Compressed Sensing Current Mapping of PV Devices Using a DLP Projector

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Abstract

A commercial Digital Light Processing (DLP) projector has been utilised for compressed sensing current mapping of photovoltaic (PV) devices. Through the projector, the necessary patterns are projected to apply compressive sampling for measurement acquisition. The reconstruction of the current map is achieved by an optimisation algorithm. The main advantage of this method is that measurement time is significantly reduced, compared to conventional LBIC measurement systems. This is achieved mainly by acquiring fewer measurements than a raster scan would need. Initial current maps of cells and modules have been acquired, showing the feasibility of the method. The issues of such a system have been investigated and its potential for fast and simple current mapping of PV modules is demonstrated.

Introduction

Current mapping of photovoltaic (PV) devices is essential for accessing the local electrical properties of samples. This is usually achieved by the light beam induced current (LBIC) measurement method, which is a non-destructive technique that provides spatial information of the electrical properties of PV devices [1]. The main difference with electroluminescence (EL) imaging [2] is that with the LBIC method information is acquired in an energy range slightly above the band-gap energy. At this range the quantum efficiency is still close to its maximum, closer to the actual operating conditions of PV devices in the field. Furthermore, wavelength can also be selected to probe different depths in devices. On the other hand, the main disadvantages of LBIC systems are long measurement times and complicated experimental setups.
Recently, an alternative method for current mapping of PV devices was proposed, based on the application of the compressed sensing (CS) sampling theory on LBIC measurements [3]. The CS sampling theory suggests that an N element signal can be measured by acquiring K observations, where K<<N [4][5]. With the standard LBIC method a point by point scan is performed by a light beam, reading the current response at every point to acquire the current map. When using CS imaging a series of predefined patterns is projected on the sample. The current response is measured for each pattern and the final current map is acquired applying an optimisation algorithm. The main advantage of this technique is that much fewer measurements are required in order to reconstruct the final current map, than in standard LBIC measurements. This can lead to significantly shorter measurement times for current mapping.
This technique has already been successfully applied to small area devices [3]. The initial small area experimental setup utilised a digital micromirror device chip (DMD) [6] in an optical system. The sampling patterns were generated by the DMD for the realisation of compressive sampling. Reliable current maps have been produced by acquiring just 40% of the measurements a standard LBIC system would need.
In this work, a digital light processing (DLP) projector is utilised for CS current mapping of PV devices, as it provides a perfect means to project the necessary patterns. Point by point current mapping using a DLP projector has already been proposed [7]. DLP projectors are also based on a DMD chip, which actually creates the projection. Its fast response time, which is shorter than 20μs, combined with the reduced number of measurements required, provides the potential to reduce current mapping time by at least an order of magnitude, compared to a standard LBIC system. In addition, using the proposed system current maps of cells in encapsulated modules can be acquired. This can be achieved by

projecting patterns on the cell under measurement while light biasing the rest of the cells at the same time, following the principles already described in [8].

Compressed Sensing Current Mapping

In order to apply CS for acquiring measurements, a series of test functions $\{\varphi_m\}_{m=1}^{M}$ have to be projected on the PV device. Random binary matrices of ones and zeroes can be used as patterns, as they are easy to implement and satisfy the requirements for compressive sampling [9]. For every projected pattern the current response of the PV device is measured, populating the measurement vector **y**. Since the projected patterns are known, constructing sensing matrix Φ, the solution to the underdetermined problem is the **x** vector with the minimum ℓ1 norm [10].

$$\hat{\mathbf{x}} = \mathrm{argmin}\|\mathbf{x}\|_1 \text{ subject to } \Phi\mathbf{x}=\mathbf{y} \quad (1)$$

With this method, current maps can be acquired with much fewer measurements than what a raster scan would require.

Experimental Setup

The projector selected for this work is a commercial Acer P7605 DLP projector with a 370W lamp. It is a reasonably high intensity projector, capable of generating a brightness of 5000 ANSI lumens. The key advantage of DLP technology is the high contrast ratio, which was extremely important for this series of experiments. It allows the system to generate a black pixel equivalent to a masked shaded spot on the PV module.

