PROPOSING AN ELECTRO-THERMAL SPICE MODEL TO INVESTIGATE THE EFFECT OF PARTIAL SHADING ON CIGS PV MODULES

J. Carolus[1,2], Z. Purohit[1,3], T. Vandenbergh[1], M. Meuris[1,2], B. Tripathi[3], and M. Daenen[1,2]
[1]Hasselt University, Martelarenlaan 42, 3500 Hasselt, Belgium
[2]imec, Kapeldreef 75, 3000 Leuven, Belgium
[3]Pandit Deendayal Petroleum University, Raisan, Gandhinagar, Gujarat 382421, India

ABSTRACT: Copper indium gallium (di)selenide (CIGS) photovoltaic (PV) modules are promising for building integrated PV (BIPV) applications because of their low weight to power production ratio. However, previous research shows that (partial) shading of a monolithically interconnected CIGS PV module can cause permanent damage to the shaded region of the module, even when the shading exposure time is very limited. [1, 2] This should be avoided in order to guarantee a 20 year life-span of the BIPV module. In this proceeding, we are investigating the impact of partial shading on CIGS PV modules. For this purpose, we are developing an electro-thermal SPICE model which maps the current density, voltage and temperature distribution of the CIGS PV module in case of shading. First simulations show a significant reverse bias over the partially shaded cell. Also interesting is the fact that the peak current density located in the non-shaded region of the partially shaded solar cell can be visualized. The model allows us to predict when a CIGS PV module may be permanently damaged in shading conditions and whether bypass diodes should be included or not.

1 INTRODUCTION

Since last decade, thin-film photovoltaic (TFPV) modules have been proven a highly efficient and cost competitive PV technology compared to most dominant PV technologies. [3] Due to its low weight to power production ratio, TFPV is interesting for building integrated PV (BIPV) applications. With the increasing demand of TFPV technologies, its long-term reliability and predictive modelling on its performance has gained a lot of attention. However, among various reliability issues, partial shading has drawn attention due to the permanent damage and its effect on the electrical performance of the PV module, even if the shading exposure time is very limited. [1, 4] In case one or more cells are shaded in a series connected configuration, the shaded cells will operate under a reverse bias, the shaded region now acts as a load to the rest of the PV module. This will force the shaded cells to go into breakdown if the voltage, and thus the number of in series connected cells, is high enough. Consequently, the solar cells material will be impacted and can cause immediate efficiency losses. In the present work, we briefly report the working principle of the electro-thermal model together with the first results. The experimental results show a significant deviation in electrical performance under partial shading conditions, whereas electro-thermal simulations allow us to visualize the distribution in electrical and thermal behaviour to predict the onset of failure of a CIGS PV module operating under partial shading conditions. The experimental results together with the simulation results will give us a better picture of the effect of shading on CIGS PV modules

2 EXPERIMENTAL

In this study, commercially available CIGS semi-fabricates on a glass substrate were encapsulated onto a glass front cover. The cells stack was composed out of a molybdenum (Mo) back contact, a CIGS absorber layer, a cadmium sulfide (CdS) buffer layer, an intrinsic zinc oxide (i-ZnO) passivation layer and an aluminium doped zinc oxide (ZnO:Al) front contact. The CIGS module contained 31 in series-connected solar cells of 14.5 x 0.4 cm2. In order to mimic (partial) shading of the CIGS PV module in the lab, opaque tape was used to cover one or more solar cells. To evaluate the electrical performance of the (partially) shaded module, dark and illuminated current-voltage (IV) measurements were performed at standard test conditions (STC). While conducting the dark IV measurements, in-situ infrared thermography was performed in order to investigate the reverse breakdown voltage of the solar cell.

3 MODEL DEVELOPMENT

The model is based on the single-diode model as described in:

$$I = I_L - I_0\left[exp\left(\frac{V+IR_S}{nV_T}\right)-1\right]-\frac{V+IR_S}{R_{SH}}$$

with I the current, I_L the photocurrent, I_0 the reverse saturation current, R_S the series resistance, R_{SH} the shunt resistance, n the ideality factor, V the voltage and V_T the thermal voltage. However, the integration of the monolithic interconnection, which can be simplified to a series and shunt resistance, respectively R_{Smod} and R_{SHmod}, is not included in this equation but are included in the model. Also the parameters for the reverse characteristics are not described in this proceeding.

