ICEGES 2009

Le Royal Hotel Amman, Jordan
November, 10-12 2009

International Conference and Exhibition on Green Energy & Sustainability for Arid Regions & Mediterranean Countries

A qualitative study of the shunt resistance of parallel-connected amorphous silicon solar cells

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Abstract

This paper introduces a theoretical methodology of investigating the performance of parallel-connected amorphous silicon solar cells by separating the shunting effects of individual component cells under different illumination intensities Φ. In completed thin film photovoltaic modules several cells are connected in parallel without granting access to the electrical contacts of each individual cell. According to traditional methods of determining the shunt resistance of each cell, one has to remove the lamination over the PV modules, which may damage the physical connections between the cells. Therefore, to solve such a problem, we make use of the illumination-intensity dependence of the shunt resistance of amorphous silicon solar cells by recording the global current density/voltage characteristics of the whole module. By this method, we determine the shunt resistance of any cell in the PV module even without accessing the electrical contacts of the corresponding cell and consequently we non-destructively identify any shunted cell in the PV modules.

Keywords: Shunt resistance, Amorphous silicon, PV module

1. Introduction

Solar cells in PV modules are connected in series and in parallel to provide high output voltages and currents, respectively. Al Tarabsheh et.al. [1, 2] investigated the shunt resistance R_P of series-connected amorphous silicon (a-Si:H) cells by applying the partial shading method. In this article, we focus on parallel-connected PV cells in evaluating their individual shunt resistances R_P. As the shunt resistance of a cell decreases, the resulting open-circuit voltage V_{oc} of the whole PV module also decreases [3] resulting in a considerable decrease in the equivalent shunt resistance R_{PT} especially for the case of parallel-connected solar cells where R_{PT} is less the smallest R_P of the cells.

Fig. 1 presents the equivalent circuit generally applied for photovoltaic modules; it consists of M current sources I_{ph_i} ($1 \le i \le M$) in parallel to M diodes, where M is the number of the parallel-connected a-Si:H solar cells in the module. When including the resistive elements $R_{s\,i}$ and R_{p_i}, the circuit of Fig. 1a) reasonably well represents the behaviour of real solar cells [3, 4]. The general idea of this paper is introduced in Fig. 1b), where we add a virtual external shunt resistance R_{ext} to the component cells inside the PV module in order to separate the effects of the individual component cells.

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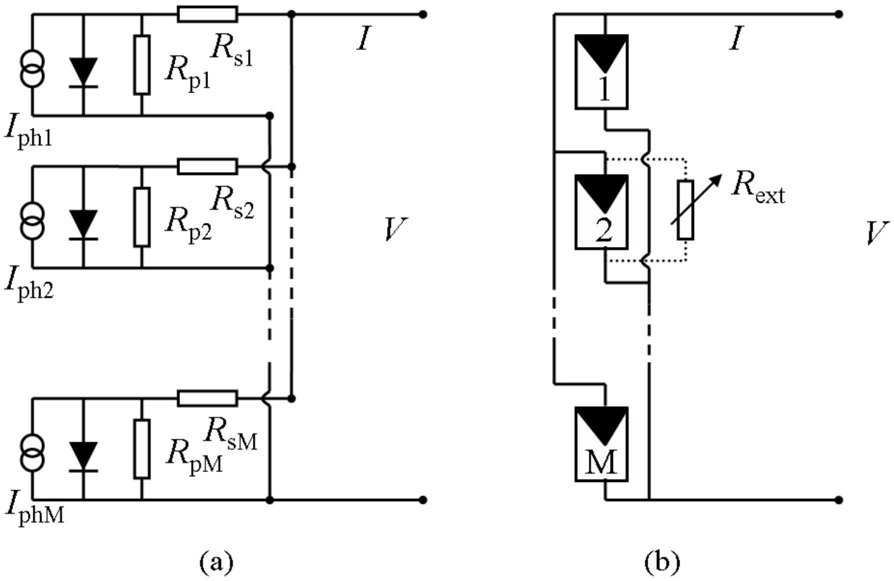

Fig. 1: Equivalent circuit of PV module; (a) consisting of *M*-parallel connected (b) with incorporating a virtual external shunt resistance R_{ext} to mimic shunting of a single cell.

