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Laser Induced Luminescence Characterization of Mechanically Stressed PV Cells

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Abstract—Electroluminescence (EL) and photoluminescence (PL) imaging are powerful solar cell and panel characterization techniques that are capable of detecting early stage solar cell failures and degradation with high sensitivity and level of detail required for proper preventive maintenance. The electrical contacts needed during measurement pose a challenge for many inspection scenarios, both for EL and PL. Light or Laser induced luminescence (LIL) is a contactless way to generate spatially resolved images of PV panels that highlight poorly connected cell areas, such as finger failures, areas with high series resistance or disconnected cell cracks. In this study, we analyze the characteristics of the LIL scan imaging method in detecting cracks in mono-Si cells, comparing single frames with reconstructed contactless EL images built with a full LIL scan image stack. A comparison between contactless EL generated by LIL and conventional contact EL is made, and finally an estimation of the required laser intensity for outdoor LIL is provided, in correlation to known contact EL performance during nighttime and daylight conditions.

Index Terms—Electroluminescence, photoluminescence, reliability, cell characterization, fault detection.

I. INTRODUCTION

Electroluminescence (EL), one of the most accurate PV fault detection techniques used today, requires electrical contacting, which complicates or even prevents effective fault detection in large PV power plants. Photoluminescence (PL) using sunlight will ultimately also require electrical or physical contact to the PV modules [1], [2]. Laser induced luminescence (LIL) technique is a fully contactless luminescence imaging method with potential to overcome field inspection drawbacks faced by EL imaging [3]–[5] and also be performed during daytime.

The location where the charge carriers are injected in LIL is very different from conventional EL. Instead of flowing from/to the electrical contacts (busbars and grid fingers), the carriers are generated where the laser-beam is localized and the conducting structures allow the induced voltage to spread to the rest of the cell. Consequently, the non-illuminated part of the cell has a voltage applied across the cell's junction as done in traditional EL imaging [6], [7]. In LIL, a structured or patterned laser beam is scanned across the surface of the solar cell or panel, causing photo-excited excess carriers and radiative recombination in the illuminated regions (a luminescence peak where the laser beam is positioned - PL), as well as current flow to the non-illuminated regions

with corresponding luminescence emissions (contactless EL). Induced lateral current generated by partial illumination of PV cells have important practical implications for laser-based luminescence examination of photovoltaic modules and cells [8].

LIL imaging can make use of the diagnostic information coming from different locations where the carriers are generated, such as on an intact or an isolated region of a cell. This property allows to characterize broken contact fingers and enhanced resistance areas. Isolated regions due to cracks for example, have a high amount of carriers generated that cannot flow electrically through the cell, decaying radiatively and emitting intense luminescence signal.

Particularly in the LIL case, the measurement does not consist of a single image captured. As the section of the cell illuminated by the laser (PL) often saturates the sensor and is not used for reconstructing a final cell image, a sequence of images is necessary to cover the entire cell area. The luminescence data obtained during the laser scan of a PV panel is considered in this work to be the correspondent to the contactless EL signal only and the final reconstructed image presents distinguishable PV diagnostic information, even when the luminescence signal is particularly low.

Since the carrier injection location characteristic of LIL can provide particularly different mapping of cell-isolated areas due to cracks than conventional contact EL imaging, we aim in this study to characterize the differences between the two, as well as the particularities of LIL imaging of cracked cells. To achieve this, in this study we analyze the luminescence signal of a healthy and a cracked cell in a single frame of an LIL scan, comparing differences between connected and disconnected areas of the broken cell. Additionally, we compare the characteristics of the single frames with reconstructed contactless EL images, compare single frames with contact EL images and make a parallel of their intensities to finally demonstrate how LIL imaging can be performed outdoors during daytime.

