HOT SPOT TESTS FOR CRYSTALLINE SILICON MODULES

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ABSTRACT

Hot spot heating occurs when a module's operating current exceeds the reduced short circuit current of a shadowed or faulty cell or group of cells within the module. In order to determine whether a crystalline silicon module is adequately protected against hot spots, two hot spot test have been developed and utilized as a part of IEC 61215 "Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval" and as part of UL 1703 "UL Standard for Safety for Flat-Plate Photovoltaic Modules and Panels". Each of these tests has some problems.

Working Group 2 of IEC Technical Committee 82 on Photovoltaics is developing a revised Hot Spot Test as a modification to IEC 61215. Major features of the revision include 1) a new way of identifying low and high shunt cells by measuring a set of IV curves for a module with each cell shadowed in turn, 2) selection and testing of 3 low shunt cells and one high shunt cell, 3) providing modified procedures to determine the worst case shadowing for the selected cells and 4) testing of the low shunt cells for 1 hour and of the high shunt cell for a longer time (still to be determined).

INTRODUCTION

Hot-spot heating occurs in a module when its operating current exceeds the reduced short-circuit current (I_{sc}) of a shadowed or faulty cell or group of cells. When such a condition occurs, the affected cell or group of cells is forced into reverse bias and must dissipate power. If the power dissipation is high enough or localized enough, the reverse biased cell can overheat resulting in melting of solder and/or silicon and deterioration of the encapsulant and backsheet. The correct use of bypass diodes can prevent hot spot damage from occurring.

The reverse characteristics of solar cells can vary considerably [1]. Cells can have either high shunt resistance where the reverse performance is voltage-limited or have low shunt resistance where the reverse performance is current-limited. Each of these types of cells can suffer hot spot problems, but in different ways.

<u>Low Shunt Resistance Cells</u>:

- The worst case shadowing conditions occur when the whole cell (or a large fraction) is shadowed.
- Often low shunt resistant cells are this way because of localized shunts. In this case hot spot heating occurs because a large amount of current flows in a small area. Because this is a localized phenomena, there is a great deal of scatter in performance of this type of cell. Cells with the lowest shunt resistance have a high likelihood of operating at excessively high temperatures at least in localized areas when reverse biased.
- Because the heating is localized, hot spot heating of low shunt resistance cells occurs quickly.

<u>High Shunt Resistance Cells:</u>

- The worst case shadowing conditions occur when a small fraction of the cell is shadowed.
- High shunt resistant cells limit the reverse current flow of the circuit and therefore heat up. The cell with the highest shunt resistance will have the highest power dissipation.
- Because the heating is uniform over the whole area of the cell, it can take a long time for the cell to heat to the point of causing damage.

The major technical issue is how to identify the highest and lowest shunt resistance cells and then how to determine the worst case shadowing for those cells.

PROBLEMS WITH PRESENT HOT SPOT TESTS

IEC 61215

The hot spot test in the first edition (1993) of IEC 61215 has problems with both the selection of cells to test and the test procedure utilized once the test cell has been selected.

The selection procedure states "Short circuit the module and select a cell by one of the following methods:

1. With the module exposed … at a stable irradiance of not less than 700 $W{\cdot}m^{-2}$, determine the hottest cell using an appropriate temperature detector.
2. Under the irradiance specified for step a), (not less than 700 $W{\cdot}m^{-2}$) completely shadow each cell in turn and select the cell or one of the cells which gives the biggest decrease in short-circuit current when shadowed."

The first method for selecting a cell to test will only find the cell that has the lowest short circuit current, which is not related at all to reverse bias performance which is what leads to hot spot problems. The second method for selecting a cell calls for shadowing each cell in turn and selecting the cell that causes the biggest decrease in short circuit current. This will find the cell with the highest shunt resistance. The cell found by this technique should be tested, but there is nothing in this procedure to guide the test lab to look for cells with localized shunts which may be susceptible to hot spot heating. A second problem with the second method is the fact that many modules have built in by-pass diodes that are always in the circuit. With these modules, fully shadowing a cell will not change the short circuit current at all as one of the diodes will turn on and carry the current around the shadowed cell.

