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Investigation of the shunting effects of parallel-connected a-Si:H solar cells

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This paper investigates the performance of parallel-connected amorphous silicon (a-Si:H) solar cells based on the separation of the shunting effects of individual cells under different illumination intensities, Φ. The cells are arranged in photovoltaic (PV) modules to meet the desired electrical requirements. According to traditional methods of determining the shunt resistance of each cell, one has to remove the lamination over the PV modules, resulting in a probable damage of 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 a-Si:H solar cells. The purpose of this study is to 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 (low quality) cell in the PV module.

Keywords: shunt resistance; amorphous silicon; PV module

Nomenclature

\[ R_{pT,0} \] total measured shunt resistance of the PV module when all the cells are fully illuminated \((\Phi = \Phi_0)\)

\[ R_{pT,n} \] total measured shunt resistance of the PV module when only cell \(n\) is partially illuminated \((\Phi < \Phi_0)\) while the rest of cells are fully illuminated

\[ R_{pn,0} \] shunt resistance (to be estimated) of cell \(n\) when it is fully illuminated \((\Phi = \Phi_0)\)

\[ R_{pn} \] shunt resistance (to be estimated) of cell \(n\) when it is partially illuminated \((\Phi < \Phi_0)\)

1. Introduction

Photovoltaic (PV) modules consist of series- and/or parallel-connected solar cells to provide high output voltages and/or high currents, respectively. The shunt resistances of series-connected amorphous silicon (a-Si:H) cells were investigated by Al Tarabsheh and Schubert (2006) and Al Tarabsheh et al. (2006) by varying the illumination intensities over the cells. This work focuses on the parallel-connected a-Si:H cells to evaluate their corresponding shunt resistances, \(R_p\)

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Figure 1. Equivalent circuit of a PV module (a) consisting of $M$-parallel connected (b) by incorporating a virtual external shunt resistance, $R_{\text{ext}}$, to mimic the shunting of a single cell.

(Breitenstein et al. 2008), without even accessing their physical contacts. The proposed methodology is applied for parallel-connected a-Si:H cells as an extension for what has been applied for series-connected a-Si:H cells (Al Tarabsheh 2007). Therefore, the motivation is to check the effect of partially illuminating a cell on the shunt resistance of the whole PV module for two cases, parallel connections and series connections, to give a full account of this effect.

As the shunt resistance of a cell decreases, the resulting open-circuit voltage, $V_{\text{oc}}$, of the whole PV module also decreases (Merten et al. 1998), resulting in a considerable decrease of the equivalent shunt resistance, $R_{pT}$, where $R_{pT}$ is less than the smallest shunt resistance, $R_p$, of the individual cells.

Figure 1 shows the equivalent circuit generally applied for PV modules. The circuit consists of $M$ current sources $I_{\text{ph}}$ ($1 \leq i \leq M$) that are parallel with $M$ diodes, where $M$ is the number of the parallel-connected a-Si:H solar cells. The parasitic series resistances, $R_{s i}$, and shunt resistances, $R_{p i}$, are included in the circuit of Figure 1(a) to represent the behaviour of real solar cells (Swanson 2003, Al Tarabsheh 2007, Bouattour et al. 2010). The general idea of this paper is introduced in Figure 1(b), where a virtual external shunt resistance, $R_{\text{ext}}$, is added to the component cells inside the PV module in order to separate the effects of the individual component cells. Addition of $R_{\text{ext}}$ in parallel with a cell results in an equivalent resistance that is less than both the actual resistance and the added one (hayt et al. 2001), that is, this addition of $R_{\text{ext}}$ simulates the shunting effect.

2. Analysis

2.1. Effect of shunting a cell

To justify the proposed method, we investigate the effect of $R_{\text{ext}}$ on the global current density/voltage ($J/V$) characteristics of the PV module. This is done using a MATLAB code that generates four $J/V$ characteristics depending on the pre-chosen electrical parameters of the cells that appear in Equation (1) (Werner 1988), where the last term represents the contribution under illumination:

$$J = J_S \left( \exp \left[ \frac{V - JR_S}{nV_t} \right] - 1 \right) + \frac{V - JR_S}{R_p} - J_{\text{ph}}, \quad (1)$$

where $V$ is the applied voltage to the cell, $J$ is the resulting current density, $V_t = 25.9$ mV (at room temperature) is the thermal voltage, $n$ is the ideality factor, $J_S$ is the reverse saturation current...
Table 1. Electrical parameters of four solar cells, assuming that cell 1 has the smallest shunt resistance (lowest quality). The other parameters are used to express the $J/V$ characteristics.

