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Unveiling the Potential of Electroluminescence Characteristics in Investigating Different Types of Defects and Degradations in c-Si PV Module

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Abstract. Photovoltaic (PV) cells can be characterized using current-voltage (*I-V)* as well as electroluminescence (EL) characteristics. However, unlike *I-V*, the potential of EL characteristics has not been well discussed in the literature. In this work, the impact of different types of defects on the EL characteristics is studied, and the possible use of EL characteristics in the qualitative and quantitative investigation of defects is unveiled. Defective field-aged and new modules with artificially induced defects were taken for experimental study. EL current-intensity (I-ϕ) and EL voltage-intensity (V-ϕ) characteristics were studied for the cells suffering from major defects such as cracks, busbar interconnect failure, and PID-shunting. It is observed that I-ϕ characteristic is useful in the investigation of shunting defects, whereas V-ϕ characteristic is in diagnosing defect that increases series resistance. Bulk defects within a cell affect EL calibration constants and increase cell-to-cell mismatch within a module. The findings of this work would be useful for extracting valuable information from EL images regarding defects and degradations.

Keywords: Electroluminescence Imaging, EL Characteristics, *I-V* Characteristic, Defects, Degradation, Solar Cell

1. Introduction

Crystalline silicon (c-Si) PV modules share 90% of PV installations and are a key source of renewable energy generation [1]. The reliable operation of a c-Si PV module is essential during its entire 25-30 years of lifespan for the profitable functioning of PV plant. However, defects and degradation are inevitable in a PV module. Defects like cracks, finger breakages, and cell breakages are normally generated in the module production line, shipping, and field installations. In a field operation, climatic conditions such as high temperature, humidity, UV exposure, hail-storming, snowfall, and ground leakage currents lead to various defects and degradations in a c-Si PV module [1], [2]. Optical defects such as discoloration and delamination caused due to aging of encapsulant consequently reduce cell short circuit current (I_{sc}) [3]. Light-induced degradation (LID) or light and elevated temperature-induced degradation (LeTID) affects the bulk parameters of a cell [4]. Potential-induced degradation shunting (PID-s) in a field, or recombinations, shunts induced during cell manufacturing cause a reduction in cell open circuit voltage (V_{oc}) and fill factor (FF) [5]. Corrosion, busbar interconnect failure, or cracks increase the series resistance (R_s) of a module. All these defects and degradation affect overall short-term and long-term PV system performance due to a drop in module efficiency, increased mismatch losses, and a high degradation rate. Hence, periodic performance monitoring and investigation of defects and degradations are essential to keep PV module performance within desirable limits.

For qualitative and quantitative investigation of defects and degradation in a c-Si PV module, current-voltage (*I-V*) measurement and electroluminescence (EL) imaging are normally used. *I-V* characteristic gives quantitative information about a module performance. Also, based on the change in its shape, predominant existing defects and degradation in a cell can be identified (e.g., R_s defects increase slope at V_{oc}, Shunt resistance (R_{sh}) defects increase slope at I_{sc}). However, based on module *I-V* characteristic spatial nature and location of defects and degradation in a module cannot be identified. EL imaging is normally used for spatial investigation of defects and degradation in a PV module, as shown in FIG. 1. Conventionally, defects and degradation in a PV module are recognized based on their characteristic appearance in EL images.

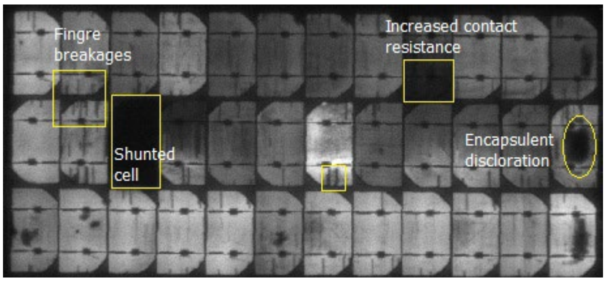


Figure 1. EL image of the field-aged module with different types of defects and degradations

Outdoor use of EL imaging has immensely increased for the inspection of utility-scale power plants. EL imaging can be performed in daylight using the lock-in approach and in night conditions using a simple biasing method [6]. From the stack of captured EL images at different EL currents, it is expected to optimally extract qualitative and quantitative information of module performance and degradation stages. From that perspective, this work aims to unveil the potential of EL characteristics in analyzing defects and degradations frequently observed in a PV module.

