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Quantitative estimation of electrical performance parameters of individual solar cells in silicon photovoltaic modules using electroluminescence imaging

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ABSTRACT

An analysis routine, based on electroluminescence (EL) imaging is presented for the quantitative determination of electrical performance parameters of individual crystalline silicon solar cells within a photovoltaic (PV) module. Specifically, the series resistance and dark saturation current density of individual solar cells are extracted, providing an in-depth diagnosis of PV module performance. The current-voltage (I-V) characteristics of the PV module can then be computed through solar cell one-diode modelling. By comparing the performance of the original module with that of a simulated module, where the solar cells with poor series resistance and dark saturation current density, are replaced by better cells, the potential performance improvement can be predicted. The technique is simple and enables a fast analysis.

1. Introduction

The global photovoltaic (PV) industry is dominated by crystalline silicon wafer solar cells and modules. For reliable PV system operation, it is important to perform periodic checks on the PV modules installed in the field, to assess their performance over time, pre-empt problems and diagnose issues that may arise in the course of their operation. Degraded PV module power output or complete module failure represent not just a power loss but also an income loss for the system owners (Köntges et al., 2014; Bigaud et al., 2010; Ndiaye et al., 2013). Reduced PV power generation can have origins in material defects, manufacturing, or damage (e.g. cell cracks) incurred during transport, installation and/or operation in the field (Koch et al., 2016; Lay-Ekuakille and Vergallo, 2013; Bhoopathy et al., 2018). The effects may be immediately apparent in initial field operation, or have a more latent nature and prolonged time frame as the PV modules are subjected to electrical, mechanical and thermal stresses (Berghold et al., 2009; Kontges et al., 2011). In the degradation analysis of PV modules, being able to quantify the performance of individual solar cells within a PV module would help in accurate problem diagnosis. For instance, cracks in individual silicon solar cells are a genuine problem for PV modules as they are hard to avoid and, so far, their impact on the efficiency of the module during its lifetime is difficult to quantify (Zafirovska et al., 2016; Kaplani, 2016; Sander et al., 2012; Mansouri and Zettl, 2012; Stoicescu and Reuter, 2014).

There are several characterization techniques to identify defects in PV cells and modules (Bhoopathy et al., 2018; Zafirovska et al., 2016; Kaplani, 2016; Sander et al., 2012; Mansouri and Zettl, 2012; Stoicescu and Reuter, 2014; Breitenstein et al., 2017; Guo et al., 2016; Peng et al., 2015; Johnston et al., 2016; Silverman et al., 2017; Rajput et al., 2016). Electroluminescence (EL) imaging is one of them and widely used to analysis defects and cracks (Breitenstein et al., 2017; Guo et al., 2016; Peng et al., 2015; Johnston et al., 2016; Silverman et al., 2017; Rajput et al., 2016). Moreover, it is possible to develop some useful guidelines to characterize modules with damaged cells and reduced power output.

Recently, performance parameters of single solar cells in a silicon PV module were determined using EL and dark lock-in thermography (DLIT) imaging. However, the calculated output power, fill factor and open-circuit voltages of the individual cells are very susceptible to systematic errors incurred during module temperature measurement. Also, this method requires a number of measurements, including EL images, corresponding thermal images and DLIT measurements, which makes this process rather tedious (Breitenstein et al., 2017). Using only EL imaging, degradation analysis was performed for a PV module that was deployed in the field for over 10 years (Guo et al., 2016). By constructing the dark current-voltage (I-V) curves using a series of EL images, maps of the series resistance (R_S) and dark saturation current density (J_0) of individual solar cells within a PV module can be

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computed. However, as several images have to be taken, each at a different forward current and with an acquisition time of 300 s, the process is time-consuming. A fast technique that is less sensitive to temperature changes but provides similar information would be desirable. In this work, we introduce a method that fulfils these criteria to study the impact of the performance of individual silicon solar cells on the overall PV module performance. The series resistance and dark saturation current density of each cell can be rapidly extracted with EL imaging, thereby allowing the identification of the good-, under- and bad-performing cells within the module. The approach builds upon previous work by Fuyuki et al. (2005), Haunschild et al. (2009). The detailed theoretical formulation of our method is elucidated in Section 2. Section 3 then describes the experimental details for application of the technique on actual PV modules for inspection. The limitations of the method are described in Section 4.

2. Theory

Degradation within a PV module can manifest as changes in electrical resistive properties. This may arise due to deterioration in individual solar cell properties (e.g. metallization related), and/or module level attributes (e.g. ribbon-busbar connection). Deterioration in semiconductor properties, for example material defects or cracks, can also occur and represent individual solar cell voltage losses or an increase in the dark saturation current density. The ability to resolve the effective series resistance $R_{S,i}$ and effective dark saturation current density $J_{0,i}$ for individual cells in a silicon PV module would be tremendously useful in module degradation studies. In this work, we demonstrate the rapid extraction of these parameters via EL imaging. Our technique is based on the principle proposed by Fuyuki et al. (2005) in which the calibration constant is proportional to the bulk diffusion length and Haunschild et al. (2009) which requires only two EL images to be taken, each at a different current bias to construct a series resistance map for a solar cell. For each bias, the terminal voltage V_T, current I and operating temperature T are measured.

