The effect of dust on photovoltaic thinfilm modules

EFFECT OF DUST ON PHOTOVOLTAIC THINFILM MODULES

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ABSTRACT

This paper investigates the effect of dust on Cadmium Telluride (CdTe) photovoltaic (PV) modules by the use of a Spatial 3 Dimensional Model (S3DM) with circuit analysis software *PSPICE*. The investigation was carried out to look into the effect of dust concentration and tilt angle variation on the PV module. It also looks into the possibility of hotspot effect due to different installation positions under dusty conditions. The simulation results showed a reduction in the sample performance with increased dust concentration and reduced tilt angle. The variation between cell positions showed that cells in configuration where they are oriented in a horizontal position to the plane tended to lead to hotspots when both low shunt cells and high shunt cells are identified, with cells identified with lower shunts being the more vulnerable.

I. INTRODUCTION

Of the currently available PV technologies, the behavior of those with the largest market share, mono and poly crystalline silicon, is well understood. Under various shading conditions, energy losses are minimized and the PV module is protected through the use of bypass diodes. On the other hand, other technologies, thin films in particular such as amorphous Silicon (a-Si) and Cadmium Telluride (CdTe), are more vulnerable to this problem [1-2]. This is due to the fact that most of them have their cells connected in series, and because the way thin film modules are fabricated does not allow for cell sorting by output during the manufacturing process or for the easy integration of protection diodes. Furthermore, it has been established that the wavelength-dependent transmittance through accumulated dust has a larger effect on modules with narrower spectral response bands [2].

Some manufacturers claim that thin film technologies are less vulnerable to shading if they are installed with their cells oriented vertically to the plane as illustrated in Figure 1. The reason being that the probability of a cell being fully shaded is reduced [3]. This claim, though holding true in terms of energy. In terms of durability it needs to be considered that hotspots due to shading do not necessarily occur when a cell is fully shaded, but can happen when a cell or group of cells are partially shaded [4-6]. In the long term, this affects not only the performance of the module, but may lead to unrecoverable damage.

In this paper the focus is specifically on CdTe modules, mainly because of its high potential in the PV market. The proposed methodology uses a Spatial 3 Dimensional Model (S3DM). Various outdoor situations are simulated, where shading has been introduced in the form of dust. The effect of dust was applied using dust density values obtained in a previous work [2], where a relation was determined between dust density and accumulation on different tilt angles.

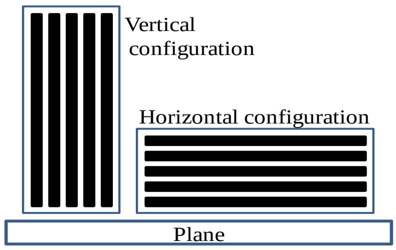

Figure 1: Horizontal and vertical orientation configurations.

III. MODELLING STRUCTURE AND SPATIAL 3 DIMENSIONAL MODEL

The effect of dust accumulation on the surface of a PV module can be compared to random shadowing on the surface of a PV cell. This means the affected areas are not homogeneous. To better understand the effect of distributed shadowing on the surface of the cell, spatially resolved measurements were required.

Spatially resolved measurement and distributed analysis in PV devices is the investigation of solar cell properties or electrical PV parameters by taking into account their location (position) on the solar cell or module [7]. It has been done in the past and is generally used to investigate the influence of the distribution and variation of physical properties on overall performance and efficiency.

A. Cadmium Telluride Solar Cell Modelling

The starting element for the development of the spatial model is to use a one diode model as the core model. The usage of this model for different types of PV technologies is possible, with some modifications to accommodate for the differences in cell technology. Since CdTe is a polycrystalline heterojunction, the standard one diode model should be applicable with only slight modification.

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$$I(V) = I_o\left(e^{\frac{qV_j}{nKT}} - 1\right) + \frac{V_j}{R_{sh}} - I_{ph} \quad (1)$$

It was reported that CdTe devices' I-V curves show a limiting current in the forward bias [8-10]. This effect can be attributed to the device structure where in the case of CdTe, the material layers form a Schottky barrier with the back contacts which creates the limiting effect. That is why CdTe devices been reported to have a back diode effect. The back diode is not represented as a part of the active photovoltaic material and its influence is only on the series resistance.

