HOT SPOT INVESTIGATIONS ON PV MODULES - NEW CONCEPTS FOR A TEST STANDARD AND CONSEQUENCES FOR MODULE DESIGN WITH RESPECT TO BYPASS DIODES

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INTRODUCTION

One of the technical requirements of PV modules for qualification according to the standard IEC 1215 is fulfilment of the pass criteria of the hot spot endurance test [1]. A hot spot situation is existent when a solar cell within a module generates less current than the string current of the module or of the PV generator. This occurs when the cell is totally or partially shaded, damaged, or when cells are electrically mismatched. The shaded cell becomes reverse biased and dissipates power in the form of heat. This article focuses on failures due to cell shading which may occur during operation of a PV system. If no measures are taken, i.e. the integration of bypass diodes in the cell interconnection circuit of the modules, a shading situation may lead to so-called irreversible hot-spot damage of cells where the cell current is concentrated with locally high intensity. This causes focal-point heating with temperatures higher than 150°C, which is above the critical temperature of cell encapsulants of commercial modules. As a result of this, deterioration of the encapsulation occurs. In the worst case this leads to a loss of the insulating properties of the module if the delamination forms a continuous path to the module edge. In addition to this safety risk, delaminations leave visual defects on the module which may affect the acceptance of PV technology among the public.

Whereas in the past publications mainly dealt with the physical process of hot-spots, the numerical simulation of the current-voltage characteristics of PV modules with shaded cells, energy output losses and hot spot susceptibility [2,3,4,5], this article focuses on the following points:

- the characterisation of commercial silicon cells under reverse biased conditions,
- the worst case hot-spot conditions for a PV module,
- a new method for determining the worst case cell within a module for hot-spot testing
- requirements for bypass diode concepts to ensure the hot-spot endurance of modules.

HOT SPOT HEATING

Because the series connection of the PV generator forces all cells to operate at the same current (string current), the shaded cell within a module becomes reverse biased which leads to power dissipation and thus to heating effects. Such a situation is illustrated in figure 1 which shows the typical IV-characteristic of a solar cell in the whole voltage range. Whereas the forward characteristic extends to the open circuit voltage of approx. 0.6 Volts, the reverse biased characteristic is much more extensive and limited by the breakdown voltage. If the cell is shaded, its short circuit current is less than the string current so that it is operated at the reverse characteristic, causing power to be dissipated.

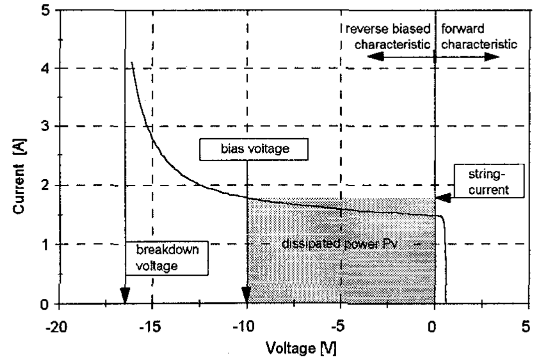

Fig. 1. IV-characteristic of a solar cell in the whole voltage range

For low bias voltages the reverse current is approx. a linear function of voltage (ohmic behaviour). The slope is a measure for leakage currents that appear as an additional component to the dark saturation current of an ideal diode. Leakage currents originate in cell defects and impurity centres in the semiconductor and can be represented by a shunt resistance. At low bias voltages the current is distributed over the whole cell area and heating takes place more or less uniformly. The maximum current density is below a critical limit and the IV-characteristic is stable against thermal effects.

Figure 1 shows that with rising bias voltage the junction breaks down and conducts very large currents. For solar cells the most important mechanism in junction breakdown is the avalanche multiplication which has its origin in a high electric field in the depletion layer that is generated by the bias voltage. At a certain level of the field strength the generated electron-hole pairs gain

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enough energy to ionize lattice atoms which again can generate charge carrier pairs. Cells do not have an homogeneous structure, regions with a higher concentration of impurity centres exist. At high bias voltages these points break down earlier. If the current density at this point exceeds a critical limit the cell is irreversibly damaged by thermal breakdown (burnout) that forms a shunt path in the cell structure. Now at reverse biased conditions the current is locally concentrated, focal-point heating is caused and damage to the cell encapsulation is to be expected (hot-spot).

