IMPACT OF SHUNTED SOLAR CELLS
ON THE IV CHARACTERISTICS OF SOLAR MODULES

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ABSTRACT: At the end of the solar cell manufacturing process an IV measurement is performed under illumination of each individual solar cell to determine its current I_{mp} at the maximum power point and sort the cells into I_{mp} classes. The reason for this is to minimize mismatch losses in the module consisting of series-connected solar cells. In addition Deutsche Cell GmbH takes a measurement of the reverse IV curve in the dark to reject badly shunted solar cells. Various solar cell manufacturers are not performing the reverse IV measurement. We demonstrate that (i) a reverse IV measurement is suitable to reject solar cells that could cause hot spot failure of the module, (ii) a reverse current limit I_{rev}(-10 V) is a sufficient reject criterion, (iii) this reject criterion also reduces mismatch loss at low illumination levels, (iv) the reverse current I_{rev} of a solar cell can be determined from the IV characteristics of the corresponding module IV curve, and (v) the operation voltage of a shunted solar cell in a module of series-connected solar cells is significantly lower than expected from simple approximations.

Keywords: Modules, hot spots, shading.

1. INTRODUCTION

Crystalline silicon solar cells are connected in series to solar modules. Consequently, the same current is passing through all solar cells and the IV curve of a solar module is derived by adding the voltages of all individual solar cells of the module at each operation current. Partial shading of solar modules causes that the shaded solar cell reaches the operation current of the module only at reverse bias condition. This causes the power of the illuminated cells to dissipate in the shaded cell.

Shunts normally occur locally in solar cells (edge isolation failure, etc.). If shunted solar cells are shaded, high current densities are driven through the shunted region and hot spot heating will occur in these cells. This can cause solder melting, blistering of the lamination, cracks of the glass or even melting of the silicon shortening the lifetime of a module.

To reduce the risk of hot spot failure of a module a bypass diode is normally placed in parallel to a string of series-connected solar cells (in most applications 18 to 24 cells per bypass diode). Under normal operation conditions the bypass diode is high resistive (reverse biased) and has no impact on the IV curve of the module. In the case of partial shading the voltage of the shaded solar cell compensates the voltage of the rest of the string. The bypass diode is forward biased causing a short circuit of the string. Consequently, the bypass diode limits the voltage that drives the shaded solar cell into reverse to the sum of voltages of the rest of solar cells of the string. It therefore reduces the risk of hot spot failure. However, if a solar cell has a very high reverse current hot spot failure still can occur at these voltages. Therefore, it is essential for the quality of the module and its lifetime that the reverse IV curve is measured and that the reverse current reject criterion is well matched to the number of solar cells per bypass diode. Rejected solar cells still can be used for modules with a smaller number of cells per bypass diode.

Herrmann at. al. [1, 2] already presented measurement results of the reverse IV characteristics and the corresponding temperature distribution recorded with an infra red camera from various commercially available crystalline silicon solar cells. It is emphasized that a reject criterion for shunted solar cells is most important for the photovoltaic industry. However, a lot of solar cell manufacturer have not implemented a reverse current limit reject criterion. Deutsche Cell has set its current limit I_{rev}(-10 V) to 2.5 A perfectly matched to strings of 20 solar cells per bypass diode. However, the production average of I_{rev}(-10 V) is significant below 1.0 A. For the presented work we have selected groups of solar cells with I_{rev}(-10 V) lower and higher than 2.5 A to review and determine a sufficient reject criterion for shunted solar cells.

2. APPROACH

At Deutsche Cell the reverse IV characteristics in the dark is measured at the end of the solar cell manufacturing process for each solar cell. The measurement is performed between 0 and 12.0 V in 50 ms. 156x156 mm² multicrystalline silicon solar cells with a reverse current I_{rev}(-10 V) higher than 2.5 A are sorted out. For our investigations we used a sorting table to group shunted solar cells into five different categories as shown in Table 1. Solar cells in each group show various origins of shunt such as edge isolation failure, over firing of the front grid, aluminum stains on the front side, material defects.

<table>
<thead>
<tr>
<th>Class name</th>
<th>I_{rev}(-10 V) range [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>2.0 – 2.3</td>
</tr>
<tr>
<td>37</td>
<td>2.3 – 2.6</td>
</tr>
<tr>
<td>38</td>
<td>2.6 – 2.9</td>
</tr>
<tr>
<td>39</td>
<td>2.9 – 3.2</td>
</tr>
<tr>
<td>40</td>
<td>3.2 – 3.5</td>
</tr>
</tbody>
</table>

With these groups of solar cells we performed the following experiments:

- The reverse IV curve in the dark and the forward IV curve at 1.0 and 0.2 Suns of all individual solar cells were recorded to calculate the module IV curves.
We developed a program [3] to calculate the module output parameters such as series-connected cells. (iv) Calculation of the module IV curve was used for comparison with the module IV curve calculated from measured cell IV curves.

