Accessing the Performance of Individual Cells of Fully Encapsulated PV Modules Using a Commercial Digital Light Processing Projector

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Abstract

Accessing the electrical parameters of individual cells in fully encapsulated photovoltaic (PV) modules can be a cumbersome and time-consuming procedure. It usually requires mechanical shading, which is achieved by using meshes. This limits the control and variability of shading, as there is always a limited variety of mesh patterns available. In this work digital projection technology is utilised as the light source to achieve this. Partial shading can be applied rapidly and performance parameters of individual cells in fully encapsulated modules can be acquired. This is demonstrated in this work using a custom mini module. Individual cells can be accessed even in the case that bypass diodes are included. Performance information of individual cells acquired with such a system can be used for studying upscaling losses or degradation mechanisms for commercial or research PV modules.

Introduction

Efficient encapsulation of commercial PV modules is an essential feature, given that they are continuously exposed for decades to potentially damaging operating climates. However, this means that individual cells in a PV module cannot be directly accessed or modified in any way without damaging the encapsulation of the module. This inhibits any direct measurement of the operational parameters of individual cells in PV modules and thus potential identification of cell level faults and degradation mechanisms. Imaging methods, such as electroluminescence (EL) and photoluminescence (PL), can provide spatial information of cells in a module, although the information is not quantitative and does not represent actual operating conditions. A PV module's performance is usually limited by the least efficient of its constituent cells, and underperforming cells reduce the total output power but can also generate damaging overheating effects.

Several attempts have been made already to access parameters of individual cells in encapsulated PV modules, mainly by applying mechanical shading on individual cells, while illuminating the rest of the module and acquiring a series of I-V curves [1][2]. The partial illumination of the cell under test ensures that the current of the specific cell is the limiting current of the module [3]. The downside of such schemes is the cumbersome procedure of manual mechanical shading. Mechanical shading is usually applied using meshes that shade the cell under test, while measurements are implemented using a solar simulator or natural sunlight. Measurements are time consuming and there are limitations on the control and variability of shading, as there is always a limited variety of mesh patterns available.

In this work, a commercial digital light processing (DLP) projector is utilised to generate partial shading patterns in order to access the performance of individual cells in PV modules. DLP projectors utilise digital micromirror devices (DMD) [4] to generate the required projections. This feature can provide much faster shading patterns, higher variability and better control of shading. By applying specific shading strategies and acquiring I-V curves of the module, the performance of individual cells is accessed, even in the case of bypass diodes. As an additional application of this approach, current mapping of individual cells is applied using these digital shading strategies and utilising compressive sampling [5].

Experimental Setup

The digital projector used for this work is a commercial Acer P7605 DLP projector with a 370W metal halide lamp, generating a brightness of 5000 ANSI lumens. Nevertheless, the average absolute value of the irradiance on the sample plane is approximately 30W/m^2. This is significantly lower than what is used in standard test conditions for PV modules (1000W/m2), but

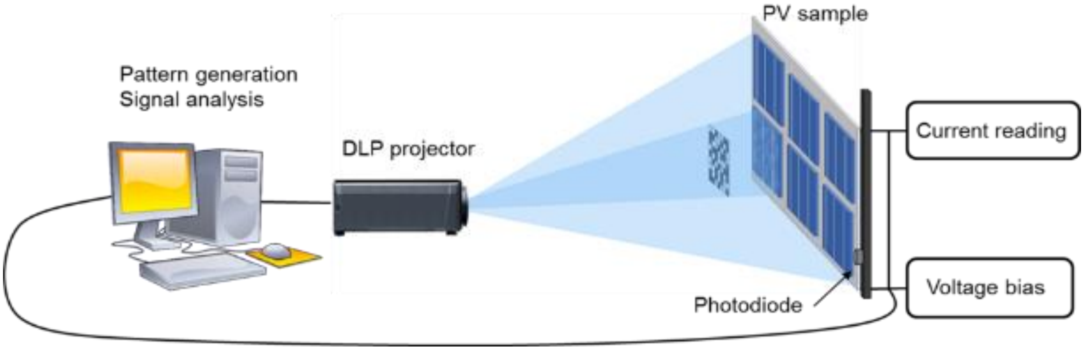

Fig. 1. The experimental layout. An image is projected on the PV device. A part of it covering a single cell includes the specific pattern for shading while the rest of the cells are fully illuminated.

it is sufficient for acquiring. The long term stability of the light source is monitored simultaneously with the measurements, using a photodiode installed next to the PV sample under test. A Keithley 2420 sourcemeter is used for voltage bias and the current response is measured with a NI DAQ card.

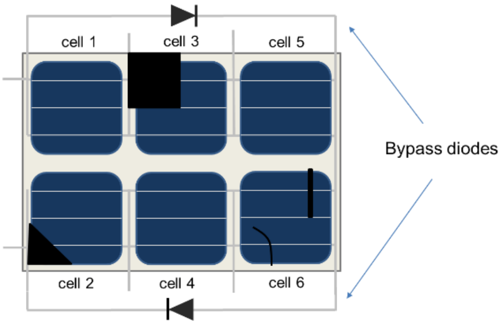

Fig. 2. The custom 6-cell mini module.