2.Analysis

Effect of shunting a cell

To study the effect of R_{ext} on the global characteristics of the PV module, we assume that the PV module comprises 4 parallel-connected cells, where each cell has different characteristics. Fig. 1 shows the current density/voltage (J/V) characteristics of each cell of the PV module depending on the electrical parameters which are listed in Tab. 1, where we find that cell 1 has the smallest value of shunt resistance while cell 4 has the largest value

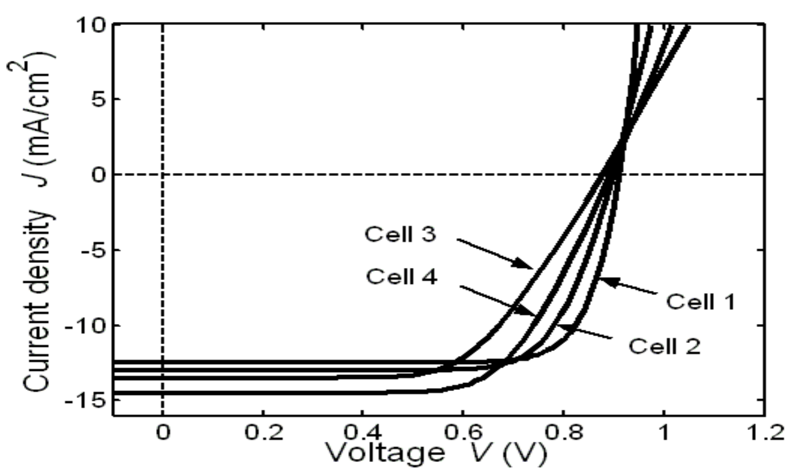

Fig. 2: Current density/voltage characteristics of four different solar cells who's electrical parameters are listed in Tab. 1.

	Cell 1	Cell 2	Cell 3	Cell 4
Series resistance $Rs\,(\Omega)$	1	5	15	10
Shunt resistance $Rp\,(k\Omega)$	100	200	150	250
Ideality factor n	1.85	1.77	1.61	1.75
Reverse Saturation current density $Js\,(mA/cm^2)$	0.7×10^{-7}	0.4×10^{-7}	0.1×10^{-7}	0.4×10^{-7}
Short circuit current density $Jsc\,(mA/cm^2)$	12.5	13	13.5	14.5
Open circuit voltage $Voc\,(mV)$	910	898	876	892
Fill factor $FF\,(\%)$	78.8	74.1	61.4	66.4
Efficiency $\eta\,(\%)$	9	8.7	7.3	8.6

Tab. 1: Electrical parameters of four different solar cells, assuming cell 1 has the smallest shunt resistance. The other parameters are used to express the J/V -characteristics.

To track the effect of R_{ext}, we refer to Fig. 1 assuming that cell 2 is shunted by R_{ext} $(15\Omega \le R_{ext} \le 1000\Omega)$, and then we recalculate the global J/V -characteristics of the PV module for each value of R_{ext}. Fig. 3 shows the resulting J/V -characteristics of the module for different values of R_{ext}.

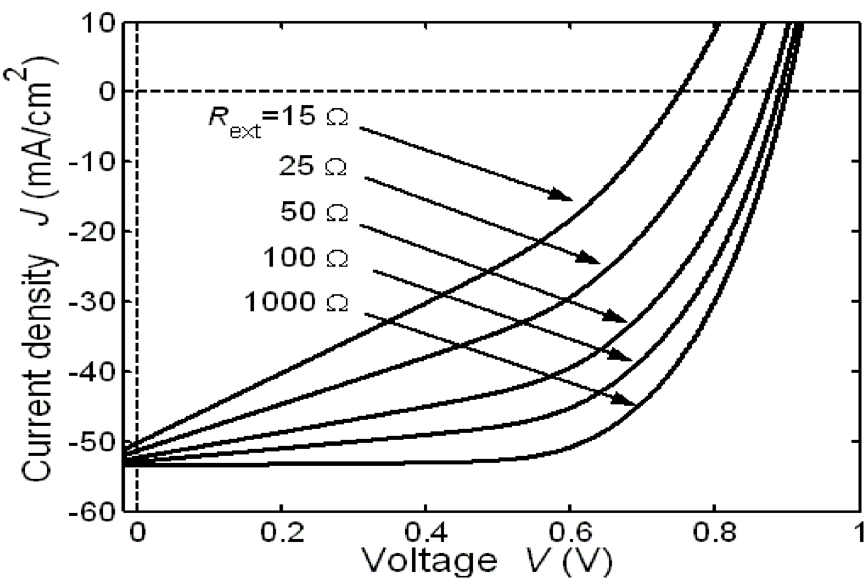

Fig. 3: Current density /voltage of PV module showing the effect of R_{ext}.

It is obvious that shunting a cell in a PV module affects its global characteristics. The main affected parameters of the J/V -characteristics are the open circuit voltage V_{oc} , the fill factor FF , and therefore the efficiency η of the whole module. Fig. 4 demonstrates the responses of V_{oc} , FF , and η of the PV module to R_{ext} . In other words, it is of great importance to determine any shunted cell in PV modules.