2. EL Characteristics of a c-Si PV cell

EL imaging is performed in dark conditions by exciting PV cell/module electrically (EL current (I) ≤ I_{sc}) as shown in FIG. 2. In response, band-to-band recombination within a cell causes emission of infrared light in the range of 900-1200 nm, which gets captured by EL camera. For a healthy PV cell, EL intensity (ϕ) follows one to one relationship with EL current (I) and forward voltage (V_f) as written in Eq. (1) and (2), respectively [7], [8].

$$log(\Phi) = A'' + n_1 log(I) \tag{1}$$

$$log(\Phi) = log(A) + \frac{V_f}{V_t} \tag{2}$$

A'' and A are the current and voltage calibration constant of an EL system, respectively. V_t - diode thermal voltage

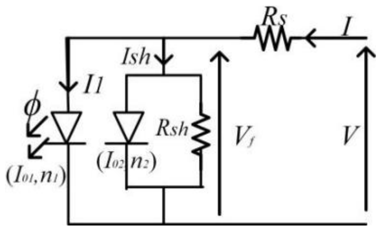
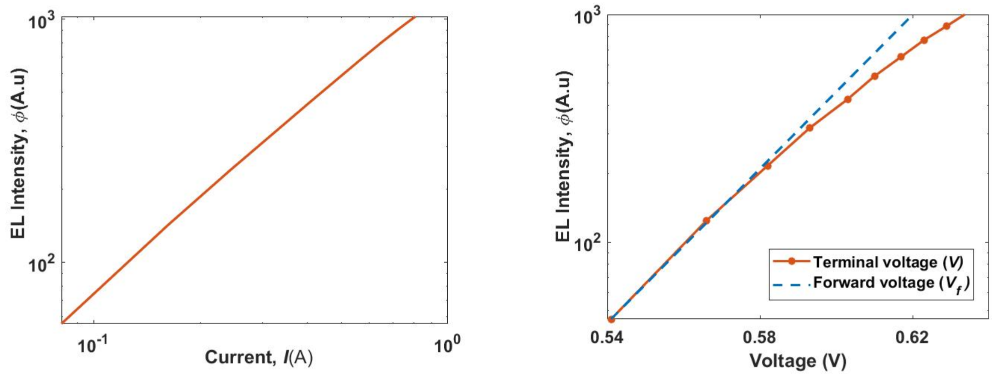


Figure 2. PV cell equivalent circuit under dark EL imaging condition (I_{01}, I_{02} - reverse saturation current of bulk and recombinative diode, n_1, n_2 - ideality factors of bulk and recombinative diode, R_s, R_{sh} - series and shunt resistance)

From FIG. 2, it may be observed that cells can be described by *I-V*, *V-*ϕ and *I-*ϕ characteristics. *I-V* characteristic is well discussed and studied in the literature for healthy as well as defective cell. In this work, EL characteristics are explored for a c-Si PV cell. FIG. 3(a) and 3(b) shows the *I-ϕ* and *V-ϕ* characteristics plotted for a healthy (defect-free) PV cell. It may be observed that *I-ϕ* curve appears to be linear on log-log plot, and the *V-ϕ* curve appears to be linear on a semi-log plot, which is also expected from Eq. (1) and (2). Due to voltage drop across R_s, *V-ϕ* curve becomes non-linear in the high voltage region. Magnitude of cell n_1 and temperature can be estimated from the slope of *I-ϕ* and *V-ϕ* characteristics, respectively.