BYPASS DIODE CONCEPTS

To avoid thermal overload and the formation of hot spots, sub-strings of cells inside the interconnection circuit of modules are bridged by bypass diodes. This measure limits the bias voltage at the shaded cell and thus the dissipated power. The principle of operation of a bypass diode is illustrated in Fig. 3, in which a string of 18 cells is considered. One of the cells is partially shaded whereas 17 are fully illuminated. The string characteristic for this situation is calculated from the IV-characteristic of the shaded cell, the IV-characteristic of the 17 illuminated cells and the transmission characteristic of the bypass diode.

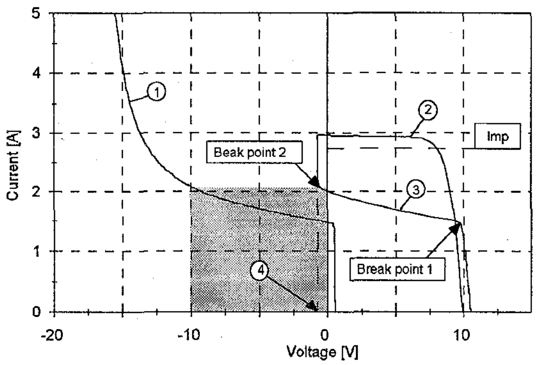

Fig. 2. Sub-string IV-characteristic in case of shaded cells

The string characteristic results from variation of the current from 0 A to the short-circuit current and addition of the associated voltages at the two IV-characteristics. The reverse IV-characteristic of the shaded cell begins to show an effect on the string characteristic when the string current exceeds the short-circuit current of this cell. The string characteristic breaks off at point 1 and proceeds according the course of the reverse characteristic. If the string voltage exceeds the transmission voltage of the bypass diode, the diode becomes conductive. This means limitation of voltage associated with a vertical rise of the string characteristic beginning at break point 2. The maximum reverse voltage at the shaded cell is approximately given by the expression: (No. of cells connected in series) x 0.5 + (transmission voltage of the bypass diode). Considering a bypass diode concept of 18 cells per bypass diode, which is often realised in commercial modules, the maximum bias voltage is approximately -10 V.

WORST CASE HOT SPOT CONDITIONS

In addition to the level of irradiance, the dissipated power at a shaded cell is strongly influenced by the shading rate. Fig. 3 shows the IV-characteristic of a module which consists of two sub-strings with 18 cells each. One cell of sub-string 1 is completely shaded. According to the considerations above, the two sub-string IV-characteristics are added by variation of current. This leads to the module characteristic which shows two break points in the upper voltage range. Worst case hot spot conditions occur when the break point reaches the string current Imp. This translatory shift of the IV-characteristic is achieved by variation of the shading rate.

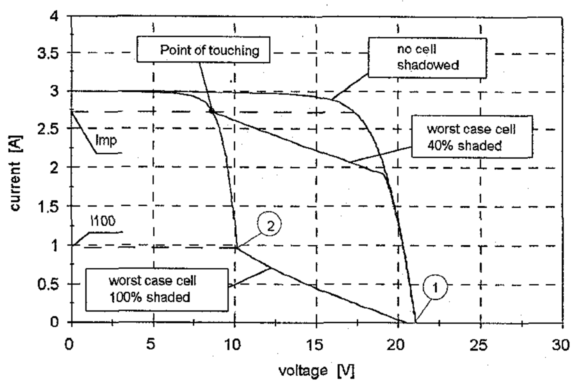

Fig. 3. Worst case hot spot conditions

The specific shading rate which causes worst case hot spot conditions depends on the slope of the reverse characteristic at low bias voltages. From figure 3 we can conclude that it is approximately given by the formula:

$$\left(1-\frac{I_{100}}{I_{mp}}\right)\times 100\% \qquad (1)$$

I_{mp}: maximum power current with no cell shading
I_{100}: current at break point ② at 100% shading rate

For conventional silicon cells, worst case shading rates in the range of 20% to 50% are to be expected. The specific shading rate increases with the number of cells in the sub-string and it is 100% if no bypass diode is present.

REVERSE BIASED CONDITIONS AT CELLS

As cell manufacturers generally provide no information about the behaviour of their cells under reverse biased conditions, the reverse IV-characteristics in the dark were measured for a selection of seven cell types on the basis of six to ten test specimens from current production.