II. METHODOLOGY

A. LIL image acquisition

In the image acquisition experiment, an InGaAs camera from Raptor Photonics (OWL640) and a short-wave infrared (SWIR) low distortion sapphire lens with fixed focal length of 25 mm were used. The device under test (DUT) was a mini-module with 9 mono-crystalline silicon 15.6 cm cells arranged

in a 3 x 3 matrix, mechanically stressed presenting two cracked cells. The DUT was kept at open circuit conditions and the test was performed in a temperature controlled environment. Further details of the setup has been published previously [5]. The LIL scans under low light were acquired using as excitation source an line-shaped 808 nm 5 W laser diode placed at 127 cm from the PV module. An angular scan of the laser line beam was performed over the entire mini-module with the use of a robot arm that rotated the laser at 10 degrees per second. The camera was kept fixed in its position at 336 cm from the DUT. The images were acquired with a fixed 17 ms exposure time, 60 frames per second, and to cut out the laser emission, a 950 nm long-pass filter was placed in front of the lens. The complete scan and image acquisition was done in 1.3 seconds. For the single frame images acquired with the laser source close to the DUT for the entire beam be inside a single PV cell area, the images were taken with 10 ms exposure time and the laser was positioned at only 10 cm from the cell.

B. LIL image reconstruction

The sequence of images acquired contain partial luminescence data for cells/regions of the module, and have to be stacked and reconstructed into a complete module luminescence image. Using the known input of module size and matrix configuration, this is done by identifying the beam position and segmenting it for its removal, stacking the luminescence signal of the image sequences acquired and averaging to eliminate noise. After this step, two images are obtained, labeled as "Highlighted Contactless EL" and "Baseline Contactless EL". The highlighted contactless EL image aggregates the high luminescence intensity provided by electrically isolated areas when the laser beam scans over them (see Profile 1 in Fig.1). In contrast, the baseline contactless EL image aggregates the luminescence when the laser scans over electrically connected areas, resulting in a luminescence image more similar to conventional EL. The PL part of the scan is not used for building an output image at this stage.

III. RESULTS

A. Single frames

In the representation of Fig.1, two single frames of an LIL scan shown side-by-side for more direct comparison of a healthy (cell to the left) and a damaged (cell the right) PV cell. On the left part of Fig.1, the frames with two different laser positions can be seen in triplicate to show the line profile in three different positions – Profile 1 at the top, Profile 2 in the middle and Profile 3 in the bottom.

The luminescence intensity profiles to the right show, at the same scale:

- A peak where the laser beam is positioned (PL);
- A baseline contactless EL in the entire healthy cell area and in the connected areas of the damaged cell;
- A bright isolated area on the part of the damaged cell (highlighted contactless EL) where the laser beam is located;

Fig. 1. Profile plots of two side-by-side single frames of an LIL scan. Left: line profile in three different positions – Profile 1 at the top, Profile 2 in the middle and Profile 3 in the bottom; Right: luminescence intensity profiles (here shown as gray values arbitrary units).

- An increased peak intensity of the PL signal on the highlighted isolated area;
- Dark isolated areas on the part of the damaged cell where the laser beam is not located.

Fig. 2. Labels on regions of interest of the healthy (top) and broken (bottom) cells.

To be able to compare the mean luminescence in these regions of interest, the areas mentioned above are labeled in Fig. 2 and their mean luminescence intensity is plotted in Fig. 3. Moreover, Fig. 3, shows that the healthy cell has consistently higher luminescence intensity than the cracked cell in areas where it is still well connected. This can be harder to observe in the images alone. PL emissions in both cells is under carrier extraction conditions as described before [9], since current flows from the illuminated to non-illuminated regions. It is observed that for the illuminated isolated area, PL and contactless EL has considerably higher mean luminescence

Fig. 3. Mean luminescence intensity of LIL single frames in the areas indicated in Fig.2.

intensity than their connected counterparts in both cracked and healthy cells. Finally, as it is usually seen in traditional EL, isolated non-illuminated areas present no luminescence and are comparable with background signal.

B. Reconstructed images

Fig. 4 shows the results of reconstructed images from the LIL scan compared with traditional EL measured at 100% and 10% short circuit current (I_{sc}) bias excitation. Qualitatively, the diagnosis of the isolated areas are correspondent to 100% I_{sc} . However, for this configuration and image reconstruction, the LIL does not detect any of the finger disconnections, visible in the EL image.

In Fig. 5, the mean luminescence intensity of reconstructed LIL images presented for the same areas indicated in Fig.2, but now corresponding to full scan reconstructed images shown in Fig.4. For the full scan, the non-illuminated isolated areas from Fig.2 have been illuminated during the scan, therefore indicated as "previously non-illuminated isolated areas". Their reconstructed image have now an equivalent highlighted signal similar to the EL isolated area. The same consistent comparison between health and cracked cells can be observed for connected regions. When compared with Fig.3, it can be observed that the reconstructed images are able to provide higher absolute luminescence signal.