The test procedure states "Under the same irradiance (within ± 3%) as used in step a) (not less than 700 W·m^{-2}), completely shadow the selected cell and check that the I_{sc} of the module is less than the I_{mp}, as determined in step a). If this condition does not occur, one can not set the condition of maximum power dissipation within a single cell. In this case, proceed with the selected cell completely shadowed omitting step d)." (Step d is where the shadowed area is decreased in order to find the shadow that causes the maximum power dissipation within the cell.) If the module has bypass diodes (which most do today) the diode will maintain the current flow through the module at I_{sc} even when a cell is shaded. The correct shadow level can be found if the diodes are removed from the circuit during this part of the test, but this is not possible for many modules and not good practice to have the test laboratory modifying the module for a portion of the test. In most cases the procedure of reducing the shadowed area to determine worst case conditions is not performed, but rather you run all the tests with the cell fully shaded. Experience has shown that high resistance cells get the hottest when the shadow only covers a small percentage of the cell. This maximizes the current flow through the reverse biased cell. With a high shunt resistance cell fully shadowed, most of the current flows through the bypass diode. This condition is far from the maximum stress that the cell may see in actual operation.

Finally, the procedure in 61215 involves a total test time of five (5) hours in one hour increments. Results from the UL hot spot test indicate that when failures occur, it is often after much longer exposure times.

UL 1703

The present UL intrusive hot spot test determines the power to be dissipated in the test cell by multiplying the expected short circuit current times the peak power voltage produced by the number of series cells per diode. So this test can be used to provide guidance as to how many cells can safely be protected by a diode. It is a good test for cells with high shunt resistance. The UL standard allows two options for selection of cells for test. One of the procedures is a non-intrusive method that will only work for modules without by-pass diodes. The second method is intrusive where leads are attached to at least 10 cells selected at random. From the 10 cell sample it does require selection of both the highest and lowest shunt resistance cells, but of course there is a reasonable likelihood of not selecting the potential small population of cells with localized shunts that can cause hot spot problems if used in high voltage systems.

One of the main problems with the UL test is the requirement to attach extra lead to all of the cells selected for test. This means that the test laboratory has to modify the module and also means that the integrity of the module's insulation system can not be evaluated after the hot spot test.

SELECTION OF CELLS FOR TEST

The major technical issue is how to identify the highest and lowest shunt resistance cells in a module. If there are no bypass diodes or the bypass diodes are removable, cells with localized shunts can be identified by reverse biasing the cell string and using an IR camera to observe hot spots. If the module circuit is accessible the current flow through the shadowed cell can be monitored directly. However, most PV modules have bypass diodes and many PV modules do not have removable diodes or accessible electric circuits. Therefore a non-intrusive method is needed that can be utilized on those modules.

The selected approach is based on taking a set of IV curves for a module with each cell shadowed in turn. Figure 1 shows the resultant set of IV curves for a sample module. The curve with the highest leakage current at the point where the diode turns on was taken when the cell with the lowest shunt resistance was shadowed. The curve with the lowest leakage current at the point where the diode turns on was taken when the cell with the highest shunt resistance was shadowed.

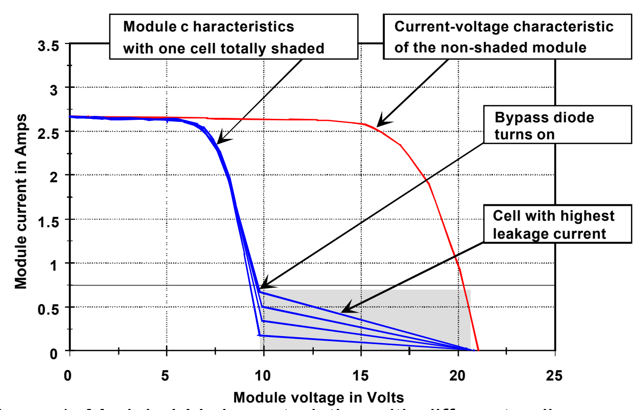

Figure 1: Module I-V characteristics with different cells totally shadowed

This approach should work to identify the cells with the highest and lowest shunt resistance with every module regardless of the diode arrangement or the cell circuitry.

DETERMINATION OF WORST CASE SHADOWING

There are two approaches for determining the worst case shadowing condition.

1. If the cell circuit is accessible, the current through the shadowed cell can be measured directly. In this case the procedure from IEC 61215 will work as long as the procedure is modified to state "Gradually decrease the shadowed area of the selected cell until the I_{SC} (short circuit current) of the selected cell coincides as closely as possible with I_{MP} (the current

through the selected cell when the unshadowed module is producing maximum power)."