Figures 4 and 5 show the measured sets of characteristics of cells made of poly-crystalline silicon (poly-Si) and mono-crystalline silicon (mono-Si) respectively. It was established that the behaviour under reverse biased conditions of cells of the same type is subject to considerable variations. This concerns both the slope of the reverse characteristics at low bias voltages as well as the value of the breakdown voltage. The breakdown voltages for poly-Si cells are within the range 12 V to 20 V, whereas for mono-Si cells the breakdown voltages can extend up to 30 V. The slope of the curves is slightly higher in the case of poly-Si cells, which indicates a larger current component due to leakage currents. On the other hand, in the case of mono-Si cells the breakdown voltage may have an enormous variation range. This phenomenon was investigated with the aid of an infra-red camera, whereby reverse current was applied to the cells with the best and worst blocking behaviour (see figure 5). The following conclusions were drawn from the thermal images of the cells:

a) The structure of the solar cells is not homogeneous, the temperature distribution is a direct measure of the current density distribution. In the case of the cell with the best blocking behaviour, an overall power dissipation of approx. 11 W resulted in a temperature difference of 25 K between the hottest (90°C) and coldest point (65°C).

b) The cell with the poorest blocking behaviour demonstrated clear temperature peaks at two points. These are probably due to cell damage, which may have occurred during cell production or during soldering of the contact ribbons. Temperatures of 150°C were measured at bias voltage -10V and current 3A.

These results show that the worst case cell within a batch of cells of the same type is characterised by the largest slope of the reverse IV characteristic and the lowest breakdown voltage. It was found that the reverse operation behaviour of cells can be characterised with the aid of the following two characteristic parameters:

a) Variation range of the current at a bias voltage of -10 V, that is approx. the max. bias voltage for a bypass diode concept of 18 cells per sub-string
b) Variation range of the bias voltages at maximum power current of the illuminated cell

Fig. 6 and Fig. 7 show the two characteristic parameters for the 7 cell types tested. If bypass diodes that are connected in parallel to a cell sub-string within a module are to have any protective effect at all, the number of cells connected in series may only be so high that the resulting voltage limit remains below the breakdown voltage of the worst cell. In Fig. 7 this point corresponds to the left range limit of the respective cell type. A (*) at the range limit indicates that the low value could be traced back to cell damages.