Infra red images of the shaded cell within the module were taken to determine the peak temperature of the shunted solar cell for the different shunt levels and various types of shunts (edge isolation failure, etc.).

Mini modules were fabricated from shunted solar cells. These modules were used to determine the reverse IV characteristics and the corresponding peak temperature with an infra red camera.

We recorded a few hundred forward IV curves at 0.2 and 1.0 Sun representing our current production. These measured cell IV curves were used to calculate the module IV curve to determine power mismatch losses caused by shunted solar cells at low illumination levels.

3 RESULTS

3.1 IV characteristics of partly shaded modules and its peak temperature

We used the software to calculate the IV curve of each string from the recorded solar cell IV curves. Figure 2 presents the IV curves of a strings calculated from the measured cell IV curves with all cells fully illuminated (illuminated) and the shunted solar cells totally shaded, respectively (37-1, 36-2 and 1-5). Shown as well are the reverse IV curves of the shaded solar cells.

It can be seen that the string IV is the shifted reverse IV curve of the cell which is shaded. This shows that it is possible to determine the reverse IV curve of an individual solar cell in a finished module if the corresponding cell is shaded. This is a very handy method to control the reverse current limit of solar cells in a finished module.

![Figure 2: Calculated IV curves of a string from the measured IV curves of all individual solar cells with all cells fully illuminated (illuminated) and the shunted solar cells totally shaded, respectively (37-1, 36-2 and 1-5). The reverse IV curves of the corresponding shunted solar cells are shown as well.](image)

We have used the IV curve of the string with the shunted solar cell 36-2 totally shaded to calculate the maximum power pint of the string. This allows us to determine the operation voltage of the shaded solar cell as shown in Figure 3. The shunted solar cell is operated at around – 6 V by the non-shaded solar cells.

We have used the IV curve of the string with the shunted solar cell 36-2 totally shaded to calculate the maximum power pint of the string. This allows us to determine the operation voltage of the shaded solar cell as shown in Figure 3. The shunted solar cell is operated at around – 6 V by the non-shaded solar cells. This voltage is much smaller than expected from simple approximations adding the voltages of the maximum power point of all solar cells of the string driving the shunted solar cell in reverse (U_{pp} x 19 = 9.5 V).

For comparison of the predicted with the measured module IV curve we fabricated solar modules with the same cells that were used in the calculation before (one shunted solar cell in each string). The solar modules where exposed to sun light. The module IV measurement...
was recorded with the shunted cell totally shaded, respectively. Figure 4 shows the outdoor IV measurement of the module with all solar cells fully illuminated at around 1000 W/cm² and with the solar cell 37-1, 36-2 and 1-5 fully shaded, respectively. For the module IV curves with one solar cell shaded the reverse IV curve of these cells can be observed nicely. In our configuration we have one bypass diode in parallel to each string of 20 solar cells. It can be seen in Figure 4 as well that the bypass diode short-circuits the string with the shaded solar cell. The other strings are still in full operation.

Infra red images of the shaded cell within the module were taken to determine the peak temperature of the shunted solar cell for the different shunt levels and various types of shunts (edge isolation failure, etc.). It can be observed in Figure 5 that the shaded solar cell is colder than the surrounding cells. The shunt is visible with a local temperature increase to around 130°C. All of our test modules with $I_{rev}(-10V) < 2.5$ A had a peak temperature below 150°C.

Figure 4: Outdoor IV measurement of a module with all solar cells fully illuminated at around 1000 W/cm² and with the solar cell 37-1, 36-2 and 1-5 fully shaded, respectively.

Figure 5: Infra red image taken from the rear side of a solar module. The module is exposed to sun light with the shunted solar cell totally shaded. All of our test modules with $I_{rev}(-10V) < 2.5$ A had a peak temperature below 150°C.