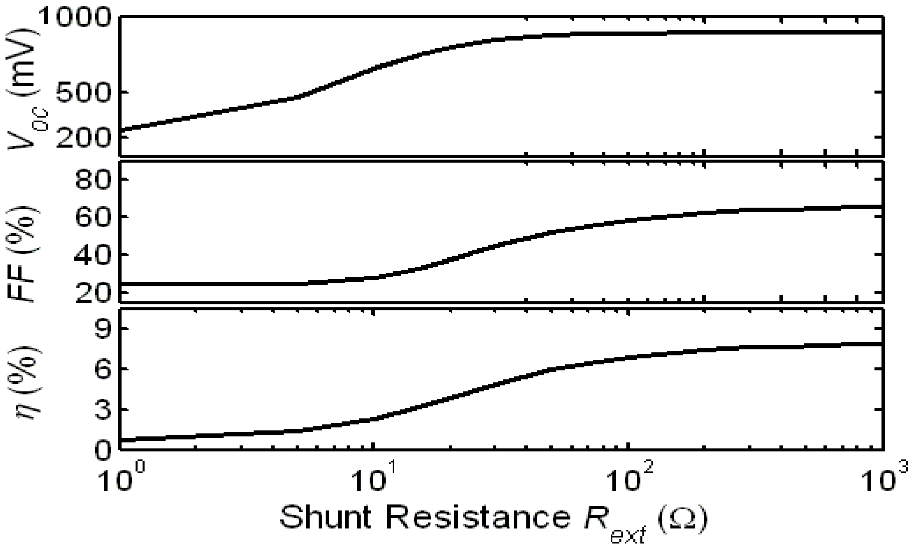

Fig. 4: Effect of decreasing R_{ext} on the electrical parameters of the J/V -characteristics of the whole PV module.

Nomencalture	
$R_{pT,0}$	total measured shunt resistance of the PV module when all the cells are fully illuminated
$R_{p1,0}$, $R_{p2,0}$	shunt resistance (to be estimated) of cells 1 and 2, respectively, when they are fully illuminated.
R_{p1} , R_{p2}	shunt resistance (to be estimated) of cells 1 and 2, respectively, when they are partially illuminated
$R_{pT}^{(1)}$, $R_{pT}^{(2)}$	total measured shunt resistance of the PV module when only cell 1 or 2, respectively, is partially illuminated while the rest of cells are fully illuminated.

Evaluation of the shunt resistance

We focus on the effect of a shunted a-Si:H solar cell on the global J/V -characteristics of a PV module consisting of *M*- cells connected in parallel. We assume that the shunt resistance (leakage through the *i*-layer in a-Si:H based solar cells) is a photo-resistive element and its resistance R_p is inversely proportional to the photo-conductivity σ_{ph}. To analyze the shunt resistance, we start by the simplest case where a PV module comprises only two parallel-connected a-Si:H solar cells. For each step, one cell is partially illuminated (using neutral density filter) while the other cell is fully illuminated by a solar simulator with an intensity of Φ_0. The total shunt resistance $R_{pT,0}$ of the above-mentioned PV module before applying any neutral density filter where the module is fully illuminated is expressed as:

$$R_{pT,0} = \frac{R_{p1,0} R_{p2,0}}{R_{p1,0} + R_{p2,0}} \tag{1}$$

Assuming cell 1 is partially illuminated, the total shunt resistance is:

$$R_{pT}^{(1)} = \frac{R_{p1} R_{p2,0}}{R_{p1} + R_{p2,0}} \tag{2}$$

While when cell 2 is partially illuminated, the total shunt resistanceequals

$$R_{pT}^{(2)} = \frac{R_{p1,0} R_{p2}}{R_{p1,0} + R_{p2}} \tag{3}$$

In both cases, the shunt resistance of a shadowed cell $(\Phi < \Phi_0)$ can be expressed [5] as

$$R_p(\Phi) = R_{p0} \left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} \tag{4}$$

where $0 \le \gamma \le 1$ is called the power-law exponent of the photoconductivity. Rewriting Eqs. (2) and (3) by including the effect of illumination on the shunt resistance of the shadowed cells results in

$$R_{pT}^{(1)} = \frac{\left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{p1,0} R_{p2,0}}{\left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{p1,0} + R_{p2,0}} \tag{5}$$

And

$$R_{pT}^{(2)} = \frac{\left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{p1,0} R_{p2,0}}{R_{p1,0} + \left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{p2,0}} \tag{6}$$

