DETERMINATION OF HOT-SPOT SUSCEPTIBILITY OF MULTISTRING PHOTOVOLTAIC MODULES IN A CENTRAL-STATION APPLICATION*

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ABSTRACT

Part of the effort of the Jet Propulsion Laboratory (JPL) Flat-Plate Solar Array Project (FSA) includes a program to improve module and array reliability. A collaborative activity with industry dealing with the problem of hot-spot heating due to the shadowing of photovoltaic cells in modules and arrays containing several paralleled cell strings is described. The use of multi-parallel strings in large central-station arrays introduces the likelihood of unequal current sharing and increased heating levels. Test results that relate power dissipated, current imbalance, cross-strapping frequency, and shadow configuration to hot-spot heating levels are presented. Recommendations for circuit design configurations appropriate to central-station applications that reduce the risk of hot-spot problems are offered. Guidelines are provided for developing hot-spot tests for arrays when current imbalance is a threat.

INTRODUCTION

An earlier report (1) discusses the development of a laboratory test to determine module hot-spot susceptibility. In the process of applying this test to large central-station arrays with extensive cell paralleling, it became clear that modifications of the test were necessary.

At the root of the problem is the fact that the standard Block V hot-spot test (2) was developed for single-string modules in which the maximum hot-spot current is limited to the maximum string current. With extensive cell paralleling and numerous cross ties, it is possible for a current imbalance to develop and for the entire source-circuit current to be channeled through the hot-spot cells. The level of severity of the problem is directly proportional to the number of parallel strings, and the probability of occurrence increases as the frequency of cross-straps increases.

In view of this, the hot-spot problem can be potentially more severe in a central-station application because of the use of multistring modules and the paralleling of modules in panels. On the other hand, it is potentially easier to control shadow conditions in a central station through personnel control policies and by positioning buildings, poles, towers, etc., carefully to limit shadowing. The relationship between the type of shadowing and subsequent hot-spot intensity is an important one to consider for reducing the risk of damage.

The study reported here addresses the problem of the system designer in assessing the potential for hot-spot problems in central stations and in applying the appropriate circuit-design strategies and policies to control shadowing. A principal objective was to gain an understanding of the major parameters influencing hot-spot heating in central stations and the sensitivities of the rising temperature to these parameters. A second objective was to acquire the information required to develop a hot-spot test that would allow module and system designers to evaluate module hot-spot susceptibility in the central-station environment. These data are also necessary in developing circuit-design strategies and shadow-prevention policies for limiting the incidence and the severity of hot-spot heating.

BACKGROUND

Before presenting the details of the present study it will be useful to review the general factors associated with cell hot-spot heating.

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Hot-spot heating occurs when a solar cell is forced to pass a current greater than its short-circuit current. This circumstance typically arises when a cell's short-circuit current level is reduced below that of its neighboring cells by partial or full shadowing, or by cell breakage.

The resulting power dissipated in the affected cell is proportional to the product of the current passing through it and the voltage developed across it. Without the introduction of bypass diodes, this reverse voltage is only limited by the system voltage itself. However, with the introduction of bypass diodes, the maximum reverse voltage is limited to that generated by the number of series cells per diode.

Figure 1 illustrates the concept of hot-spot heating where the I-V curve of the affected cell is given by curve B and that of the normal cells by curve A. With a bypass diode around three cells, the maximum voltage drop across the bypassed cells is limited to the 1.0-volt diode drop, or, with an ideal diode, to zero volts. This operating point, defined by the intersection of the A + B curve and the zero-voltage axis, results in the full voltage of the A cells being developed across the affected B cell. The resulting power dissipation is denoted by the crosshatched area.