Since the superposition principle with voltage-independent photocurrent does not comply with the experiments for CIGS PV modules as shown by Sun et al. [5], we limited our model to two states which can occur in one TFPV module: 1) fully shaded regions (0 W/m2) and 2) fully irradiated regions (1000 W/m2). For both the

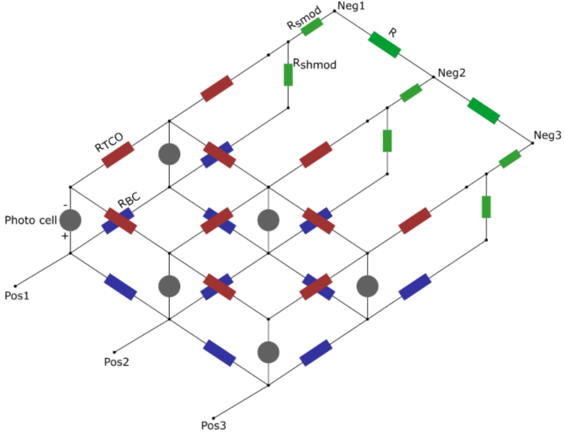

Figure 1 Visual representation of the topology of the pre-defined elements as included in the model together with the resistance of the back and front contact respectively shown as blue and red resistances.

shaded and illuminated solar cells. The parameters are extracted as included in the single-diode model. For simplicity, only the reverse behaviour was taken into account for the shaded cells and the forward behaviour for the illuminated cells. The pre-defined element approach we included in the model allows us to obtain a voltage, current density and temperature distribution over the PV module. For this purpose, each in series connected solar cell of the TFPV module is divided into a predefined number of finite elements. Each element is composed of a current source, a diode and a shunt resistance and connected to four adjacent elements by the series resistance of the top grid (TCO) and the series resistance of the back contact (Mo). This is shown in Figure 1, in which the elements and their electrical connections to their adjacent elements is shown. Next to the topology of the pre-defined elements, Figure 1 also shows the integration of the monolithic interconnection. Note that this figure represents only one cell divided in six pre-defined elements including the monolithic interconnection (shown as green resistances).

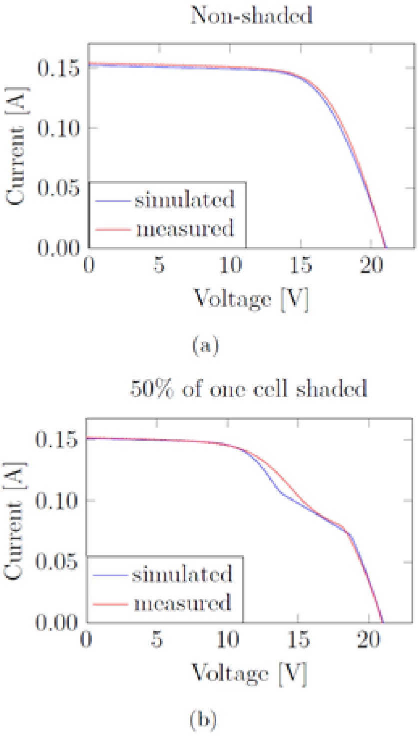

Figure 2 The IV-curves of a simulation at micro scale in comparison with the measured IV-curves with (a) an unshaded cell and (b) a 50% shaded cell.

4 MODEL VALIDATION

Figure 2 shows the IV curves of both the measured PV modules and the simulated PV modules. From here, it is clear that the model is accurate in case of no shading (a). When 50% of one cell is shaded, the IV curve deviates slightly in the region of the bending point (b). This might be solved by using the double-diode model instead of the one-diode model. Nevertheless, since the effect of this small deviation is neglectable at the operation point of the PV modules, the one diode model will be used.

5 RESULTS

In what follows, the simulation results of a 8 x 8 cm² CIGS mini-module composed out of 20 in series connected CIGS cells in which the tenth solar cell is 100% shaded for 50% of its area will be briefly discussed. Each cell was divided into 25 square shaped finite elements of equal size per cm². Figure 3 represents the mini-module as included in this simulation together with the opacity level for each cell.