Dividing both Eq's. (5) and (6) by (2) results in

$$\frac{R_{pT}^{(1)}}{R_{pT,0}} = \frac{\left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} \left(R_{p1,0} + R_{p2,0} \right)}{\left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{p1,0} + R_{p2,0}} \tag{7}$$

and

$$\frac{R_{pT}^{(2)}}{R_{pT,0}} = \frac{\left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} \left(R_{p1,0} + R_{p2,0} \right)}{R_{p1,0} + \left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{p2,0}} \tag{8}$$

Therefore, the actual shunt resistances $R_{p1,0}$ and $R_{p2,0}$ of cells 1 and 2 are calculated as

$$R_{p1,0} = R_{pT}^{(0)} \left(1 + \frac{R_{pT}^{(1)} - \left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{pT}^{(2)}}{R_{pT}^{(2)} - \left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{pT}^{(1)}} \right) \tag{9}$$

and

$$R_{p2,0} = R_{pT}^{(0)} \left(1 + \frac{\left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{pT}^{(1)} - R_{pT}^{(2)}}{\left(\frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{pT}^{(2)} - R_{pT}^{(1)}} \right) \tag{10}$$

where $R_{pT}^{(m)}$ is the total shunt resistance of the PV module when cell m is partially illuminated. Note that $R_{pT}^{(m)}$ is straight forward calculated from the global characteristics of the PV module using Werner plot [6].

Now, we generalize the case where a PV module consists of M parallel-connected a-Si:H solar cells $(M > 2)$. The total shunt resistance $R_{pT}^{(0)}$ of the PV module when it is fully illuminated is given by:

$$R_{pT}^{(0)} = \left(\sum_{k=1}^{M} \frac{1}{R_{pk,0}} \right)^{-1} \tag{11}$$

and the total shunt resistance $R_{pT}^{(m)}$ of the PV module when only cell m ($1 \le m \le M$) is partially illuminated while $M-1$ cells are fully illuminated is calculated as:

$$R_{pT}^{(m)} = \left(\frac{1}{\left(\frac{\Phi}{\Phi_0}\right)^{-\gamma} R_{pm,0}} + \sum_{\substack{k=1 \\ k \ne m}}^{M} \frac{1}{R_{pk,0}} \right)^{-1} \tag{12}$$

The matrix form of the above equation is presented in the following Jacobian matrix

$$\begin{bmatrix} \left(\frac{\Phi}{\Phi_0}\right)^{\gamma} & 1 & 1 & \cdots & 1 \\ 1 & \left(\frac{\Phi}{\Phi_0}\right)^{\gamma} & 1 & \cdots & 1 \\ 1 & 1 & \ddots & \cdots & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & 1 & \cdots & \left(\frac{\Phi}{\Phi_0}\right)^{\gamma} \end{bmatrix}_{M\times M} \begin{bmatrix} \frac{1}{R_{p1,0}} \\ \frac{1}{R_{p2,0}} \\ \vdots \\ \frac{1}{R_{pM-1,0}} \\ \frac{1}{R_{pM,0}} \end{bmatrix}_{M\times 1} = \begin{bmatrix} \frac{1}{R_{pT}^{(1)}} \\ \frac{1}{R_{pT}^{(2)}} \\ \vdots \\ \frac{1}{R_{pT}^{(M-1)}} \\ \frac{1}{R_{pT}^{(M)}} \end{bmatrix}_{M\times 1} \tag{13}$$

Therefore, the shunt resistance of any cell in PV module can be evaluated by solving the last system as

$$R_{pm,0} = \left(\frac{\left(\left(\frac{\Phi}{\Phi_0}\right)^{\gamma} + (M-2)\right)\left(R_{pT}^{(m)}\right)^{-1} - \sum_{\substack{k=1, \\ k \ne m}}^{M} \left(R_{pT}^{(k)}\right)^{-1}}{\left(\frac{\Phi}{\Phi_0}\right)^{2\gamma} + (M-2)\left(\frac{\Phi}{\Phi_0}\right)^{\gamma} + (M-1)} \right)^{-1}$$

$$,1 \le m \le M \tag{14}$$

Quality of parallel-connected cells

To justify our methodology, by which we can determine any shunted cell from the global characteristics of the PV module; we assume a PV module consisting of four parallel-connected solar cells $(M = 4)$ with $\gamma = 0.7$ and any partially cell is shadowed using a neutral density filter of 20% $(\Phi = 0.2\Phi_0)$ of transmission for all wavelengths.