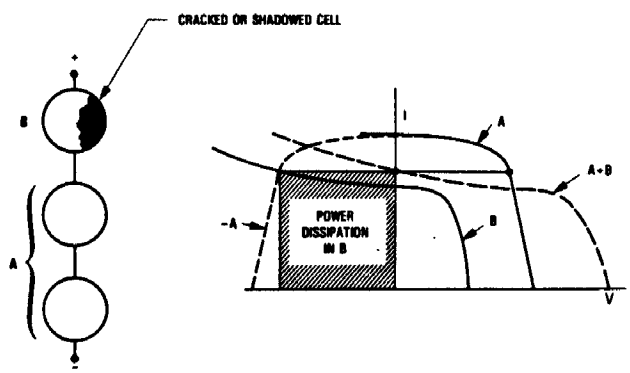

Figure 1. Visualization of Hot-Spot Cell Heating With a High-Shunt-Resistance Cell

In general, the current passing through the affected cell is influenced by its attenuated short-circuit current and its shunt resistance, and is limited by the short-circuit current of the normal cells in series with it. With high-shunt-resistance cells, such as cell B in Figure 1, worst-case power dissipation occurs when the current of B is only slightly reduced (partially shadowed) as shown. On the other hand, with low-shunt-resistance cells, such as cell C in Figure 2, maximum power is developed under full shadow conditions where the photocurrent of the affected cell is reduced to near zero. Note that the power dissipation in the high-shunt-resistance cell (B, Figure 1) tends to be controlled by its own photocurrent, whereas that of the low-shunt-resistance cell (C, Figure 2) is controlled by the maximum string current.

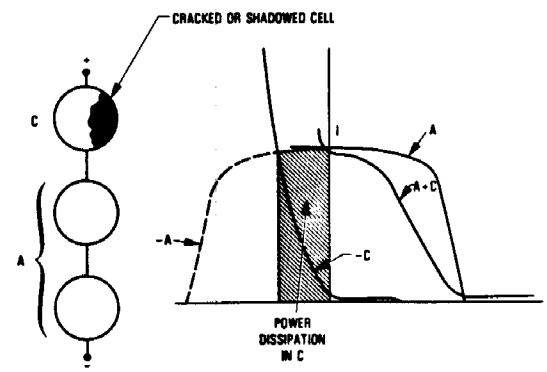

Figure 2. Visualization of Hot-Spot Cell Heating With a Low-Shunt-Resistance Cell

Figures 1 and 2 show that the string current is generally limited by the short-circuit current of the unaffected cells in series with the affected cell. However, when there are cell strings within the bypass-diode circuit that are connected in parallel with the affected cell string, current from the parallel strings can pass through the reverse-biased cell in certain circumstances. This unequal current-sharing by parallel strings under reverse-bias conditions, referred to as current imbalance, occurs when the shunt resistance of one of the cell strings is significantly lower than that in the others. This phenomenon does not occur in cells like cell B in Figure 1, where the maximum current passed by the cell at a given voltage is limited by the photocurrent. Instead, it occurs in cells like cell C in Figure 2, which can pass a large amount of current without reaching the limiting voltage. Inasmuch as the amount of power dissipated by such a cell can be quite large, due to the high overcurrent, the most severe overall hot-spot heating occurs when such a cell is fully shadowed and current imbalance exists.

Another factor contributing to the eventual hot-spot-induced temperature rise is the degree of localized heating within the cell caused by nonuniform current density. The total current flowing through the cell is composed of the photocurrent, which is directly proportional to the illumination level and is distributed uniformly over the illuminated area, and the current passing through the shunt resistance. The latter is highly concentrated because of the nonuniformity of the shunt resistance, the actual conducting paths being highly localized regions caused by point defects. The degree of nonuniformity of the heating over the cell area, and therefore the hot-spot temperature rise, is generally greater for cells (such as C, Figure 2) where most of the power is dissipated in the localized shunt resistance.

A second factor that exacerbates the nonuniform heat dissipation is the nonlinear temperature dependence of doped silicon. With semiconducting silicon, electrical resistivity increases with temperature to a point, and then rapidly decreases with further temperature increases. The result is an unstable channel of current to the lower-resistance hot spot, once the critical temperature is reached. This leads to still more localized heating and higher temperatures. An example of nonuniform heating is shown in Figure 3, which shows the typical degradation obtained from cell hot spots that almost always occur at one of the edges of the cell.

Figure 3. Example of Nonuniform Hot-Spot Cell Heating in a Four-Inch Test Cell

In summary, the hot-spot temperature of a reverse-biased cell is related to the power dissipated in the cell, but not in a linear, easily definable way. Although a minimum amount of power dissipation is necessary to achieve a significant temperature increase, the same power dissipation may lead to different levels of temperature rise even in the same cell under different shadow conditions and different states of localized heating. The actual temperature rise is strongly influenced by the degree of nonuniformity of heating within the cell.