2. If the cell circuit is not accessible, direct measurement of the module short circuit current will not work since the by-pass diode will conduct the current around the shadowed cell. The proposed approach is similar to the method utilized to determine the cell shunt characteristics. Take a set of I-V curves which the each of the test cells shadowed at different levels (for example 100%, 75%, 50%, 25%, 10%) as shown in Figure 2. From this data determine the worst case shadowing condition, which occurs when the maximum power point current of the shadowed module coincides as closely as possible with I_{MP} (the current through the unshadowed module at its maximum power).

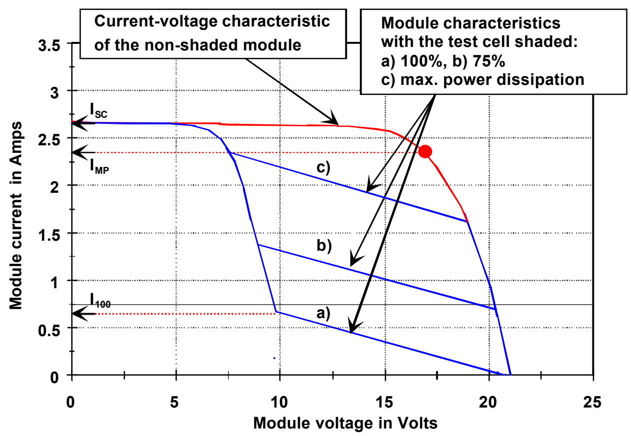

Figure 2: Module I-V characteristics with the test cell shadowed at different levels

In both cases the worst case shadowing occurs when the bypass diode turns on at a current equal to the unshadowed modules maximum power current I_{MP}. The hot spot test should then be conducted at this shadowing level.

TEST DURATION

The IEC 61215 hot spot test is conducted for five (5) one hour exposures each separated by 30 minutes in the dark. The UL 1703 hot spot test is conducted for one hundred (100) one hour exposures each separated by an off-period sufficient to allow the cells to cool within 10 °C of ambient temperature. Clearly there is a major difference between the two. The 100 hour UL test duration is certainly more likely to identify problems, but dramatically increases the cost of the test. The 5 hour IEC 61215 test is certainly more economic, but is it long enough to identify the vast majority of potential hot spot problems?

Our selection for the hot spot test duration must be guided by the results from previous tests. Experience indicates that if a cell has a localized shunt it would fail quickly usually within the first cycle or at least showing signs of degradation within the first hour.

In using the UL hot spot test to define the maximum allowable number of cells per diode, pushing the limit can result in failures. Often these failures occur late in the 100 hour test. These long term test failures usually occur with the better, higher shunt resistance cells as such cells must use fewer cells per diode.

It appears that the lowest shunt resistance cells can be tested in a short amount of time, either using the present IEC 61215 five (5) hour test or maybe even shortening this time if data indicates that less time is sufficient to test for this failure mechanism. On the other hand the highest shunt resistance cells clearly require longer time than 5 hour, but how long still needs to be determined by experiment.

It is also clear that in the field any hot spot will cycle with the sun. However, it is not clear whether it is necessary to cycle during the test procedure as cycling certainly adds to the time and cost. A constant exposure test may allow for overall reduction in the time required to reach thermal equilibrium and therefore to determine if damage is going to occur.

EXPERIMENTAL RESULTS

The proposed method to identify the highest and lowest shunt resistance cells and the method for determining the worst case shadowing conditions has been applied to modules with a number of different cell technologies.

- Multicrystalline silicon BP3160 and BP3125 modules had the diodes turn on whenever a full cell was shaded. The worst case shadowing occurred at approximately 33% for the lowest shunt resistance cells and approximately 20% shadowing for the highest shunt resistance cells. The reverse bias performance of these multicrystalline cells was the most uniform seen for any module type with no cells that can be really be called low shunt resistance cells.
- Saturn mono-crystalline BP7170 modules have 6 diodes per 72 cell modules (12 cells per diode) resulting in a lower percentage power loss than seen for other module designs when a cell is fully shadowed. With Saturn we have seen the highest shunt resistance cells where the worst case shadowing occurs at 12 to 15% shadowing.
- A 40 cell module with new silicon sheet technology cells had very different results. Fully shadowing the cells did not result in the diodes turning on. All of the cells had such low shunt resistance that when shadowed, they passed the reverse current before reaching high enough reverse voltage to turn the diodes on. In one case there was no difference between the shadowed and unshadowed I-V curve, indicating that the cell junction was shorted. These low shunt cells are in the worst case shadowed condition when they are shadowed 100%.