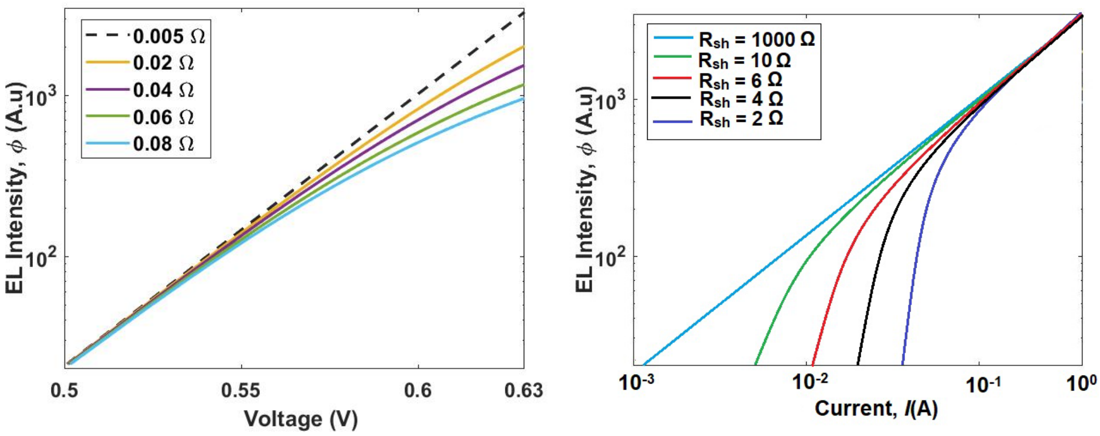


(a) (b)

Figure 3. Characteristics of healthy PV cell (a) *I-ϕ* (b) *V-ϕ*

Generation of defects or degradation affects one or a few cell parameters. From FIG. 2, Eq. (1) and (2), the impact of different types of defects and degradation on EL characteristics can be simulated. FIG. 4(a) and 4(b) shows the impact of R_S and R_{sh} variation on *V-ϕ* and *I-ϕ* curve, respectively. In both cases, the increasing magnitude of R_s or R_{sh} increases the non-linear appearance of *V-ϕ* curve and *V-ϕ* curve, respectively. To describe the non-linearity of a *I-ϕ* curve, Eq. (1) can be modified to Eq. (3), since the current flowing through a bulk diode only causes EL emission [5]. Eq. (3) may be useful to quantify leakage current (I_{sh}) or R_{sh} within a cell.

$$log(\Phi) = A'' + n_1 log(I - I_{sh}) \tag{3}$$



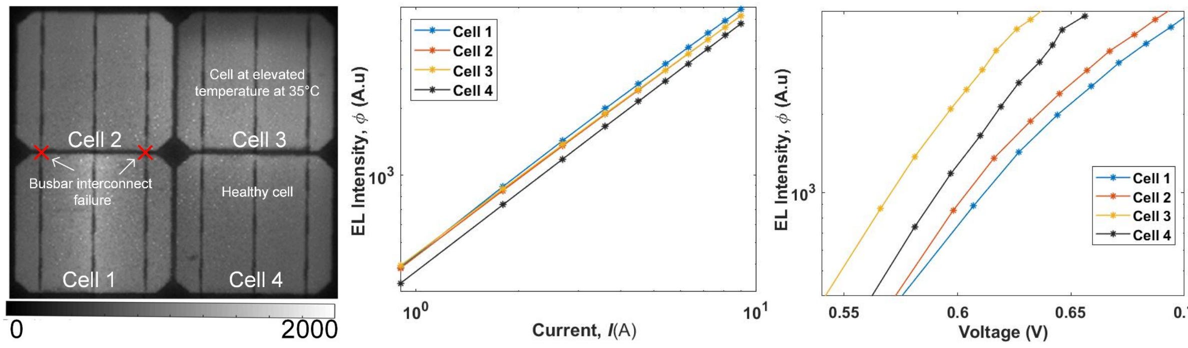
(a) (b)

Figure 4. (a) Effect of R_s defects on *V-ϕ* characteristic (b) Effect of R_{sh} on *I-ϕ* characteristic

From Eq. (1) and (2), it may be predicted that bulk defects or degradation such as LID or LeTID affecting I_{01}, n_1 parameters would change EL imaging constants (*A, A''*), since they contain the effect of bulk semiconductor material properties [7]. Change in *A* or *A''* would result in shifting both the curves up or down on y-axis without causing any change in shape.

