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Dhimish, Mahmoud, Holmes, Violeta, Dales, Mark et al. (1 more author) (2017) Effect of micro cracks on photovoltaic output power:case study based on real time long term data measurements. Micro and Nano Letters. pp. 803-807. ISSN: 1750-0443

https://doi.org/10.1049/mnl.2017.0205

The effect of micro cracks on photovoltaic output power: case study based on real time long term data measurements

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This paper analyses the impact of micro cracks on photovoltaic (PV) module output power performance and energy production. Electroluminescence imaging technique was used to detect micro cracks affecting PV modules. The experiment was carried out on ten different PV modules installed at the University of Huddersfield, United Kingdom. The examined PV modules which contains micro cracks shows large loss in the output power comparing to the theoretical output power predictions, where the maximum power loss is equal to 80.73%. LabVIEW software was used to simulate the theoretical output power of the examined PV modules under real time long term data measurements.

1. Introduction: Cell cracks appear in the photovoltaic (PV) panels during their transportation from the factory to the place of installation. Also, some climate proceedings such as snow loads, strong winds and hailstorms might create some major cracks on the PV modules surface [1-3]. These cracks may lead to disconnection of cells parts and, therefore, to a loss in the total power generated by the PV modules [4].

There are several types of cracks that might occur in PV modules: diagonal cracks, parallel to busbars crack, perpendicular to busbars crack and multiple directions crack. Diagonal Cracks and multiple directions cracks always show a significant reduction in the PV output power [5].

Moreover, the PV industry has reacted to the in-line non-destructive cracks by developing new techniques of crack detection such as resonance ultrasonic vibration (RUV) for screening PV cells with pre-existing cracks [6]. This helped to reduce cell cracking due to defective wafers, but, it does not mitigate the cracks generated during the manufacturing process of PV modules.

When cracks appear in a solar cell, the parts separated from the cell might not be totally disconnected, but the series resistance across the crack varies as a function of the distance between the cell parts and the number of cycles for which module is deformed [7]. However, when a cell part is fully isolated, the current decrease is proportional to the disconnected area [8, 9].

Collecting the data from damaged PV modules using installed systems is a challenging task. Electroluminescence (EL) imaging method is used to scan the surface of the PV modules, the light output increases with the local voltage so that regions with poor contact show up as dark spots [10, 11]. The thermography technique is simpler to implement, but the accuracy of the image is lower than with the EL technique, and does not allow the estimation of the area (in mm2) that is broken in the solar cells [12, 13]. Therefore, in this paper we have used EL imaging method which can be illustrated and discussed briefly in the following articles [14-16].

As proposed in [17 & 18] the performance of PV systems can be monitored using proprietary software such as LabVIEW. Also MATLAB software allows users to create tools to model, monitor and estimate the performance of photovoltaic systems. The simulation tool is important to compare the output measured data from PV module with its own theoretical performance.

There are a few statistical analysis tools that have been deployed in PV applications. The common used tool is the normal standard deviation limits (± 1 SD or ± 3 SD) technique [19]. However a statistical local distribution analysis in identifying the type of cracks in a PV modules has also been used [20]. In order to differentiate between a foreign object affecting the PV panel and micro crack, EL lab experimental setup was carried out for the investigation of PV micro crack affect. In practice, PV solar cells cannot be easily classified as cracked cells unless using some imaging techniques such as EL, thermal and fluorescence.

The main contribution of this work is the development of an electroluminescence imaging system which can detects micro cracks in PV modules. Additionally, a comparison between the theoretical output power vs. the PV cracked output power was carried out on various PV modules under real time long term data measurement.

2. Electroluminescence Setup: The electroluminescence system developed is presented in Fig. 1. The system is comprised of a light-tight black-box where housed inside is a digital camera and a sample holder. The digital camera is equipped with a standard F-mount 18–55 mm lens. To allow for detection in the near infrared, the IR filter was removed and replaced with a full spectrum window of equal optical path length. In our setup a Nikon D40 was used, but in principle any digital camera with similar grade CCD or CMOS sensor and where the IR filter can be removed would serve the purpose. The bias was applied and the resultant current and the voltage are measured by a voltage and current sensors which are connected to the personal computer (PC).