<table>
<thead>
<tr>
<th></th>
<th>Cell 1</th>
<th>Cell 2</th>
<th>Cell 3</th>
<th>Cell 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series resistance $R_s$ (Ω)</td>
<td>1</td>
<td>5</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Shunt resistance $R_p$ (kΩ)</td>
<td>100</td>
<td>200</td>
<td>150</td>
<td>250</td>
</tr>
<tr>
<td>Ideality factor $n$</td>
<td>1.85</td>
<td>1.77</td>
<td>1.61</td>
<td>1.75</td>
</tr>
<tr>
<td>Reverse-saturation current density $J_s$ (mA/cm$^2$)</td>
<td>$0.7 \times 10^{-7}$</td>
<td>$0.4 \times 10^{-7}$</td>
<td>$0.1 \times 10^{-7}$</td>
<td>$0.4 \times 10^{-7}$</td>
</tr>
<tr>
<td>Short-circuit current density $J_{sc}$ (mA/cm$^2$)</td>
<td>12.5</td>
<td>13</td>
<td>13.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Open-circuit voltage $V_{oc}$ (mV)</td>
<td>910</td>
<td>898</td>
<td>876</td>
<td>892</td>
</tr>
<tr>
<td>Fill factor $FF$ (%)</td>
<td>78.8</td>
<td>74.1</td>
<td>61.4</td>
<td>66.4</td>
</tr>
<tr>
<td>Efficiency $\eta$ (%)</td>
<td>9</td>
<td>8.7</td>
<td>7.3</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Figure 2. $J/V$ characteristics of four solar cells whose electrical parameters are listed in Table 1.

density, $J_{ph} = J_{SC}$ is the short-circuit (assumed to equal the photogenerated) current density, $R_s$ is the series resistance and $R_p$ is the shunt resistance of the cell. The electrical parameters ($R_s$, $R_p$, $n$ and $J_s$) listed in Table 1 are not measured but are chosen randomly and then inserted in Equation (1) just as a case study, while the rest of the electrical parameters ($J_{SC}$, $V_{oc}$, $FF$ and $\eta$) are evaluated from the resulting curves of the $J/V$ characteristics.

Figure 2 shows the $J/V$ characteristics of each cell of the PV module depending on the corresponding electrical parameters listed in Table 1. It is assumed that cell 1 has the smallest value (lowest quality) of shunt resistance, while cell 4 has the largest (best quality) one.

To track the effect of $R_{ext}$, we refer to Figure 1, assuming that only cell 2 is externally shunted by $R_{ext}$ ($15 \Omega \leq R_{ext} \leq 1000 \Omega$). This range is selected because if $R_{ext}$ is larger than 1000 Ω, then the $J/V$ curves do not show much difference, and if $R_{ext}$ is less than 15 Ω, then the cell becomes a short circuit one as shown in Figure 3. After this step, we recalculate the global $J/V$ characteristics of the PV module using Equation (1) by varying the value of $R_{ext}$ associated with cell 2 while fixing the other electrical parameters of other cells. The resulting global $J/V$ characteristics of the PV module are plotted as shown in Figure 3, by summing the generated currents of each cell (shown in Figure 2) for the same voltage since they are connected in parallel. This step is repeated for different values of $R_{ext}$.

It is obvious that shunting a cell in a PV module deteriorates the global $J/V$ characteristics of the module. The most affected parameters of the $J/V$ characteristics are the open-circuit voltage, $V_{oc}$, the fill factor, $FF$, and therefore, the efficiency, $\eta$, of the whole module. For each curve
Figure 3. $J/V$ characteristics of PV module for different values of $R_{ext}$. 

Table 2. Electrical parameters ($V_{oc}$, $FF$ and $\eta$) of the global $J/V$ characteristics of the PV module for different values of shunt resistance $R_{ext}$.