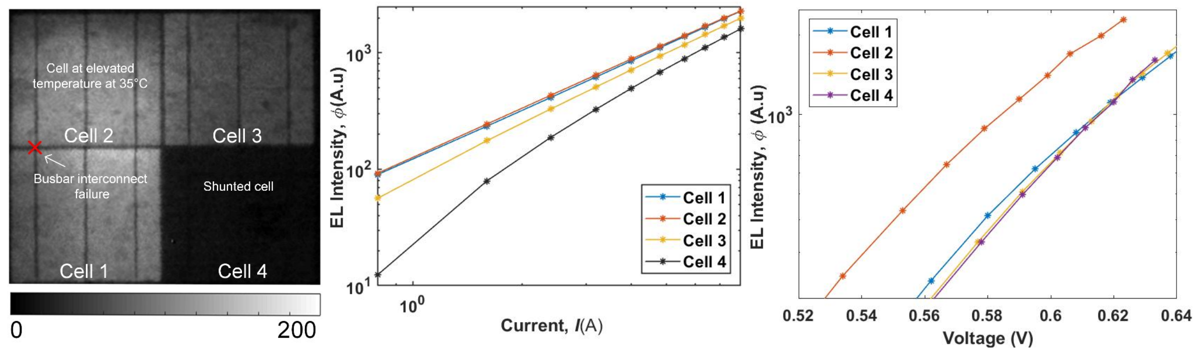
3. Experimental results and discussion

In a field, a module experiences different types of defects and degradations. In order to see usefulness of EL characteristics in dealing with them, new test modules with full-size commercial cells were taken accessing an individual cell. Major defects that are normally observed in a field were artificially created in PV cells, such as cracks, PID-shunting, busbar interconnect failure, and elevated cell temperature to replicate mismatch. *I*-ϕ and *V*-ϕ curves of the defective PV cells are plotted in FIG. 5 and 6, respectively, from the EL images taken at EL current $0.1I_{sc}$ to I_{sc}.



(a) (b) (c)

Figure 5. Defective mono c-Si Module A (a) EL image taken at $0.2 \cdot I_{sc}$ (b) *I*-ϕ characteristics (c) *V*-ϕ characteristics of the cells



(a) (b) (c)

Figure 6. Defective multi c-Si Module B (a) EL image taken at $0.2 \cdot I_{sc}$ (b) *I*-ϕ characteristics (c) *V*-ϕ characteristics of the cells

3.1 Busbar interconnect failure

Busbar interconnect failure increases the net R_s of a cell. It may be observed from FIG. 5(b) and 6(b), R_s defects in Cell 1 and 2 (Module A) and Cell 2 (Module B) does not affect the shape of *I*-ϕ characteristics, and it is linear as healthy cell. Healthy cell has slight non-linearity in high voltage region (FIG. 2(b)) due to voltage drop across R_s (refer to FIG. 1) as discussed in Section 2. From FIG. 5(c) and 6(c)), it is evident that the progression of R_s-defect increases the non-linearity of *V*-ϕ characteristics, and degree of non-linearity is proportional to the severity of defects. Hence, *V*-ϕ curve of cell would be useful in detecting R_s-defects as well as estimating magnitude of increased cell R_s.

3.2 PID shunting

Cell 4 of Module B is shunted and shows a dark appearance in the EL image. FIG. 6(b) show that shunted cell causes non-linearity in *I*-ϕ characteristic. It has been observed that the degree of non-linearity of *I*-ϕ increases with the degree of shunting. This observation would be useful in the efficient detection of shunt-related defects such as PID-s, and process-induced shunts in a c-Si PV module. *V-ϕ* curve of shunted Cell 4 (FIG. 6(c)) shows no remarkable difference compared to healthy cells. *I-ϕ* curve has the additional advantage over *V-ϕ* curve that it can be traced for an individual cell within a module with a series connected cells.

3.3 Bulk defects

Defects within a bulk region increase I_{01}, n_1 parameters of a cell. For artificially replicating bulk defects, Cell 3 and Cell 2 of Module A and B, respectively kept at elevated temperature. It may be observed that temperature change does not affect the shape of either *I-ϕ* or *V-ϕ* characteristics (FIG. 5 and 6). However, it shifts the *V-ϕ* characteristics away from healthy cell more compared with *I-ϕ* curve. It implies that cell temperature affects EL constant *A* more significantly than *A”*. Cell to cell mismatch due to bulk defects within a module may be analyzed using the EL characteristics. Figure 7 shows the comparison of *I-V, I-ϕ* or *V-ϕ* characteristics plotted for different types of defects and degradations