A custom mini PV module is used in this work, produced at CREST. This is a 6-cell crystalline Silicon (c-Si) mini module with all terminals of each individual cell extended to the outside of the encapsulation. This allows direct contact with each cell, as it can be observed in Fig. 2. Removable bypass diodes are also attached to the module, to simulate commercial products. Synthetic features are inserted by covering small areas of specific cells with different shapes in order to alter the performance of individual cells as presented in Fig. 2.

Results

The projection system offers the opportunity to set very precise shading levels on individual cells while fully illuminating the remainder, which is something very useful for this investigation. I-V curves of the PV module were acquired with and without connecting the bypass diodes. As a first step, the by-pass diodes were disconnected and a sequence of 10 patterns with increasing levels of shading is applied to one of the cells while the rest are fully illuminated. I-V curves of the module for each shading level are acquired. This means that for the first I-V curve the cell is completely shaded (all pixels dark for this cell) while the last I-V curve is the same in all cases, as there is no shading at all. The I-V curves for the module when cell 3 (large 'defect') is gradually shaded is presented in Fig. 3. For the graph of 50% shading of specific cells, while illuminating the rest, the maximum current depends on the performance of the individual shaded cell.

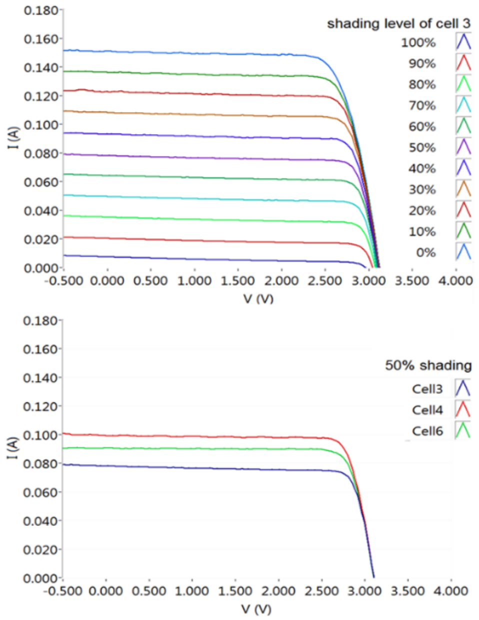

Fig. 3. On top, I-V curves of the PV module, acquired by shading cell 3 with different levels of shading. Bottom, I-V curves of the module for 50% shading for 3 different cells.

When by-pass diodes are installed as shown in Fig. 4, the I-V curves differ significantly from the case when all the cells are series connected. Following the same procedure as before, gradually shading the same three cells, the results of Fig. 4. are acquired. It is noteworthy that even with no shading, the bypass diodes are activated. This is due to the masks that have been applied on some of the cells, resulting in current mismatches, which activate the by-pass diodes.

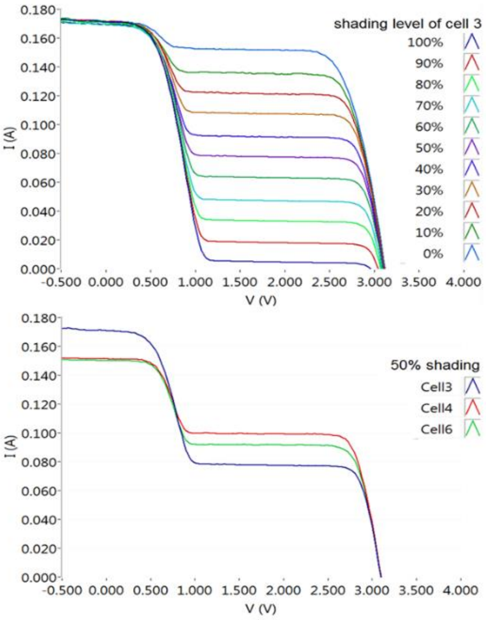

Fig. 4. On top, I-V curves of the PV module, acquired by shading cell 3 with different levels of shading. Bottom, I-V curves of the module for 50% shading for 3 different cells.

In order to reduce the effect of the bypass diodes, an additional shading strategy is adopted. Since there are three cells in each sub-string with a by-pass diode, by adjusting the projection pattern on the PV module one string is completely shaded, while the sub-string that includes the cell that is measured is properly illuminated. The shading patterns are projected on the cell under test and the rest of the cells of this specific sub-string are fully illuminated. The procedure is illustrated in Fig.5.

Applying the above shading strategy, the previous procedure for acquiring I-V curves is followed. The results are presented in Fig. 6. The influence of the non-illuminated sub-string is almost negligible and it is barely visible, very close to the horizontal axis, where a very low current exists for voltage values higher than 1.1V. If this region is not considered, the I-V curves resemble those that would be acquired from a 3-cell mini module, with a small voltage drop. It is apparent that the current of the I-V curve in this instance depends on the performance of the cell of interest. Using this methodology, all the cells of a module can be sorted according to their performance.