In EL imaging, the local luminescence intensity $\Phi(r)$ is an exponential function of the local voltage $U(r)$, where r is the two-dimensional position vector.

$$\Phi(\mathbf{r}) = c(\mathbf{r})\cdot exp(U(\mathbf{r})/U_{Th}) \quad (1)$$

Here, $c(r)$ is the local calibration constant and U_{Th} is the thermal voltage. The dark local current density $J(r)$ (assumed positive) may also be described as an exponential function of $U(r)$ as:

$$J(\mathbf{r}) = J_0(\mathbf{r})\cdot exp\left(\frac{U(\mathbf{r})}{U_{Th}}\right) \text{for } U(\mathbf{r}) >> U_{Th} \quad (2)$$

To simplify our calculations, we use Fuyuki's linear approximation (Fuyuki et al., 2005) which proposed that $c(r)$ is proportional to the local effective diffusion length $L_e(r)$ and therefore inversely proportional to $J_0(r)$:

$$J_0(\mathbf{r}) = f/c(\mathbf{r}) \quad (3)$$

where f is assumed to be a constant over the range of applied electrical currents. The case of low forward bias conditions in EL imaging is first examined to derive parameters $c(r)$ and $J_0(r)$ that are considered to be independent of bias conditions. The Appendix provides further details of the derivation.

The case of higher forward bias conditions in EL imaging is then considered. The resulting higher voltage non-uniformity provides an avenue to examine series resistance effects of the solar cells. Considering that the cell terminal regions are where current is first injected and would have the highest voltage and hence the highest luminescence (Potthoff et al., 2010), the individual cell terminal voltage V_i is assumed to correspond to the highest luminescence intensities and can be calculated by Eq. (1) as $U(r)$ applied at these locations. In order to reduce the influence of noise-related outliers, the brightest

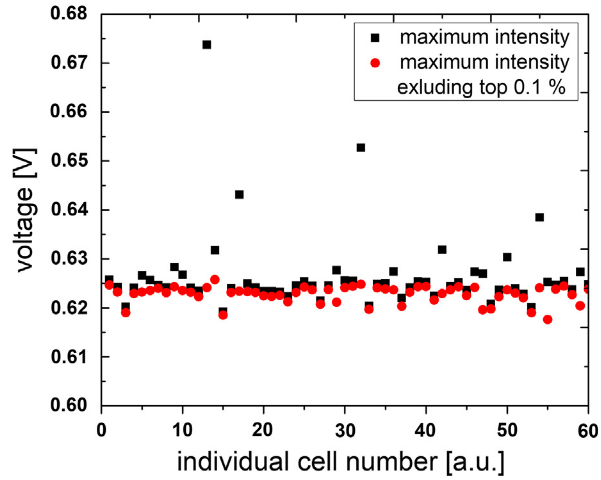

Fig. 1. Voltage distribution of individual cells extracted from EL imaging under high bias condition (I = 8A) as calculated from (i) pixel with maximum intensity and (ii) after exclusion of the top 0.1% of pixels.

0.1% of pixels in the EL image are excluded. Fig. 1 shows the comparison of the calculated voltage using the highest EL intensity and that after excluding the top 0.1% of pixels at high biasing condition for I = 8A for one of the PV modules examined in this work. It is found that by excluding the top 0.1% of pixels, the influence of noise is reduced without significantly affecting the analysis.

Computation of V_i and the spatial distributions of $U(\mathbf{r})$ and $J(\mathbf{r})$ from Eqs. (1) and (2) then allows $R_S(r)$ to be calculated:

$$R_S(\mathbf{r}) = \frac{V_i - U(\mathbf{r})}{J(\mathbf{r})} \quad (4)$$

The effective series resistance of the ith cell $R_{S,i}$ is taken to be the mean of the cell's $R_S(r)$ distribution. The overall procedure is summarized in the flow chart of Fig. 2.

After computing the $J_{0,i}$ and $R_{S,i}$ for each individual cell, the module I-V characteristics can be modelled. The one-diode model (Chin et al., 2015; Farivar and Asaei, 2010) is applied to each series-connected cell in the module. After changing the variables from local to global, the cell J-V characteristics is given by Eq. (5).

$$J = J_L - J_0\left[exp\left(\frac{V_i + JR_S}{nU_{Th}}\right) - 1\right] \quad (5)$$

where J_L is the light-induced current density, n is the ideality factor and V_i is the global cell voltage measured using Potthoff's method (Potthoff et al., 2010). Here, photocurrent is taken to be positive in contrast to Eq. (2).

Modelling of each individual cell requires the short-circuit current I_{SC} which is the same for all the series-connected cells, dark saturation current density $J_{0,i}$, and series resistance $R_{S,i}$ which are obtained as outlined in the preceding sections. To simplify our calculations, we

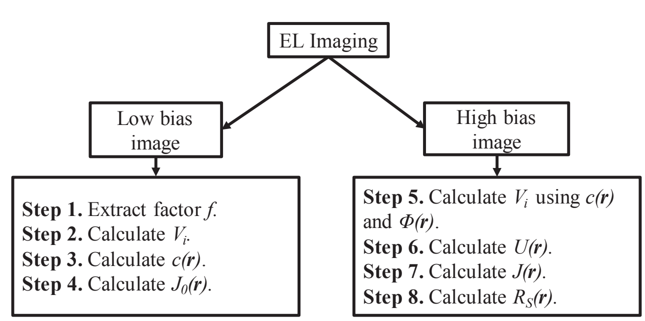

Fig. 2. Flow chart of the method proposed in this work.