes of degradation as all degradation show a similar dark appearance. Thus, cross-characterization using EL and DLIT imaging has been used to differentiate major degradation modes. In DLIT imaging, the module has been supplied a periodic current of I_{sc} and temperature modulation has been measured by an indium antimonide detector infrared camera from the backside of the module. The sensitivity of the infrared camera was in the range of 3-5 μm.

3. Results and Discussions

In this section, modes of degradations imaged by EL and DLIT in the 20-year-old FEPV modules from India have been discussed in detail. Herein, the analysis of five modules namely A, B, C, D, and E has been performed.

3.1 Encapsulant discoloration

Discoloration is a widely reported degradation mode in PV module encapsulant caused by UV light and high temperature. Discoloration reduces the amount of radiation that reaches the solar cells through the encapsulant, which reduces I_{sc} of a PV module. Acetic acid and other gases produced as a co-product of the reaction for discoloration lead to corrosion and delamination in PV modules, which reduces the efficiency. The discoloration is typically non-uniform in the PV module, which causes mismatches within the cell and among the cells in a PV module which results in a drop in power [3]. Uneven encapsulant discoloration has been observed in EL images of FEPV modules as shown in Figure 2 (a), Figure 2 (b), and Figure 3 (a) (green encircled). Encapsulant discoloration has a dark appearance in EL images as it reduces the transmission of IR radiation. These dark patterns have also been visible in DLIT images as shown in Figure 2 (a), Figure 2 (b), and Figure 3 (a) (green encircled). It can be attributed to uneven heat absorption owing to uneven distribution of discoloration over the cells. Herein, the photobleached area has a bright appearance in DLIT images. Uneven discoloration observed in FEPV can be due to the photobleaching of encapsulant because of moisture ingression from the edge of solar cells and near the busbar. The presence of discoloration has also been confirmed by visual examination.



(a) (b)

Figure 2. EL and DLIT images of (a) module A and (b) module B.

3.2 Busbar-ribbon interface degradation

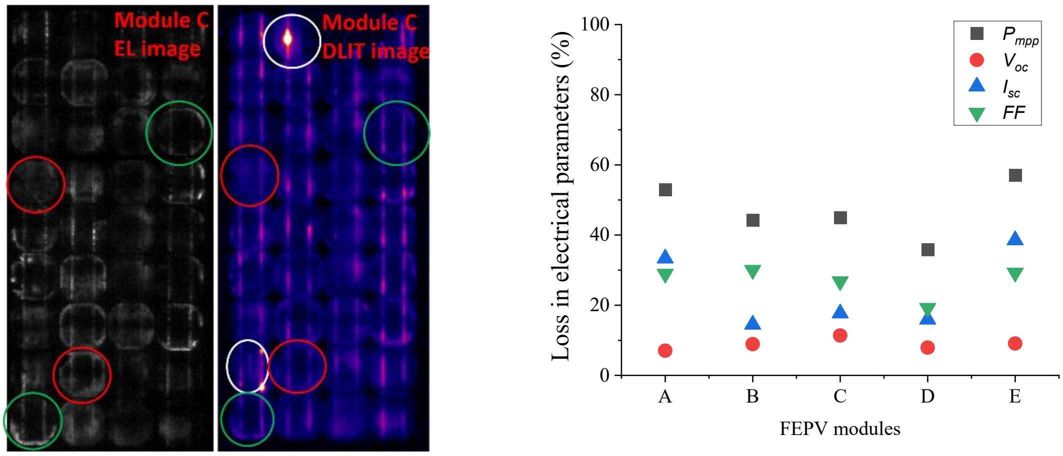
Degradation of solder bond between cell metallization (busbar) and copper ribbon interface due to thermomechanical fatigue or formation of intermetallic compound develops cracks in solder bonds. Also, moisture ingression in the PV module can cause corrosion by creeping into the joints at the solder bond which decreases the busbar contact with the copper ribbon. Solder bond degradation is one of the main reasons for increasing the series resistance (R_s) that can affect the reliability and performance of a PV module [5]. The busbar appears dark in EL images, making busbar-ribbon interface degradation difficult to identify. However, in DLIT bright spots on the busbar-ribbon interface can be seen as shown in Figure 2 (a), Figure 2 (b), and Figure 3 (a) (white encircled). It can be due to corrosion or solder bond failure or both. Corrosion and solder bond failure increases the heat dissipation due to joule heating at the degraded region and appears as bright spots in DLIT. In Figure 2 (b), it can be seen in red rectangular of the EL image as some bright regions in-between busbars and black regions near busbars. In the literature, it has been reported that these black spots in EL images were due to tin migration caused by solder material degradation [2]. These patterns have also been visible in the DLIT image of Figure 2 (b) (in red rectangular).

3.3 Cracks

Cracks in the PV module are a significant issue that may introduce in the PV cells at the wafer phase, during cell/module manufacturing, and in handling during transportation and installation. In outdoor operating conditions, temperature cycling and mechanical loading can also propagate existing cracks or introduce new cracks in solar cells. Cracks can reduce the power/performance of PV modules over time and can cause electrical disconnection in certain areas of the cells [7]. Cracks have been observed in EL images (encircled in red) of modules B and C as shown in Figure 2 (b), and Figure 3 (a), respectively. Severe cracks in module C have appeared as a dark region in the DLIT image as shown in Figure 3 (a) (encircled in red). These cracks had delamination along their length which has been observed by visual inspection. The presence of delamination can be attributed to the moisture ingression from the backsheet side through the gap in the severely cracked region.