3. Electroluminescence Imaging: In order to reduce noise and increase the accuracy all the EL images are processed by removing background noise and erroneous pixels. Firstly a background image is taken under the same conditions as the EL images but without forward biasing the cell. This background image is subtracted from each EL image in order to reduce noise. The images are cropped to the appropriate size and in the case of the high resolution imaging system cell images are compiled together to form an image of the entire module. Additionally, to increase the accuracy and the vision of the EL image, each PV module cell is captured separately because the El image was captured using low cost camera.

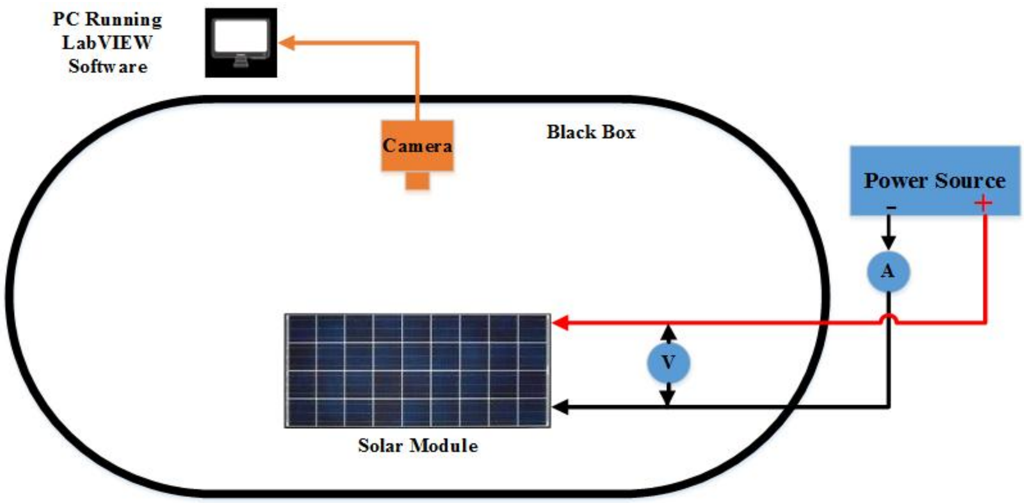


Fig. 1 Electroluminescence experimental setup

4. EL Image under Various Bias Levels: To identify the bias voltage and the current on the PV module. Firstly, the PV module main electrical characteristics must be identified. In this paper SMT 60(P) PV module is used, the module main characteristics are shown in Table 1.

The PV cells of the examined PV module was biased at various levels. The voltage and current bias ranges from a forward current of about 10% of the module Isc to just over 110% Isc. Fig. 2 shows El image of a single PV cell at different bias levels. As can be noticed, at low current levels, the solar cell has mush lower intensity comparing to a high bias level. Additionally, the solar cell features become more prominent at higher bias levels which could potentially be related to the series resistance across the PV cells.