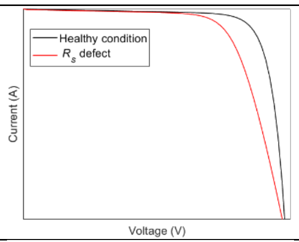
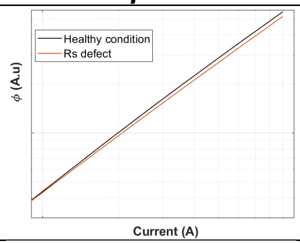
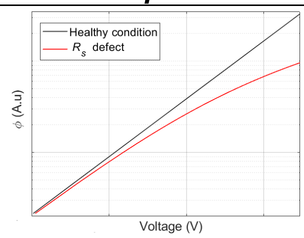
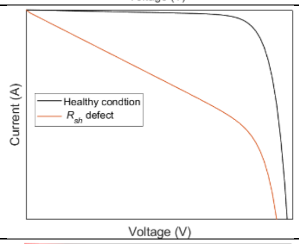
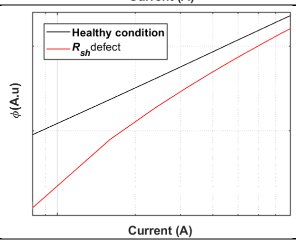
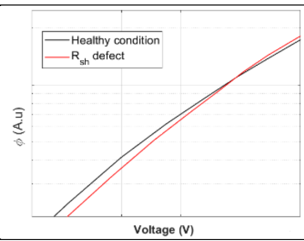
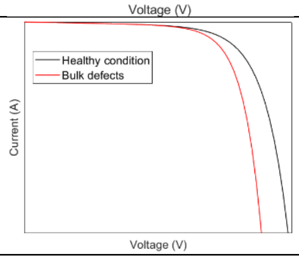
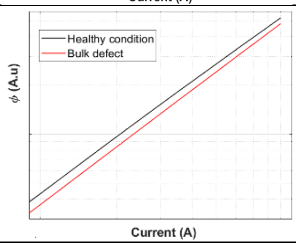
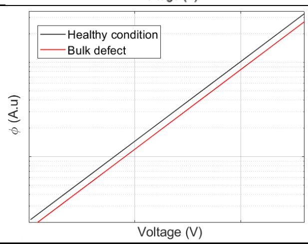
Defect	*I-V* curve	*I-ϕ* curve	*V-ϕ* curve
R_s *defects*			
R_{sh} *defects*			
Bulk *defects*			

Figure 7. Comparison of *I-V* and EL curves for different types of defects and degradations

Compared to *I-V* characteristics, EL characteristics can also provide spatial analysis of defects over a cell area, whereas *I-V* characteristic gives lumped information about the defect or cell parameter. On the limitation side, EL characteristics do not directly provide information about module or cell power loss. Also, EL characteristics are not useful in analyzing optical defects and degradations such as encapsulant degradation, delamination, or cell breakages, which attenuates the EL signal.

4. Conclusions

In this work, the impact of major defects and degradation on the EL characteristics of a PV cell was studied. Key findings of the work are listed as follows,

1. *V-ϕ* characteristic is more useful in detecting R_s-related defects as well as quantifying increased R_s based on the nonlinearity of a curve. R_s-defects insignificantly affect a cell *I-ϕ* characteristic.

2. *I*-ϕ characteristic is suitable in investigating shunt-related defects and degradation based on the degree of nonlinearity. Shunting defects do not affect a cell *V*-ϕ characteristic. This characteristic would be useful, especially in a module with a series connected cells.
3. Bulk defects within a cell do not affect the shape of EL characteristics; however, they increase the cell to cell mismatch and affect EL calibration constant.
4. EL characteristics enable the estimation of cell parameters. However, it does not provide direct module or cell power loss information.

Data availability statement

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

Author contributions

Vishal E. Puranik: Conceptualization, Methodology, Formal Analysis, Validation, and Writing – original draft, **Ravi Kumar:** Investigation, Data Curation, Visualization, and Writing – review & editing, **Rajesh Gupta:** Writing – review & editing, Project Administration, and Supervision

Competing interests

The authors declare no competing interests.

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