<table>
<thead>
<tr>
<th>$R_{ext}$ (Ω)</th>
<th>$V_{oc}$ (mV)</th>
<th>$FF$ (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>255.95</td>
<td>25.00</td>
<td>0.68</td>
</tr>
<tr>
<td>5</td>
<td>468.59</td>
<td>25.07</td>
<td>1.38</td>
</tr>
<tr>
<td>10</td>
<td>663.11</td>
<td>27.78</td>
<td>2.26</td>
</tr>
<tr>
<td>15</td>
<td>750.92</td>
<td>33.17</td>
<td>3.13</td>
</tr>
<tr>
<td>20</td>
<td>798.79</td>
<td>38.08</td>
<td>3.87</td>
</tr>
<tr>
<td>30</td>
<td>844.97</td>
<td>44.82</td>
<td>4.89</td>
</tr>
<tr>
<td>50</td>
<td>873.98</td>
<td>51.97</td>
<td>5.94</td>
</tr>
<tr>
<td>70</td>
<td>883.17</td>
<td>55.65</td>
<td>6.47</td>
</tr>
<tr>
<td>100</td>
<td>888.88</td>
<td>58.67</td>
<td>6.89</td>
</tr>
<tr>
<td>200</td>
<td>894.48</td>
<td>62.45</td>
<td>7.43</td>
</tr>
<tr>
<td>300</td>
<td>896.13</td>
<td>63.78</td>
<td>7.61</td>
</tr>
<tr>
<td>400</td>
<td>896.92</td>
<td>64.44</td>
<td>7.71</td>
</tr>
<tr>
<td>600</td>
<td>897.68</td>
<td>65.12</td>
<td>7.80</td>
</tr>
<tr>
<td>800</td>
<td>898.06</td>
<td>65.46</td>
<td>7.85</td>
</tr>
<tr>
<td>1000</td>
<td>898.28</td>
<td>65.67</td>
<td>7.88</td>
</tr>
</tbody>
</table>

Figure 4. Effect of decreasing $R_{ext}$ (shunting) on the electrical parameters of the global $J/V$ characteristics of the PV module.
(corresponding to a different value of shunting) in Figure 3, the parameters \(V_{oc}, FF\) and \(\eta\) are depicted as done by Al Tarabsheh (2007) as shown in Table 2. The electrical parameters are then plotted as a function of \(R_{ext}\) as shown in Figure 4, where the parameters of the PV module deteriorate as a cell of the module becomes more shunted (having a smaller \(R_{ext}\)). Therefore, if a PV module is of low quality, then it is of great importance to determine the position of any shunted cell in the module.

### 2.2. Evaluation of the shunt resistance

We focus on the effect of shunting a-Si:H solar cells on the global \(J/V\) characteristics of a PV module that consists of \(M\) parallel-connected cells. We assume that the shunt resistance (leakage through the \(i\)-layer in a-Si:H-based solar cells) is a photoresistive element and its resistance is inversely proportional to the photoconductivity, \(\sigma_{ph}\). The analysis starts by monitoring the shunt resistance of the PV module.

The first step of the analysis is to record the global \(J/V\) characteristics of the PV module, where all the cells are fully illuminated with an illumination intensity of \(\Phi_0\) (\(\Phi_0 = 100 \text{ mW/cm}^2\)). The resulting shunt resistance, \(R_{pT,0}\), of the PV module is then defined as the equivalent parallel resistance of the \(M\) cells:

\[
R_{pT,0} = \left( \sum_{n=1}^{M} \frac{1}{R_{pn,0}} \right)^{-1}.
\]

(2)

The second step is to partially illuminate only one cell (i.e \(\Phi < \Phi_0\)) by applying a neutral density filter that is compatible with the dimensions of the cell while the other cells are fully illuminated by a solar simulator with an intensity of \(\Phi_0\). The last step is repeated for each cell of the module (i.e. \(M\) times). The corresponding shunt resistance of any partially illuminated cell \(k\) can be expressed (Swanson 2003, Al Tarabsheh 2007) as

\[
R_{pk}(\Phi) = R_{pk,0} \left( \frac{\Phi}{\Phi_0} \right)^{-\gamma},
\]

(3)

where the factor \(\gamma(0 \leq \gamma \leq 1)\) is called the power-law exponent of the photoconductivity. The total shunt resistance \(R_{pT,k}\) of the PV module, when only cell \(k\) (\(1 \leq k \leq M\)) is partially illuminated while \(M - 1\) cells are fully illuminated, is calculated from Equations (2) and (3) by considering the effect of illumination on the shunt resistance of the partially illuminated cells as

\[
R_{pT,k} = \left( \frac{1}{R_{pk}} + \sum_{n=1}^{M} \frac{1}{R_{pn,0}} \right)^{-1}
\]

\[
= \left( \frac{1}{\left( \frac{\Phi}{\Phi_0} \right)^{-\gamma} R_{pk,0}} + \sum_{n=1}^{M} \frac{1}{R_{pn,0}} \right)^{-1}.
\]