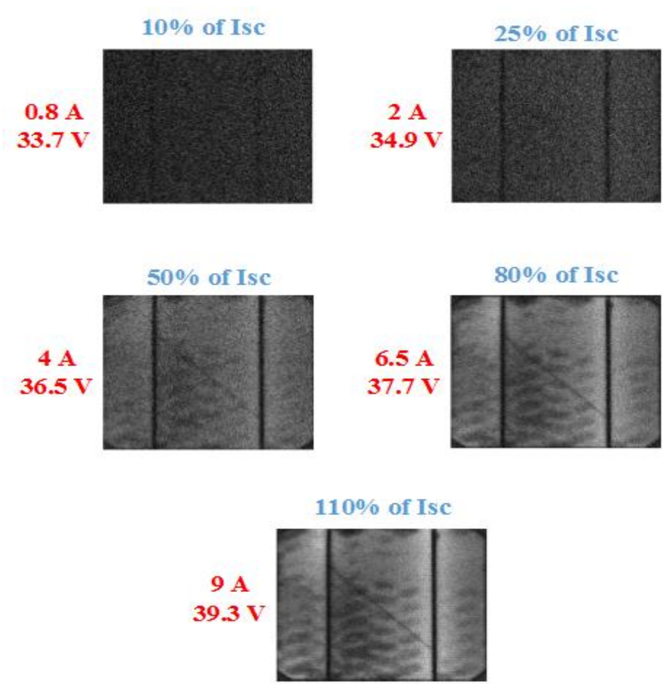


Fig. 2 EL image of a single PV cell at different bias levels

Table 1: Electrical Characteristics of SMT6 (6) P PV Module

Solar Panel Electrical Characteristics	Value
Peak Power	220 W
Voltage at maximum power point (V_{mpp})	28.7 V
Current at maximum power point (I_{mpp})	7.67 A
Open Circuit Voltage (V_{OC})	36.74 V
Short Circuit Current (I_{sc})	8.24 A
Number of cells connected in series	60
Number of cells connected in parallel	1
R_s , R_{sh}	0.48 Ω , 258 Ω
dark saturation current (I_o)	2.8×10^{-10} A
Ideal diode factor (A)	0.9117
Boltzmann's constant (K)	1.3806×10^{-23} J.K^{-1}

5. Examined PV Modules: In this research, ten different PV modules have been examined under various environmental conditions. Fig. 3 shows the PV installation and the real time long term data logging system which contains LabVIEW software. The PV modules were installed at the cite 7 years ago. All PV modules have the same output characteristics as shown previously in Table 1. In addition, all PV modules were affected by the same environmental conditions.

Each PV module is connected separately though the PV software. Where the load use across each PV module is equal to 3.74 Ω. The resistive load value was chosen according to the calculation of the maximum power point voltage and current as shown in (1).

$$R_L = V_{mpp} / I_{mpp} \quad (1)$$

$$R_L = 28.7 / 7.67 = 3.74\ \Omega$$

Before examining the cracks in the PV modules, a real time long term data measurements are taken to compare the output power performance of the PV modules vs. the theoretical predictions simulated using LabVIEW software. This test was made to investigate the degradation level of the power in each PV module separately. Therefore, it can be used as an indicator if there is a real damage (cracks) in the PV module or not before going to the next step (EL imaging technique).

The output power of each PV module under real time long term environmental conditions is shown in Fig. 4. As can be noticed that PV modules 1, 2, 3, 5, 6, 8, 9 and 10 has almost the same output power during the test comparing to the theoretical output power which has been simulated using LabVIEW software. The value of the power has been simulated according to the value of the temperature and irradiance sensors which are available from Davis weather station placed next the PV system as shown in Fig. 3. There is a slightly difference in the output power of the PV modules since there is no maximum power point tracking (MPPT) units used with each PV module separately.

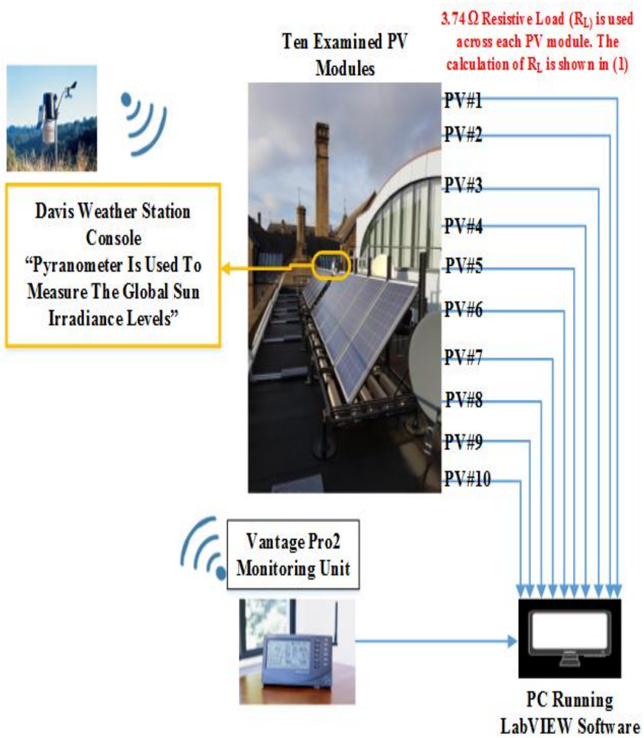


Fig. 3 Examined PV modules under various environmental conditions – PV installation age: 7 years

Furthermore, the measured output power of PV4 and PV7 shows a large amount of reduction in the power comparing to the theoretical predictions. Fig. 5 demonstrates the measured data of PV4 and PV7 vs. the theoretical simulated power. The measured and theoretical output power presented in Fig. 4 and Fig. 5 are taken from averaging 60 samples, each sample is taken at 1 second interval.