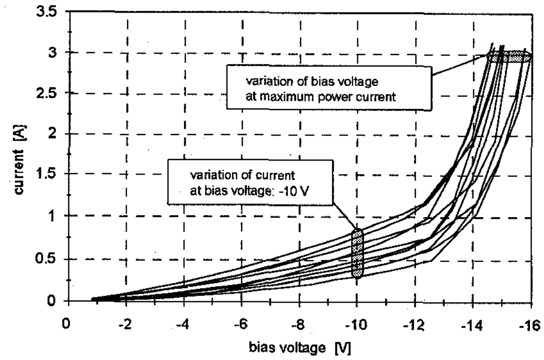

Fig. 4. Reverse IV-characteristics of a poly-Si cell type

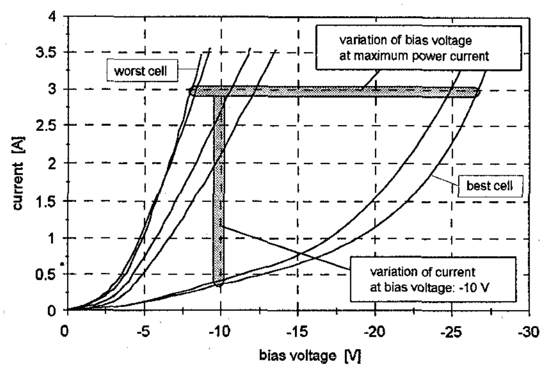

Fig. 5. Reverse IV-characteristics of a mono-Si cell type

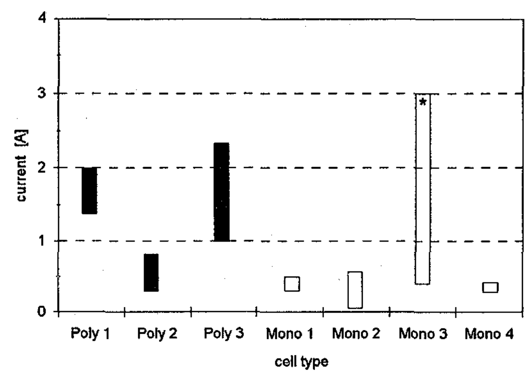

Fig. 6. Variation range of current at bias voltages of -10 V

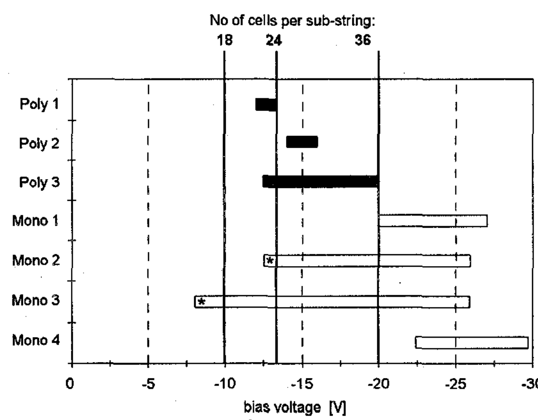

Fig. 7. Variation range of the bias voltage at maximum power current

From Fig. 7 can be concluded that only a concept of 18 cells per sub-string guarantees a protection against hot spots and thermal overload. A concept of 24 cells allready fails in case of 4 cell types investigated.

It should be noted that bypass diodes no longer have a protective effect if cells have previously been damaged as a result of burnout.

HOT SPOT TEST PROCEDURE

The hot spot test procedure is part of the standard IEC 1215, which forms the basis for type approval and design qualification of PV modules. It is one of 11 qualification tests and is performed in the following steps:

a) determination of the worst case cell in the module
b) setting worst case hot spot conditions
c) exposure to 1000 W/m² irradiation at worst case hot spot conditions (5 cycles)
d) diagnostic measurements to detect module failures

With the IEC test procedure, the worst case cell is determined either by measuring the short-circuit current or the stabilised temperature at the shaded cell. Each cell is shaded in turn, a random selection of 30% of the total cells is permitted for large-area modules. The cell which causes the highest decrease of short-circuit current or causes the highest cell temperature is considered to be the worst case cell. However determination by current measurement is not suitable for modules which consist of two or more sub-strings, which is the case with practically all commercial modules. As shown in figure 3, the short-circuit current is not influenced by the shading, as the break in the characteristic ② only becomes noticeable in the upper voltage range. The method based on measurement of the stabilised cell temperature, on the other hand, is time consuming and cost intensive. Because of these disadvantages of the IEC 1215 procedure, a new method was developed to determine the worst case cell. This can be characterised in 2 steps.

Step 1: The module IV-characteristic is recorded without shading and with shading of an arbitrary cell. As the module characteristic in the case of shading follows the shape of the reverse IV-characteristic of the shaded cell starting from the open-circuit voltage, and the worst case cell is characterised by the steepest curve, the worst case cell is the one which supplies the highest module current at the break point ② of the IV characteristic at complete shading. To illustrate this, figure 8 shows the measured IV-characteristics of a 40-cell module with complete shading of a sample of 4 cells. Step 2: The module is operated at a fixed load point by means of a variable electronic load, whereby the voltage is set slightly above the break point ② of the IV-characteristic. The module current at complete shading of each cell is measured and the worst case cell is selected from the series of measurements.

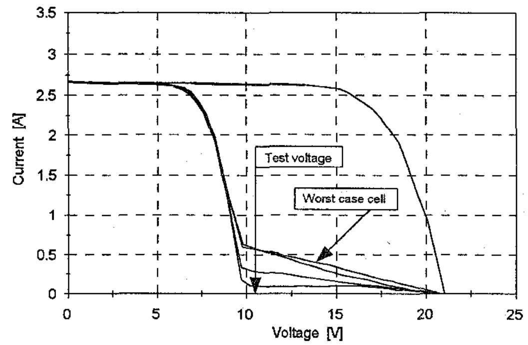

Fig. 8. New method to determine the worst case cell

The advantage of this improved method is that it can be applied in the same way for all types of cell connection in the module (serial and parallel connection of sub-strings). It is a reliable method to determine the worst case cell in a short time.

SUMMARY

Cell manufacturers should provide information to module manufacturers about the operation of their cells under reverse biased conditions. The inhomogeneous behaviour of cells under reverse biased conditions needs further investigation. In particular, cell damage during manufacture should be evaluated. To guarantee resistance of the module design to thermal overload due to partial shading, the number of cells in a sub-string should be limited to 20. The hot-spot test procedure of IEC 1215 should be generalised for all types of cell interconnection circuits. The selection of the worst case cell should be improved by measurement of the module current at the characteristic break point of the IV-characteristic.

ACKNOWLEDGEMENTS

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