C. LIL and EL luminescence intensity comparison

Considering a frame of LIL scan with the laser positioned close to one cell such that the entire beam hits the cell and the full laser intensity is converted into luminescence in the PV cell, an luminescence comparison is made with traditional EL images. In the top of Fig.6, the EL (left) and the LIL (right) images can be seen, where the correspondent EL image has the current bias that match the luminescence intensity of the Baseline Contactless EL from the LIL image. This match can be verified in the profile plots in the bottom of Fig.6. The match occurs at 13% of I_{sc} current bias of contact EL. In these images, the camera settings were identical.

Fig. 4. Comparison between traditional EL images at 10 and 100% I_{sc} (left) and reconstructed images from LIL scan (right).

Fig. 5. Mean luminescence intensity of reconstructed LIL images in the areas indicated in Fig.2.

When different laser intensities are used, a linear dependence of the Baseline Contactless EL signal with the laser intensity. If the same match is addressed for contact EL, the graph shown in the inset of Fig.7 is observed. When extrapolating this apparent linear dependency (Fig.7), we have the indication that a laser power of 48.5 W illuminating a single PV cell will generate a contactless EL image as intense as a contact EL with 100% I_{sc} . This is a very high power laser and, with a collimated beam, can possibly provoke burns in some PV components.

The higher intensity presented by the reconstructed images and particularly by isolated cracks, however, indicates that one of the most significant faults observed via luminescence imaging - C mode cracks - will require less laser intensity than that to be easily detectable outdoors. In this case, the ambient conditions during the LIL scan must be observed.

D. LIL under sunlight environment

For sun irradiances above approximately 100 W/m², it is indicated that EL imaging reaches a limit in being performed with cameras that required long exposure (cameras with Si-

Fig. 6. LIL single image (top right) compared with contact EL (top left), and profiles (bottom) of the blue and red lines indicated in the images on top.

Fig. 7. Laser intensity match with contact EL current bias in % of I_{sc}

based sensors) [10]. For InGaAs cameras, full daylight EL imaging is possible using electrical signal modulation and sunlight noise filtering via background image subtraction [11]–[13]. This is reported for 100% I_{sc} EL signals. In Fig. 8, a single image LIL is acquired under low daylight (approximately 2 W/m^2) with 20 ms exposure time. For a 5 W laser, this level of ambient noise was enough to fade considerably the luminescence signal, requiring background subtraction. As the LIL image is obtained successfully with background subtraction, it is expected that, for higher luminescence intensities, the same strategy used for contact EL could be used. In the LIL case, the modulation can be performed still contactlessly, controlling the laser duty cycle and synchronizing it with the camera during image acquisition while the PV panels are in open circuit.

It might not be necessary to only make use of the contactless EL part of the LIL scan. With different laser shapes and efficient image processing, the PL part of the scans can be reconstructed, and they present a higher luminescence intensity than contactless EL. With this, lower power lasers can be used for daytime LIL in the future.

Fig. 8. Single frame LIL under sunlight at app. 2 W/m^2 with subtracted background

IV. CONCLUSIONS

In this work we presented some of the advantages and limitations of LIL imaging cracked mono-Si cells, as well as the PL and EL components of LIL and their relative intensities. We also presented LIL reconstructed images considering only the contactless EL part of the signal. Isolated cracks such as C mode cracks are very easy to detect with LIL and clearly visible in Highlight Contactless EL reconstructed images.

The luminescence intensity of LIL and conventional EL were compared, showing that to obtain contactless EL generated by a laser with the same intensity as contact EL at 100% I_{sc} , it would be necessary a 48.5 W power laser scanning over one single cell. However, using the PL part of the LIL and detecting mode C cracks only would make the power requirement much less demanding. Moreover, under daylight, the LIL signal is significantly affected by the ambient noise, especially for low power lasers, however, a laser modulation method combined with LIL image background subtraction, can improve the signal to noise ratio of the LIL image. Considering that LIL under daylight conditions would work only with luminescence intensities close to 100% I_{sc} EL signals, the use

of the PL part of the LIL signal is a requirement and should be observed in the future.

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