In Reference 1 it has been reported that no clear correlation exists between the maximum cell temperature at localised shunts and the reverse current of cells as heating depends on the severity and the area of the shunt defect. However, experience has shown that there is a good likelihood for catching the worst-case low shunt cell if the 3 cells with lowest shunt resistances out of a batch of cells are selected. As an example Figure 3 shows the plot of stabilised maximum cell temperatures versus leakage currents (100 cells with attached leads) for continuous operation of at –10 V reverse voltage. For some data points marked with numbers the corresponding infrared images are displayed in Figure 4. These thermal images clearly demonstrate that reverse current can be more or less localised leading to different hot-spot heating.

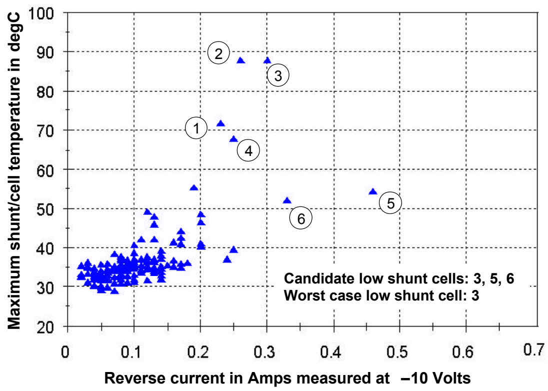

Figure 3: Maximum cell temperature as a function of reverse current measured at 10 volts reverse bias.

SUMMARY

This paper presented an improved methodology for hot spot testing to determine which cells in a module should be tested and what fraction of a cell to shadow for worst case power dissipation. Because this is a new proposal for a standard, it is important that many PV laboratories try to conduct hot spot tests using this new approach and provide their feedback to working Group 2 of IEC Technical Committee 82 on PV.

REFERENCES

[1] W. Herrmann, M. Alonso, W. Boehmer and K. Wambach, “Effective Hot-Spot Protection of PV Modules - Characteristics of Crystalline Silicon Cells and Consequences for Cell Production”, **17th European Photovoltaic Solar Energy Conference**, Munich, 2001.

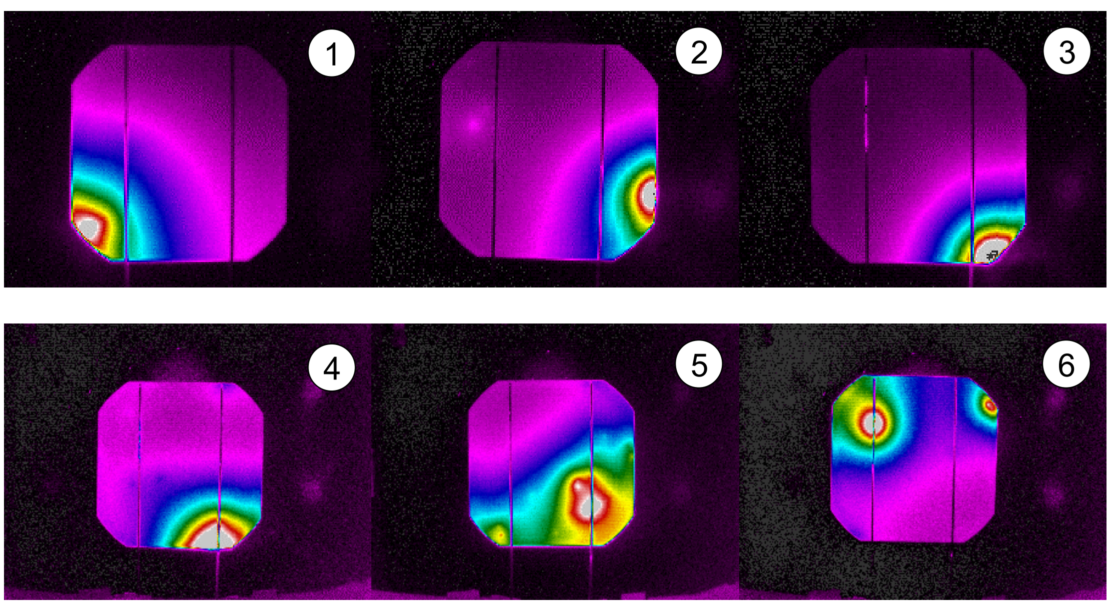

Figure 4: Illustration of heating effects and the formation of hot spots due to increased reverse voltage on six different cells.