The basis of DLP projectors technology is the use of a beam of white light generated by the lamp. The beam is collimated and divided into its red, green and blue spectrum by a colour filter wheel. The micro-mirrors of the DMD operate at a frequency much higher than the human eye can perceive. At the same time, the colour wheel is synchronised with the DMD and the colours are displayed at a very high rate so that eventually only the final combination of colours can be observed. This operation may be well suited for usual projection utilities, but creates significant spectral and temporal variations of irradiance for PV characterisation. In order to overcome this limitation, the colour wheel of the projector was removed from the light path. As a result the projector only projects in black and white, the spectrum being the stable spectrum of the lamp.

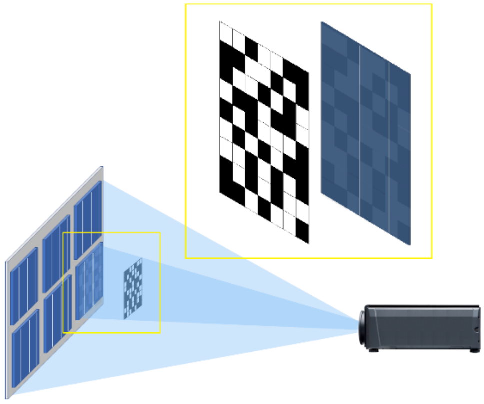

Figure 1: The experimental layout. An image is projected on the PV device. A part of it covering a single cell includes the specific pattern for compressive sampling while the rest of the cells are fully illuminated.

The aim of the proposed system is to demonstrate the feasibility of CS current mapping with a DLP projector, for both single PV cells and PV modules. For the case of PV modules particularly, the patterns are projected on the cell under measurement while the rest of the cells are light biased. This is necessary to ensure the cell under measurement is the limiting cell of the module [8]. As a result, the current measured at the contacts of the module is the current of the cell under test. The layout of the experimental setup is presented in figure 1. Following this method, current maps of full modules can be acquired with this simple setup.

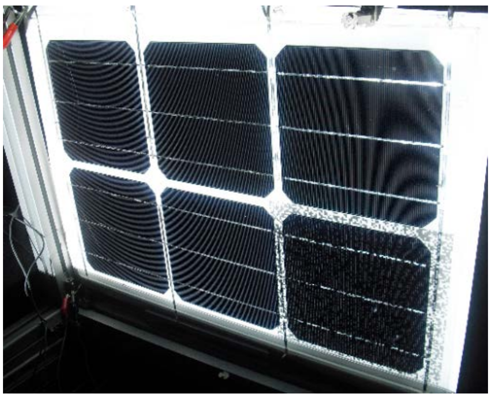

Figure 2: The 6-cell mini module used for these experiments. Patterns are projected on one of the cells (bottom right cell) while the rest are light biased.

This work uses the standard laminate size modules used for ageing experiments at CREST. These are 6-cell crystalline Silicon (c-Si) mini modules which are produced in-house. All terminals of each individual cell were extended to the outside of the encapsulation, allowing direct contact with each cell. This alternative operation allows a robust validation of measurements results.

Although the projector is controlled through LabView environment, there is not absolute control of the internal DMD chip of the projector. The micromirrors that create the projections still turn on and off at a rate faster than 20μs, inserting temporal variations of irradiance on the sample. Fortunately these variation are periodic, with a period of approximately 4ms, shown in figure 3. Thus, current readings were acquired with an integration time of multiples of this period, to minimise measurement noise.

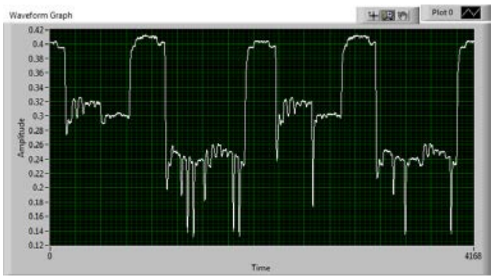

Figure 3: Variations of intensity due to the fast independent switching of the internal DMD chip, over one period.