As shown in the modelled circuit in Figure 2, the back diode is reversed biased, though it does not reach break-down for normal operating conditions [9]. The reason for that is the voltage of the cell is in the magnitude of less than one Volt, while a break-down voltage is in the range of several volts. As per the previous model, this model can be calculated in the same manner with the only difference being in calculating V_j, as the back diode has to be accounted for and thus can be calculated by:

$$V_j = V - IR_s - V_{BD} \quad (2)$$

The back diode can be modelled as a Schottky diode, and thus, the voltage across the diode is given by:

$$V_{DB} = \frac{kT}{e}\, ln\left(\frac{I}{I_{BD}} + 1\right) \quad (3)$$

I_{BD} in this equation represents the saturation current of the back diode which is exponentially dependant on the temperature. Modifying equation 1 with the equation 2 to obtain:

$$I(V) = I_o\left(e^{\frac{q(V-IR_s-V_{DB})}{nKT}} - 1\right) + \frac{V - IR_s - V_{DB}}{R_{sh}} - I_{ph} \quad (4)$$

This is known as the backdiode model modified by Stollwerck to represent the behaviour of CdTe technology [8].

B. Spatial 3 Dimensional Model

A one dimensional model usually consists of a one diode model with additional lateral resistance $R_{s,Lat}$. In our case, as shown in Figure 2, the model is made of two diodes I_D & I_{DB}, photocurrent source I_{ph}, shunt resistance R_{sh} and series resistance R_s. The shunt resistance represents the photo-generation, recombination and parasitic losses. The series resistance in this case is the bulk resistivity of the semiconductor material and is represented as R_{se} without the contribution of the contact layers resistivity.

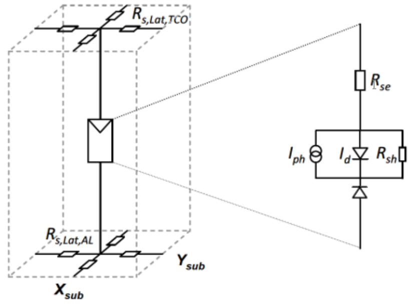

Figure 2: A single unit back diode model taking into consideration the lateral resistance ($R_{sLa-TCO}$, R_{sLa-Al}) for the TCO and the back contacts.

IV. LOSSES DUE TO THE INFLUENCE OF DUST

One of the preliminary investigations of dust effect is performance reduction with different dust concentrations. This effect was explored modelling three cells connected in series. The total area of the sample is 9 cm^2 (3cm x 3cm). The sample was simulated with PSpice under 25°C, AM1.5 and 1000 W/m^2. Different dust concentration values representing the effect of dust were applied by the impact of the spectral transmittance in the range 350-900 nm of 89.9% (2.3 mg/cm^2), 68.9% (12.2 mg/cm^2), 36.5% (28.7 mg/cm^2) and 7.7% (36.7 mg/cm^2)[2]. The simulation results are shown in Table 1 and Figure 3.

The simulation showed a reduction in the power output under higher concentration of dust, where the cell performance decreased. This approach is used to simplify the effect of dust settling on the PV cell. The simplification came from the fact that dust deposition can produce complicated patterns that vary under different influences such as wind direction, particle size and gravitational effect which is represented by the tilt of the surface. In this work, only the last element was taken into consideration. The effect of gravity was represented by a gradual variation of dust on the surface of the PV cell. The simulation showed that increasing the tilt angle supports the removal of dust. This was shown by the increase in the cell output by increasing tilt angle. A high increase in the tilt angle (>60°) can reduce the effect of dust, although in most installations it is not the preferred tilt used to optimize the solar resource utilisation.

An optimized tilt, though reducing the effect of dust relative to a 0° tilt, can introduce a significant variation in settled dust concentration on different areas of the module. In most cases, where no rain effect is introduced, tilting the PV module can introduce a gradual settlement of dust where higher concentration is settled at the bottom and lower concentration at the top.

	V_{oc} (V)	I_{sc} (A)	MPP (W)	I_m (A)	V_m (V)	FF
36.7 mg/cm^2	0.326	0.077	0.010	0.049	0.199	0.392
28.7 mg/cm^2	0.908	0.355	0.205	0.249	0.823	0.636
12.2 mg/cm^2	0.972	0.689	0.602	0.626	0.961	0.898
2.3 mg/cm^2	0.995	0.899	0.869	0.879	0.989	0.971
0°	0.982	0.764	0.696	0.716	0.972	0.928
15°	0.986	0.824	0.772	0.785	0.983	0.951
30°	0.991	0.850	0.806	0.819	0.983	0.957
45°	0.991	0.888	0.855	0.864	0.989	0.972
90°	1.000	0.979	0.973	0.973	1.000	0.994

TABLE 1: SIMULATED CELL PARAMETERS UNDER DIFFERENT DUST SCENARIOS NORMALIZED TO THE CLEAN SAMPLE.