According to Table 2, the efficiency of the PV4 and PV7 is equal to 85.43% and 80.73% respectively, where the efficiency is calculated using (2). The minimum calculated efficiency for all other tested PV modules is equal to 97.18%. These results indicates that there is a large reduction in the output power for PV4 and PV7. The calculated efficiency shown in Table 2 are taken from averaging the data samples of each PV module over one day period of time.

$$Efficiency\ (\%) = (P_{measured} / P_{Theoretical}) * 100 \qquad (2)$$

Table 2: PV output power efficiency %

PV	Efficiency %
PV1	98.17
PV2	98.10
PV3	97.18
PV4	**85.43**
PV5	98.97
PV6	97.69
PV7	**80.73**
PV8	97.38
PV9	97.85
PV10	98.25

6. EL image for PV4 and PV7: In order to evaluate the degradation of the PV panels associated to PV4 and PV7, EL images of cracks solar cells have been captured. Since the camera used in this work supports a low cost experimental design, it has been decided to take the EL image of the solar cells individually since it provides more resolution and focus on the PV cracks.

Fig. 6(a) and Fig.6 (b) shows the EL image of the cracked solar cells combined with the real image of the whole tested PV module 4 and 7 respectively.

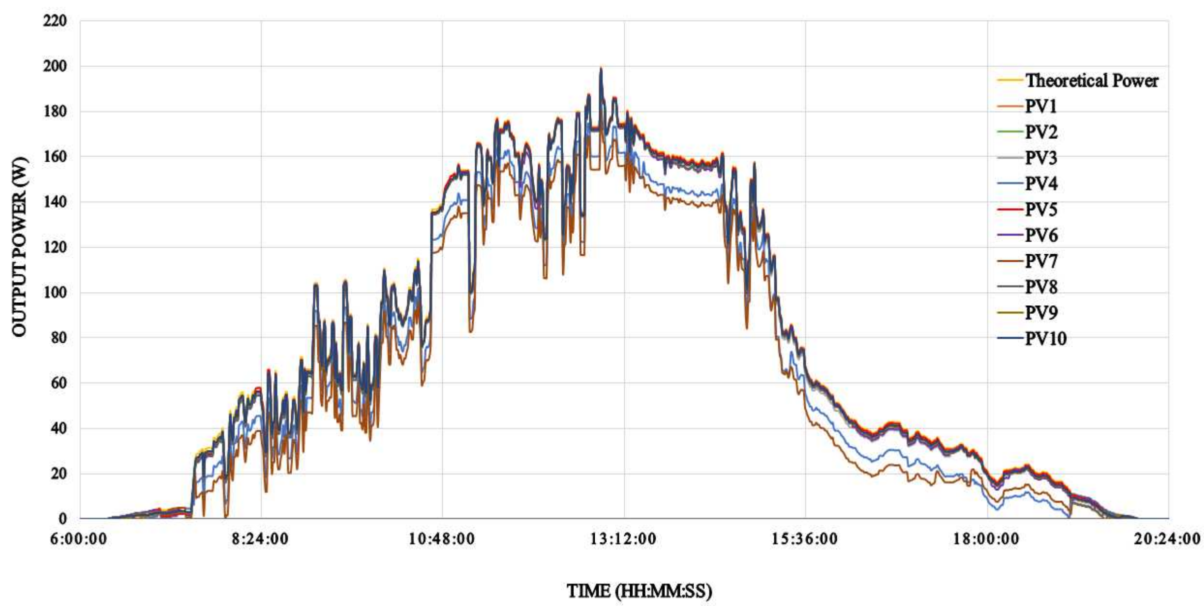


Fig. 4 Measured output power of each examined PV modules vs. theoretical output power