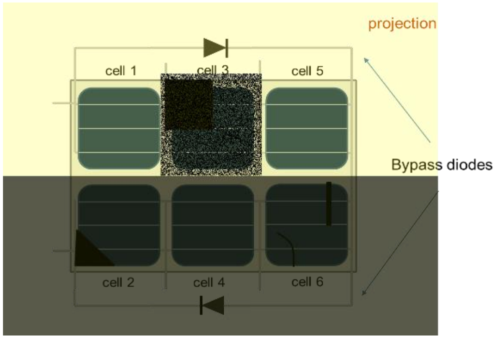

Fig. 5. The patterns are projected on the cell under test and the rest of the cells of this specific sub-string are fully illuminated, while the other sub-string is completely shaded.

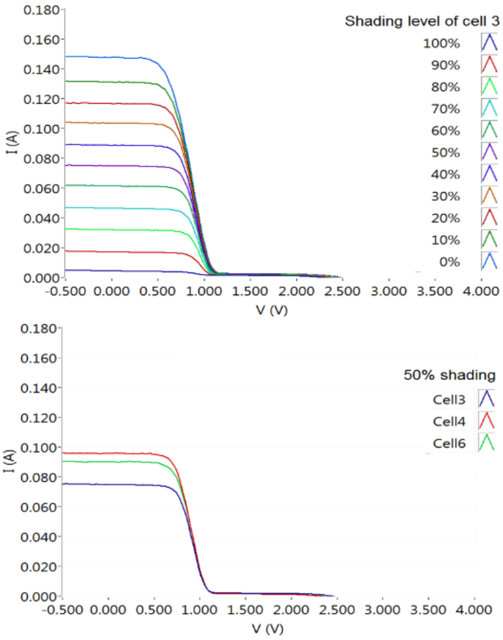

Fig. 6. On top, I-V curves of the PV module, acquired by shading cell 3 with different levels of shading. Bottom, I-V curves of the module for 50% shading for 3 different cells.

As an application of the above strategy when bypass diodes are present, Compressed Sensing (CS) current mapping measurements [6] are implemented. A forward voltage bias of 0.6V is applied during measurements. This value was selected by considering the I-V curves of Fig.6. The illuminated cells of the module produce a voltage of around 1V, hence, by choosing a forward bias of 0.6V the cell under test is operating very close to short-circuit conditions. This approach also shows that by acquiring the above I-V curves before current mapping measurements, one can reveal which cell underperforms and how much compared to the rest of the cells. Such tests are implemented in seconds, the cells can be sorted depending on their performance and the correct forward voltage bias levels for the CS current mapping procedure can be chosen. More importantly, with this procedure the correct shading level can be chosen for the patterns used for compressive sampling [6]. This is necessary to ensure that the patterns will shade the cells to a lower level than the output of the worst performing cell.

Following the procedure of Fig.6. for all cells of the mini module with the by-pass diodes installed, the current map shown in Fig. 7. is acquired, for an under-sampling level of 50% (30000 measurements, 60000 pixels). In the same figure, a photograph of the module during measurements is also presented. Measurement results are rather noisy, mainly due to low irradiance and light source instability. Nevertheless, meaningful measurements are acquired and current mapping of a PV module with by-pass diodes can be achieved, even with this low resolution.

In these series of experiments a simple commercial projector was used. For increasing measurement accuracy and speed, a custom projection system dedicated for this application would be optimal.

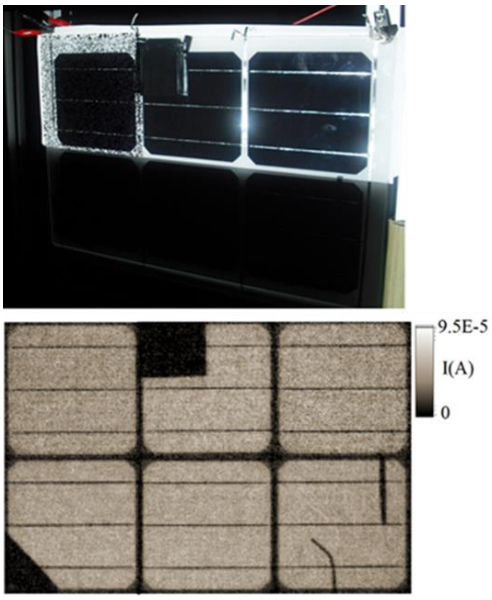

Fig. 7. On top a picture of the PV module with the attached masks, during measurements. At the bottom, a CS current map of the PV module with by-pass diodes, with 50% under-sampling.

Conclusion

A projection based methodology for PV module characterisation is presented in this work. Established methods to access individual cells, previously implemented with mechanical manual shading can be now applied in a straightforward way, much faster and without the need for any mechanical components. Performance information of individual cells is extracted using I-V curves of the PV module, while also current maps of the module can be acquired using compressed sensing techniques. Such a projection system can become a useful tool for accessing individual cells in PV modules, for investigating upscaling losses of new technologies or for studying degradation mechanism of PV modules.

Acknowledgments

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