Results

As a first step, current maps of a single c-Si cell were acquired to test the functionality of the system. Acquired current maps are presented in figure 4. The percentages is the ratio of measurements acquired, by the total number of pixels of the current map. Random patterns are used for compressive sampling, while the ℓ1 magic solver is used for reconstruction. Although the resolution is not high enough to distinguish the fingers of the cell, the busbars are clearly visible, which shows that the method is feasible. In order to reconstruct the current map, fewer measurements that the pixels of the current map are needed. This is the most significant advantage of CS current mapping. In addition, as the pattern illuminates half of the cell, a high signal to noise ratio is achieved.

The next step is to test if CS current mapping of PV modules is feasible with such a simple system based on a DLP projector. The module used consisted of c-Si cells of the same type. Every cell was sampled with the necessary patterns consecutively, while the rest were fully illuminated. The resolution achieved in these results is approximately 1.5mm.

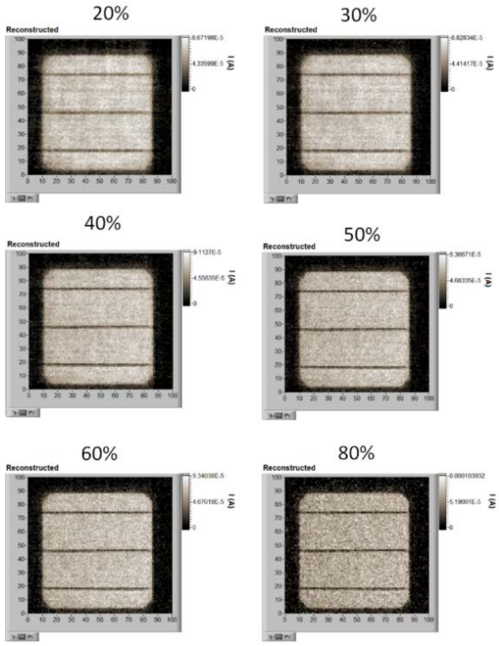

Figure 4: CS current maps of a single c-Si cell. Number of measurements is expressed as a ratio of number of measurements acquired by the number of pixels of the images.

A reconstructed CS current map of the 6-cell PV module is presented in figure 5. 50% of measurements were acquired, compared to the pixels of the current map. Results still contain a significant amount of noise, due to the temporal variations of light intensity. Due to the large integration time for every measurement, total sampling time was 6 hours (1 hour for every cell). Reconstruction time is approximately one minute, which is a negligible amount compared to actual measurement time.

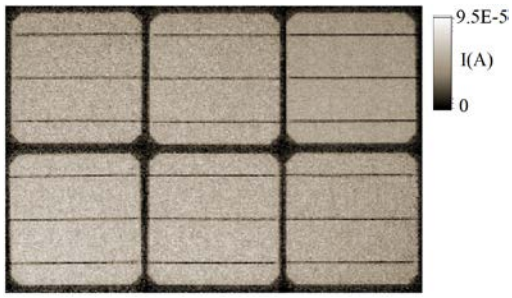

Figure 5: CS current map of the 6 cell PV module used in these experiments. The SC current map is produced having acquired 50% of measurements.

Any commercial projector will produce temporal variations of illumination, as there is not absolute control on the internal DMD. This inserts noise in the measurements but also makes sampling much slower, as a large integration time is used. To achieve higher resolution, faster and more accurate results, a custom built DLP projector measurement system is necessary. A custom system would include the DMD chip, a high power collimated light source and a projection lens. High power lasers can be used instead of lamps to provide a single wavelength system. A sampling rate of 10 or 30 patterns per second with such a system will also boost measurement speed. Such a value of sampling rate is feasible, considering the high signal to noise ratio of the system and the switching speed of the DMD chip that generates the patterns.

Conclusions

A projection based current mapping system is being developed at CREST that utilises CS for current mapping of PV devices. The aim of this system is to provide a faster, significantly simpler and inexpensive tool for current mapping of PV cells and especially modules. Current maps of individual PV cells can be acquired even in encapsulated modules, making this a useful tool for crystalline silicon based or thin film PV modules.

Experimental results demonstrated that a DLP projector based CS system is feasible. More specifically, a CS current mapping system based on DLP projection technology could provide a realistic solution for current mapping of PV modules. On the other hand, the prototype system cannot achieve very high accuracy and resolution by using a commercial DLP projector. A custom system will provide more control and will be able to reduce temporal variations of light intensity and provide higher accuracy.

Acknowledgements

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