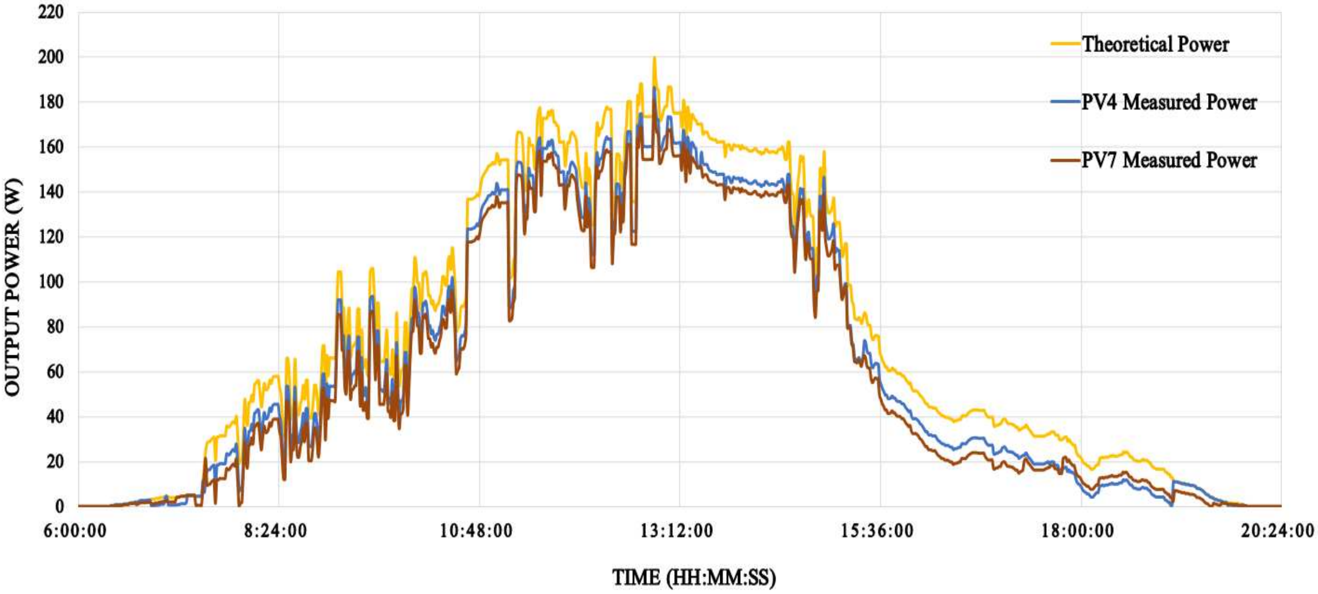


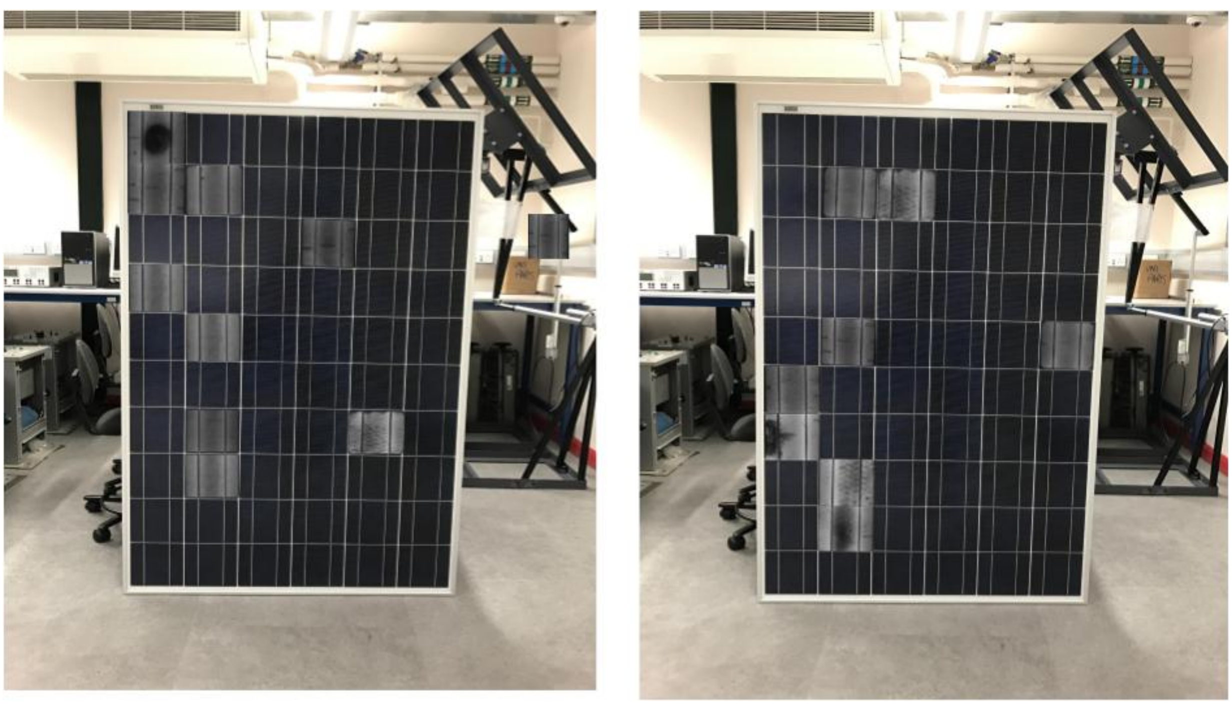
Fig. 5 Measured output power for PV4 and PV7 vs. theoretical output power simulated using LabVIEW software

9 solar cells out of 60 have been affected by micro cracks in PV module 4. There is a large damage on the top left solar cell of the PV module, this big damage in the PV solar cell affects the total amount of current flows from the PV module. Therefore, as illustrated previously in Table 2, the output efficiency of the PV module is equal to 85.43%.

The degradation in the PV output power might get worst if the PV module kept effected by various environmental conditions such as change in the humidity, wind speed, temperature variations and PV partial shading conditions.

PV module 7 contains only 8 solar cells out of 60 which are effected by micro cracks. These micro cracks reduces the amount of power generated by the PV module up to 19.27%. This reduction of the PV output power could be enhanced by replacing the cracked PV solar cells or adding a bypass diode in parallel with the solar cells PV string.

On the whole, this section shows that the degradation of the PV output power of the PV modules could be examined using a simple/reliable EL imaging technique to examine the PV solar cells which are effected by micro cracks.



(a) (b)

Fig. 6 EL images of cracked solar cells combined with the real images of the examined PV modules
(a) PV4 - output efficiency 85.73%
(b) PV7 - output efficiency 80.73%

7. Discussion and Conclusion: This paper analyzes the impact of micro cracks on the performance of photovoltaic (PV) modules. Electroluminescence (EL) technique was used to examine the micro cracks in the PV modules.

The main contribution of this paper is the examination of ten different PV modules under real time long term environmental conditions and the impact of micro cracks on the overall output power performance of each PV module separately.

The results obtained by this research shows that two tested PV modules have large reduction in the output power due to the impact of micro cracks affecting various solar cells. The minimum and maximum calculated output power efficiency of the PV modules is equal to 80.73% and 99.97% respectively.

The efficiency of the PV module is not directly related to the number of micro cracks affecting the PV panel, some micro cracks have a remarkable degradation on the measured output power due to the crack size, location and the PV age of operation. As an example, the examined PV7 has lower output power efficiency comparing to PV4, however, the number of PV solar cells which are affected by micro cracks is less than PV4.

PV micro cracks could be avoided or reduced by taken into account a risk assessment before the shipment of the PV modules into the site. In addition, arranging a regular visit to the PV filed to check dust, wires, converters, and micro-inverters could be beneficial to avoid PV micro cracks. Finally, there are few environmental conditions which are hard to be avoided such as the humidity and temperature variations among the PV modules which result a PV micro cracks.

8. Acknowledgments: This work was supported by School of Computing and Engineering, University of Huddersfield, United Kingdom.

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