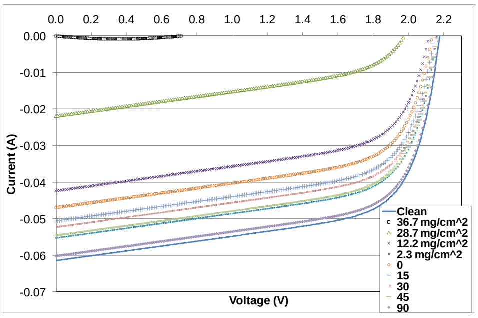

Figure 3: I-V curves for the simulated samples under different dust concentration and different tilt angles.

This effect poses a risk of triggering hotspots in the cells. The simulated sample was divided into 4 regions where higher concentration of dust was settled in a smaller area in the bottom of the cell, while the top area, which represents the major area of the cell, has a very low dust concentration. This configuration aims to represent a scenario of a 30° tilted module exposed to a very dusty climate for a short period of time. Two different variations of material defects were introduced; high shunt (voltage limited -VL) and low shunt (current limited -CL). The sample was simulated under two installation orientations, with cells oriented in a horizontal position to the plane (Hor) and vertical position (Vert) as illustrated in Figure 1. The simulations are shown in Figure 4 and Table 2.

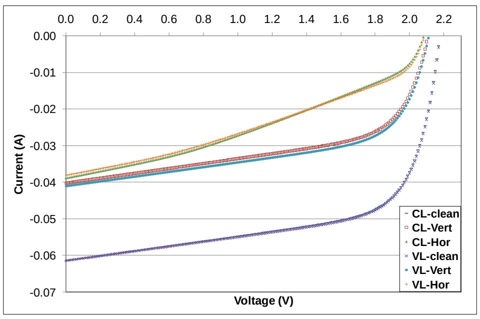

Figure 4: I-V curves for the simulated samples with different defects.

	Voc(V)	Isc(A)	MPP (W)	Im (A)	Vm(V)	FF
CL-Vert	0.968	0.655	0.559	0.585	0.956	0.882
CL-Hor	0.959	0.633	0.337	0.480	0.702	0.555
VL-Vert	0.972	0.668	0.578	0.605	0.956	0.890
VL-Hor	0.959	0.620	0.333	0.459	0.725	0.559

TABLE 2: SIMULATED SAMPLES PARAMETER VALUES NORMALIZED TO THE CLEAN SAMPLES

The variation between defect types introduced a small difference (1%) between the dust-free samples. The worst case was seen in the horizontal cell configuration, where the sample lost 66.3% of its maximum power when a current limiting cell was introduced in comparison to 66.7% for a voltage limiting cell. This can be attributed to the horizontal configuration allowing a full length of the cell to be covered by dust while the vertical configuration introduced 44.1% and 42.2% reductions for the current-limiting and voltage-limiting scenarios, respectively. The power loss in the two cell orientations varied within each module and so a detailed investigation was undertaken under maximum power point as shown in Table 3.

*Total power is with respect to maximum power point of the cell.

	CL-Clean	CL-Vert	CL-Hor	VL-clean	VL-Vert	VL-Hor
TCO	0.185	0.085	0.066	0.190	0.095	0.061
BC	0.0005	0.0003	0.0001	0.0005	0.0003	0.0001
Rsh	99.794	99.906	99.928	99.789	99.895	99.934
Rse	0.117	0.097	0.093	0.117	0.099	0.086
Rin	0.014	0.006	0.004	0.014	0.006	0.004
Rbc	0.006	0.003	0.002	0.006	0.003	0.002
Total*	25.865	42.151	63.864	25.081	39.545	64.099

TABLE 3: PERCENTAGE POWER VARIATION IN THE SAMPLE CELL DUE TO THE HIGH AND LOW SHUNT.

The voltage limiting samples showed a more uniform power dissipation per cell and less uniform power dissipation between the cells than that of the none-shaded sample, see Figure 5. The effect occurred when the sample was placed in the horizontal cells configuration due to uniform shading on the first cell at the bottom (Figure 5-right). Less uniform power dissipation was observed when the voltage limited sample was simulated in the vertical cells configuration (Figure 5-bottom). This can be attributed to the lower current limiting of the cell in this configuration compared to the horizontal cell configuration. The first configuration orientation can lead to a slow and uniform heating in the shaded cells when it operates at higher current than that of the cells maximum power point.