(4)
In order to end up with a form that directly relates the recorded shunt resistances of the cells investigated in each step, the last equation is rewritten in a Jacobian matrix form as

\[
\begin{bmatrix}
\left(\frac{\Phi}{\Phi_0}\right)^\gamma & 1 & 1 & \cdots & 1 \\
1 & \left(\frac{\Phi}{\Phi_0}\right)^\gamma & 1 & \cdots & 1 \\
1 & 1 & \ddots & \cdots & 1 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
1 & 1 & 1 & \cdots & \left(\frac{\Phi}{\Phi_0}\right)^\gamma \\
\end{bmatrix}_{M \times M} \begin{bmatrix}
\frac{1}{R_{p1,0}} \\
\frac{1}{R_{p2,0}} \\
\vdots \\
\frac{1}{R_{pM-1,0}} \\
\frac{1}{R_{pM,0}}
\end{bmatrix}_{M \times 1} = \begin{bmatrix}
\frac{1}{R_{pT,1}} \\
\frac{1}{R_{pT,2}} \\
\vdots \\
\frac{1}{R_{pT,M-1}} \\
\frac{1}{R_{pT,M}}
\end{bmatrix}_{M \times 1}.
\] (5)

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

\[
R_{pk,0} = \left(\left(\frac{\Phi}{\Phi_0}\right)^\gamma + (M - 2)\right) (R_{pT,k})^{-1} - \sum_{n=1, n \neq k}^{M} (R_{pT,n})^{-1}
\]

\[
\frac{1}{\left(\frac{\Phi}{\Phi_0}\right)^{2\gamma} + (M - 2)\left(\frac{\Phi}{\Phi_0}\right)^\gamma + (M - 1)}
\]

\[
, \quad 1 \leq k \leq M.
\] (6)

### 2.3. Quality of parallel-connected cells

To prove 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 illuminated cell is shadowed using a neutral density filter of 20\% \((\Phi = 0.2 \Phi_0)\).

According to Table 1, the total shunt resistance, \(R_{pT,0}\), when the PV module is fully illuminated equals 38.96 kΩ. Assuming that cells 1–4 are successively shadowed with a neutral density filter, the shunt resistance of each partially illuminated cell increases by a factor of \(0.2^{-0.7} = 3.09\), that is, \(R_{pT,1} = 52.89\ kΩ\), \(R_{pT,2} = 44.87\ kΩ\), \(R_{pT,3} = 47.26\ kΩ\) and \(R_{pT,4} = 43.55\ kΩ\) as shown in Figure 5.

As a figure of merit, we compare \(R_{pT,k}\) \((1 \leq k \leq M)\), which is calculated directly from the global \(J/V\) characteristics when only cell \(k\) is partially illuminated, with \(R_{pT,0}\), which is also determined from the global \(J/V\) characteristics when all cells of the PV module are fully illuminated.

The difference, \(R_{pT,k} - R_{pT,0}\), is a decreasing function of \(R_{pk,0}\) as can be found by subtracting Equation (2) from Equation (4), as follows:

\[
R_{pT,k} - R_{pT,0} = \frac{R_{pk,0} \left(1 - \left(\frac{\Phi}{\Phi_0}\right)^\gamma\right)}{\left(\frac{\Phi}{\Phi_0}\right)^\gamma + R_{pk,0} \sum_{n=1, n \neq k}^{M} R_{pn,0}} + \left(1 + R_{pk,0} \sum_{n=1, n \neq k}^{M} R_{pn,0}\right)
\] (7)
Therefore, the smallest the shunt resistance of cell $k$, the largest the difference between $R_{pT,k}$ and $R_{pT,0}$ will be. Applying the above-mentioned result in Figure 5, we conclude that the lowest shunt resistance is that of cell 1, while the best cell is cell 4, which is in full agreement with the values of the shunt resistances listed in Table 1.

Finally, all the results in this work were obtained using the MATLAB (a numerical computing environment and fourth-generation programming language that was developed by MathWorks).

3. Conclusion

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

References