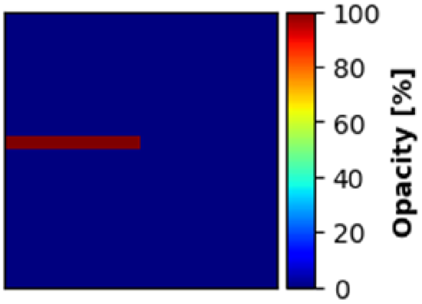

Figure 3 Representation of the 8 x 8 cm² CIGS mini-module with 50% of the area of the tenth cell totally shaded.

Figure 4 shows the voltage distribution of the CIGS mini-module. It is clear that the shaded part is subjected to a significant reverse bias of up to 3.5 V. Even the non-shaded part of the third cell is subjected to a (lower) reverse bias. From this plot, it is clear that the third cell is fully acting as a load while only 50% of its area is shaded. Furthermore, a gradient can be observed around the nonshaded region of the third cell.

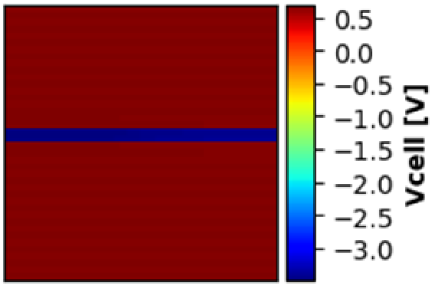

Figure 4 The voltage distribution of the partially shaded minimodule.

In Figure 5, the distribution of the current density of the shaded PV modules is shown. It is clear that the shaded region acts as a bottle neck for the current while the current density of the non-shaded region of the shaded cell exceeds the nominal current density of the mini-module. Also interesting is the gradient of current density at the

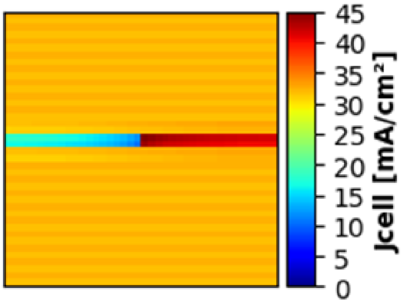

Figure 5 The current density distribution of the partially shaded mini-module.

interface between the shaded and non-shaded part of the third cell.

The temperature distribution of the partially shaded mini-module is shown in Figure 6. A slight decrease in temperature at the shaded region is observed while a temperature increase is observed at the non shaded region of the partially shaded solar cell. This is in accordance with previous results. However, the thermal output of our model is not yet validated and the temperature scale is therefore not absolute.

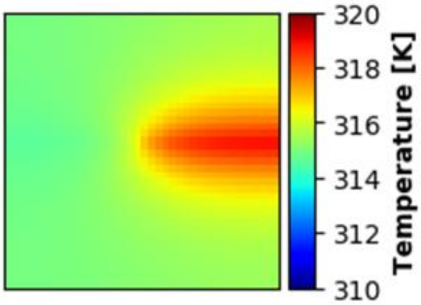

Figure 6 The temperature distribution of the partially shaded mini-module.

4 CONCLUSIONS

In this proceeding we proposed a pre-defined element electro-thermal SPICE model in order to investigate the impact of shading on monolithically interconnected CIGS PV modules. The model was simplified by limiting the possible irradiation levels (0 W/m2 for the shaded part and 1000 W/m2 for the illuminated part). This allowed us to use the single-diode model even when the superposition principle with voltage-independent photocurrent does not hold for CIGS solar cells.

The model is electrically validated, and the IV curves of the measurements and simulations are in accordance with each other. Nevertheless, a slight deviation of the IV curve around the bending point can be observed in case of 50% shading while in case of no shading, no significant difference can be observed. The results might be improved by using the double diode model instead of the one diode model.

This tool outputs the distribution of the current density and voltage of the PV module in case of a shaded cell. Due to a significant reverse bias over the shaded cell, i.e. 3.5 V in this case, a reverse current is enables to flow through the shaded region of the solar cell, which now acts as a load and dissipates power. Note that the reverse bias stretches over the full length of the partially shaded solar cell and thus is the partially shaded solar cell fully acting as a load. The thermal distribution is also carried out by SPICE. This is done by the Foster RC thermal model. The results are in accordance with other simulations, but still needs to be validated in the future by lab experiments.

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