The current limiting cell showed a more severe power dissipating area around the forced defect regions as shown in Figure 6. The horizontal cell configuration showed a higher sensitivity to power dissipation around the defect regions. On the other hand, the vertical cell configuration did not show any signs of heated hotspot. This is mainly due to the placement of the local defects in the sample with respect to the area exposed to higher dust concentration in the sample.

Operation of the PV sample under maximum power point will set the operating current of the PV cell lower than the short circuit current and thus slows down the process of heating around the defect areas. This is illustrated in Figure 7 where the same current limited sample was simulated in a horizontal cell configuration at short circuit current to introduce the worst case scenario. The heated area showed a higher value of that showed in the sample simulated operating at the maximum power point.

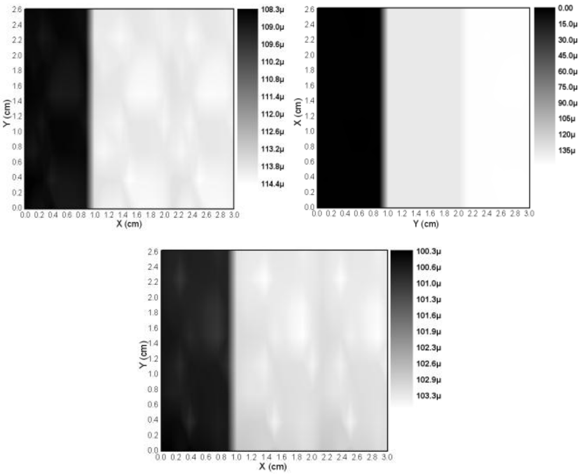

Figure 5: Voltage limited samples. From the top left, clean, dusted horizontal, dusted vertical samples. X-axis always represents the plane position. The scales on the contour maps are in watt (W).

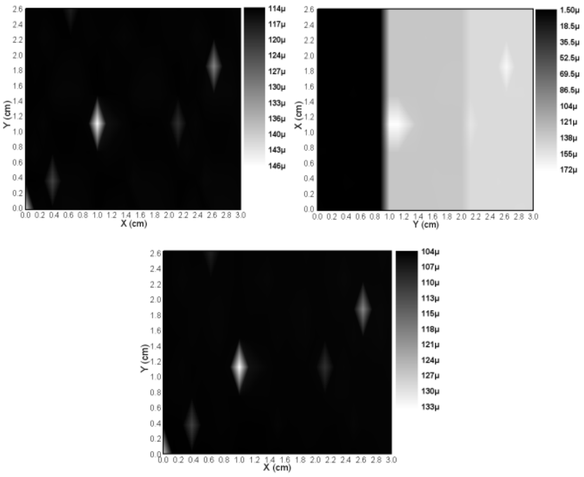

Figure 6: Current limited samples. From the top left, clean, dusted horizontal, dusted vertical samples.

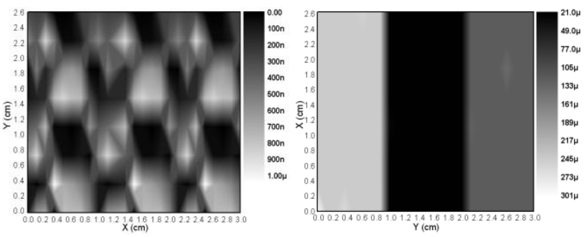

Figure 7: Variation between current limited samples at short circuit current in a horizontal configuration. From the left, clean sample and dusty sample.

V. CONCLUSION

The accumulation of dust on the surface of a PV module reduces the performance with respect to dust concentration and the module tilt angle. With increasing tilt angle the effect of dust is reduced, although it can introduce a density variation of the accumulations of dust on the surface of the module which can increase the possibility of triggering hotspots.

Simulated dust samples showed higher reduction in power when the PV module is installed in a configuration where the cells are oriented in the horizontal. This gives a higher dust concentration at the bottom cell, reducing the power of the module by 66.7% for a voltage limiting cell and 66.3% for a current limiting cell in comparison to 42.2% and 44.1% respectively for a vertical cell configuration.

PV cells identified with low shunts and high shunt are more vulnerable to hotspots in horizontal cell configuration at normal operating conditions. On the other hand, PV cells identified with higher shunt and lower shunt are less vulnerable to uniform hotspot heating when exposed to dust at vertical cell configurations. Lower shunt cells tend to be more vulnerable to hotspots in the horizontal configuration than that of the high shunt cells. This is mainly due to the fact fully shaded cells are required to overheat cells identified with low shunt.

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