According to Tab. 1, the total shunt resistance $R_{pT}^{(0)}$ when the PV module is fully illuminated equals $38.96\ k\Omega$. Assuming cells 1 to 4 are successively shadowed with a neutral density filter, the shunt resistance of each partially illuminated cell increases by a factor of $0.2^{-0.7} = 3.09$, i.e., $R_{pT}^{(1)} = 52.89\ k\Omega$, $R_{pT}^{(2)} = 44.87\ k\Omega$, $R_{pT}^{(3)} = 47.26\ k\Omega$, $R_{pT}^{(4)} = 43.55\ k\Omega$, as shown in Fig. 5. As a figure of merit, we compare $R_{pT}^{(m)}$ $(1 \le m \le M)$ which is calculated directly from the global J/V-characteristics when only cell m is shadowed, with $R_{pT}^{(0)}$ which is also determined from the global J/V-characteristics but when all cells of the PV module are fully illuminated.

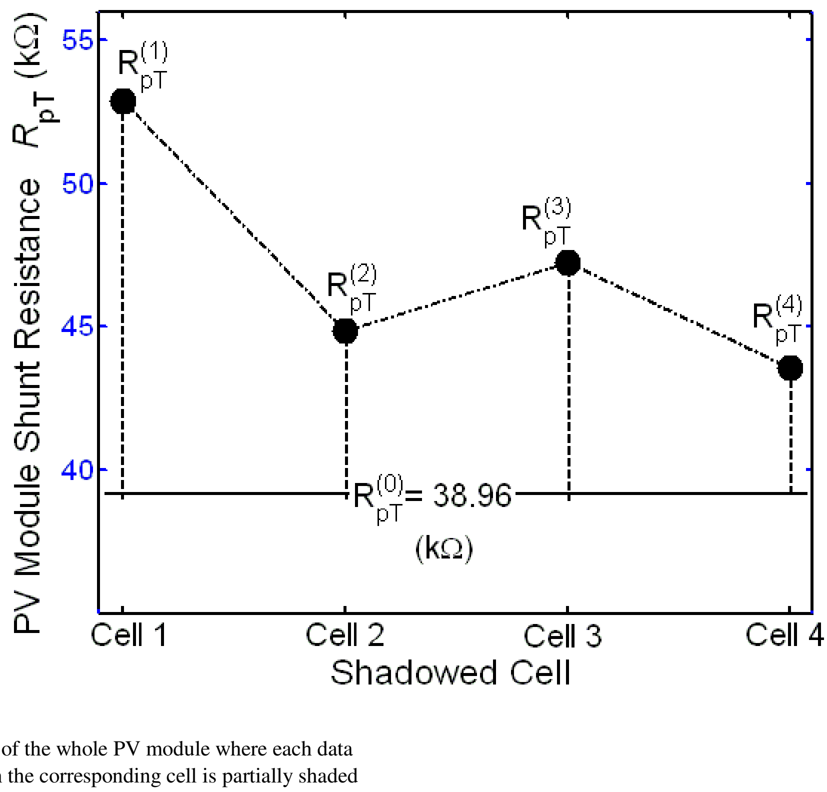

Fig. 5: Shunt resistance of the whole PV module where each data point is calculated when the corresponding cell is partially shaded to while all other cells of the module are fully illuminated

The $R_{pT}^{(m)} - R_{pT}^{(0)}$ is a decreasing function of $R_{pm,0}$ as can be proven by subtracting Eq. (11) from (12), i.e.,

(15)

$$R_{pT}^{(m)} - R_{pT}^{(0)} = \frac{R_{pm,0}\left(1-\left(\frac{\Phi}{\Phi_0}\right)^{\gamma}\right)}{\left(\left(\frac{\Phi}{\Phi_0}\right)^{\gamma} + R_{pm,0}\sum_{\substack{k=1 \\ k\neq m}}^{M} R_{pk,0}\right)+\left(1+R_{pm,0}\sum_{\substack{k=1 \\ k\neq m}}^{M} R_{pk,0}\right)}$$

Therefore, the smallest the shunt resistance of cell m the largest the difference between $R_{pT}^{(m)}$ and $R_{pT}^{(0)}$ will be. Applying the above-mentioned result in Fig. 5, we conclude that the lowest shunt resistance is that of cell 1 while the best cell is cell 4 which agrees with Tab.1.

3. Conclusion

In this work, we study the performance of a-Si:H-based modules by applying our methodology of characterizing the shunt resistance of parallel-connected cells without even accessing the electrical contacts of these individual cells. The method includes a sequential partial shading of each cell and then tracking the global shunt resistance of the PV module. The evaluation the maximum and minimum values of the global shunt resistance when only one cell is partial illuminated allows us to non-destructively determine which cell of the PV module is shunted.

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