3.2 Peak temperature of shunted mini modules under reverse bias conditions

It is very material and time consuming to fabricate large modules for these hot spot tests. Therefore, we fabricated single solar cell mini modules as shown in Figure 1. For these modules we used solar cells with (i) different $I_{rev}(-10V)$ values and (ii) different type of shunts such as edge isolation failure, over firing of the front grid, aluminum stains on the front side, material defects. The mini modules were used to determine the reverse IV characteristics in dark and the corresponding peak temperature with an infra red camera as shown in Figure 6. The peak temperature of the modules featuring various types of shunt is plotted versus $I_{rev}(-10V)$. Note that for modules with $I_{rev}(-10V) \leq 2.5$ A delamination caused by hot spot heating did not occur. In most cases the temperature stayed below 80°C. For one sample featuring a small area point shunt a very high temperature of up to 200°C was reached. However, the laminat was not damaged. For most modules with $I_{rev}(-10V) > 2.5$ A delamination did occur. This experiment shows that the reverse current limit $I_{rev}(-10V) \leq 2.5$ A of Deutsche Cell is a sufficient reject criterion to protect solar modules from hot spot failure.

Figure 6: Infra red image taken from the rear side of a mini module biased with – 10 V. The surrounding of the module is around 18°C.

Figure 7: Peak temperature of various mini modules with different $I_{rev}(-10V)$ determined from infra red images. Note that for modules with $I_{rev}(-10V) \leq 2.5$ A blistering due to hot spot heating did not occur.

Figure 8: Peak temperature of mini modules taken from infra red images for different bias conditions. The full circles show a typical solar cell produced at Deutsche Cell. Shown is the dissipated power of two shunted solar cells with $I_{rev}(-10V) > 2.5$ A as well featuring a large and a small area shunt (point shunt).
Solar cells with the same power dissipation $I_{rev} \times 10V$ reach very different peak temperatures as visible in Figure 7. Shunts which are distributed over a large area stay normally colder than shunts focused onto a small spot. In Figure 8 the peak temperature versus the dissipated power of mini modules is shown for a solar cell that is produced within our reverse current limit of $I_{rev}(–10V) \leq 2.5 A$, a solar cell with $I_{rev}(–10V) > 2.5 A$ featuring a small and a large area shunt, respectively. For the solar cell with $I_{rev}(–10V) \leq 2.5 A$ a dissipated power of less than 5 W is reached at – 10V heating the solar cell from room temperature to 34°C. The solar cell with the large area shunt reaches a lower temperature than the cell with the point shunt. The module with the large area shunt was actually destroyed at around 180°C corresponding to 30 W.

### 3.3 Mismatch losses at low illumination levels caused by shunted solar cells

Low illumination levels can cause shunted solar cells to generate much less current than non-shunted solar cells. This can cause mismatch losses at low illumination levels. It can even happen that shunted solar cells within the module are operated under reverse bias conditions at low illumination even though the module is illuminated uniformly. In this case hot spot burning of the module can occur without partial shading.

![Image](image_url)

Figure 9: Calculated mismatch losses of solar modules for 0.2 and 1.0 Sun illumination for different power classes if solar cells are used in solar modules that are close to our shunt limit of $I_{rev}(–10V) < 2.5 A$.

In order to investigate the power loss caused by shunted solar cells we performed the following calculation. We recorded a few hundred forward IV curves at 0.2 and 1.0 Sun illumination representing our current production. We determined the average $I_{rev}(–10V)$ and used solar cells with $I_{rev}(–10V)$ close to this average to calculate the module IV curve using our calculation software [3]. In addition we performed the same calculation with solar cells that are close to our reverse current limit of 2.5 A. The difference of both calculations shows the maximum mismatch loss caused by shunted solar cells at low illumination levels as shown in Figure 9. This indicates that with the shunt limit of Deutsche Cell no power losses occur due to shunted cells for 1.0 Sun illumination. The power loss caused by shunted solar cells for 0.2 Sun illumination is still very small, however, it decreases with the power of the class and has its peak at around 1% for 3.25 W solar cells. These values are very small. Therefore we can conclude that the shunt limit of Deutsche Cell also helps to reduce mismatch losses at low illumination. However, the introduction of a shunt limit for the shunt of the forward IV curve should give an additional control limit to reduce mismatch losses at low illumination levels.

### 4 CONCLUSIONS

- In modules of series-interconnected solar cells shaded solar cells are reverse biased
- Reverse current can cause hot spot failure
- The reverse current limit $I_{rev}(–10V) < 2.5A$ of Deutsche Cell avoids hot spot failure
- Reverse IV of individual solar cells within a module can be determined from the module IV if the cell of interest is shaded
- The operation voltage of a shaded solar cell is smaller than predicted from the simple approximation $U_{mpp}\times Strng-1$
- No significant power loss at low illumination is caused by shunted solar cells if the criterion $I_{rev}(–10V) < 2.5A$ is maintained

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**REFERENCES**