3.4 Finger interruptions

Finger interruptions, which can occur during cell metallization and module lamination, are a prevalent problem in the screen-printed Si solar cells industry [8]. In field operating conditions, large temperature variations cause thermo-mechanical fatigue that can also result in finger interruptions in solar cells [9]. It can result in reduced performance of the PV module due to an increase in effective R_s. Interruptions of fingers have been observed in the EL images (enclosed in brown) of modules A and B as rectangular dark regions (lines) as shown in Figure 2 (a) and Figure 2 (b). However, they are not visible in DLIT images, which can be due to negligible effect on temperature.



(a) (b)

Figure 3. (a) EL and DLIT images of module C, (b) Degradation in power at maximum power point (P_{mpp}) I_{sc}, V_{oc}, and FF in 20-year-old FEPV modules.

The impact of degradations has also been analysed on the electrical parameters of FEPV modules as shown in Figure 3 (b). A major impact has been observed on I_{sc} and FF that has decreased up to 40% and 30%, respectively. Analysis of EL and DLIT images has shown encapsulant degradation as the primary mode of degradation impacting I_{sc}. Busbar-ribbon interface degradation has been observed as another major mode of degradation that increases the R_s of the module and mainly affects FF. This shows that encapsulant and busbar-ribbon interface degradations are the two major modes of degradation that affect module performance under deployed Indian climatic conditions.

4. Conclusion

The Major mode of degradations observed in 20-year FEPV modules under India's sub-tropical climate were encapsulant discoloration and busbar ribbon interface degradations. Cell cracks and finger interruptions were found to be minor modes of degradation since they were only noticed in a very small number of module cells. Cross-characterization using EL and DLIT images had been useful to investigate degradations in FEPV modules in presence of several degradations. Encapsulant degradation had a dark appearance in both DLIT and EL images, while busbar-ribbon interface degradation was observable only in DLIT images as bright spots. In addition, cracks and finger interruptions have also been observed in the EL image while severe cracks were visible in both images. Busbar-interface degradation mainly results in a loss in FF and was reported in FEPV modules up to 30%, while encapsulant degradation mostly affects the I_{sc} of the module and has been observed in those same modules up to 40%. In the presence of multiple degradations in PV modules, cross-characterization using EL and DLIT can help determine the modes of degradation in a non-destructive way.

Data availability statement

The data that support the findings of this study are available within the article.

Author contributions

Arti Pareek: Formal analysis, Investigation, Validation, Writing – original draft. Roopmati Meena: Investigation, Methodology, Visualization, Writing – review & editing. Rajesh Gupta: Conceptualization, Methodology, Writing – review & editing, Supervision.

Competing interests

The authors declare no competing interests.

References

1. M. Kumar, A. Kumar, Performance assessment and degradation analysis of solar photovoltaic technologies: A review, Renew. Sustain. Energy Rev., vol. 78, no. October, p. 554–587, 2017, doi: https://doi.org/10.1016/j.rser.2017.04.083.

2. C.M.S. Kumar, S. Singh, M.K. Gupta, Y.M. Nimdeo, R. Raushan, A. V. Deorankar, T.M.A. Kumar, P.K. Rout, C.S. Chanotiya, V.D. Pakhale, A.D. Nannaware, Solar energy: A promising renewable source for meeting energy demand in Indian agriculture applications, Sustain. Energy Technol. Assessments., vol. 55, no. February, p. 102905, 2023, doi: https://doi.org/10.1016/j.seta.2022.102905.

3. A. Sinha, O.S. Sastry, R. Gupta, Nondestructive characterization of encapsulant discoloration effects in crystalline-silicon PV modules, Sol. Energy Mater. Sol. Cells., vol. 155, no. October, p. 234–242, 2016, doi: https://doi.org/10.1016/j.solmat.2016.06.019.

4. A. Sinha, M. Bliss, X. Wu, S. Roy, R. Gottschalg, R. Gupta, Cross-characterization for imaging parasitic resistive losses in thin-film photovoltaic modules, J. Imaging. vol. 2, no. August, p. 1–19, 2016, doi: https://doi.org/10.3390/jimaging2030023.

5. A. Tummala, J. Oh, S. Tatapudi, G. TamizhMani, Degradation of Solder Bonds in Field Aged PV Modules: Correlation with Series Resistance Increase, In 2017 IEEE 44th Photovolt. Spec. Conf. (PVSC), p. 2912–2917, 2018, doi: https://doi.org/10.1109/pvsc.2017.8366714.

6. R. Meena, M. Kumar, R. Gupta, Investigation of dominant degradation mode in field-aged photovoltaic modules using novel differential current-voltage analysis approach, Progress in Photovoltaics: Research and Applications, vol. 30, no. November, p. 1312–1324, 2022, doi: https://doi.org/10.1002/pip.3580.

7. V. Gade, N. Shiradkar, M. Paggi, J. Opalewski, Predicting the long term power loss from cell cracks in PV modules, 2015 IEEE 42nd Photovolt. Spec. Conf. (PVSC), p. 2–7, 2015, doi: https://doi.org/10.1109/PVSC.2015.7355665.

8. I. Zafirovska, M.K. Juhl, J.W. Weber, J. Wong, T. Trupke, Detection of finger interruptions in silicon solar cells using photoluminescence imaging, Chinese Phys. B. vol. 27, no. November, p. 1496–1502, 2018, doi: https://doi.org/10.1088/1674-1056/27/6/068801.

9. S. Kumar, R. Meena, R. Gupta, Finger and interconnect degradations in crystalline silicon photovoltaic modules: A review, Sol. Energy Mater. Sol. Cells. vol. 230 no. September, p. 111296, 2021 https://doi.org/10.1016/j.solmat.2021.111296.