STUDY APPROACH

The chosen approach to understanding hot-spot heating in a central-station environment involved an extensive series of field experiments on actual central-station source circuits or portions thereof. The experiments were done at the Acurex Corp. field-test site in Mountain View, California, at JPL's field-test site in Pasadena, California, and at the ARCO Solar, Inc., test site in Chatsworth, California.

Detailed objectives of the tests involved four major issues:

(1) Quantifying the conditions under which current inbalance is likely to occur and to cause aggravated hot-spot heating.

(2) Quantifying circuit-design strategies such as series-paralleling and bypass diodes for controlling hot-spot heating damage. Two effects work in opposite directions with respect to the need for diodes. The potential for current imbalance implies more bypass diodes or fewer crossties to ensure that hot-spot problems do not occur. On the other hand, if shadow conditions can be controlled so that the risk of the occurrence of hot spots is minimized, use of fewer bypass diodes may be acceptable, thus lowering system costs.

(3) Understanding quantitatively which shadow conditions lead to worst-case heating. This is important for developing proper controls over array shadowing for the alternative strategy that makes possible the use of fewer bypass diodes.

(4) Developing recommendations for a more general hot-spot heating test applicable to cases where current imbalance is likely.

Acurex Tests

To obtain data on these issues, tests were performed on the verification array built for Phase I of the Sacramento Municipal Utility District (SMUD) one-megawatt photovoltaic central station. The array, situated at the Acurex Corp. facility in Mountain View, California, consisted of 32 ARCO Solar modules in series by eight modules in parallel. The modules were assembled in panels, with each panel containing four modules in series by eight in parallel. Each module consists of 12 four-inch-square cells in series by three cells in parallel, with cross ties after every three cells. The array, mounted on a single north-south horizontal-axis tracker, produced 10.5 kW peak power and approximately 56 A maximum-power current at standard test conditions (STC), 25°C and 100 mW/cm^2.

Tests performed with and without bypass diodes demonstrated that significant hot spots could occur in conditions such as those presented by persons standing in front of an array that lacks diode protection. The phenomenon of current imbalance was demonstrated in its extreme when a section of eight parallel modules was shadowed with the array at short circuit and with no bypass diodes. All of the current from a panel (≈56 A) was channeled through one string of cells in a matter of seconds, causing substantial local damage. This type of event would not be expected in normal operation, with adequate use of diodes.

Subsequent tests were performed with the array operating near the maximum power point and with bypass diodes around every two series modules

(every 24 cells). To investigate the effect of internal paralleling and cross-tie frequency on the frequency of diode placement, leads were attached directly to the cell interconnects of a number of modules in one of the panels. The number of cross ties was then varied and the currents and voltages of the cells being tested were measured. The cell hot-spot temperatures were monitored with an IR camera.

JPL Tests

The types of tests performed on the SMUD verification array were continued at the JPL test site with the same modules and with some new ARCO SMUD-type modules. Eight modules in all were connected in a panel, with two in series by four in parallel. The JPL panel faced south with a fixed tilt angle normal to the sun at noon. Figure 4 shows its back side.

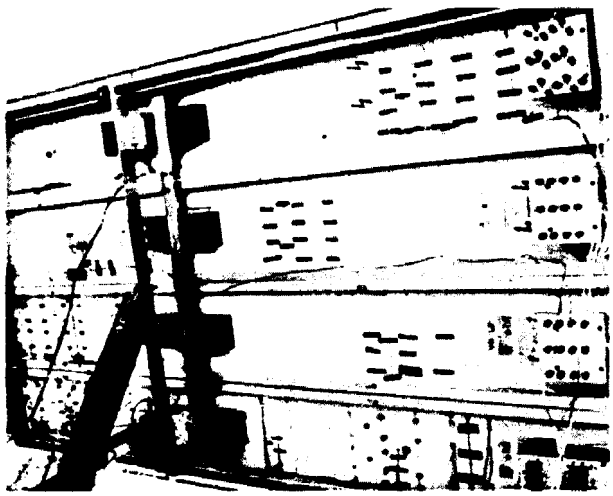

Figure 4. JPL Hot-Spot Test Panel

During testing the panel was operated at short circuit, simulating operation with the bypass diode turned on (one diode per two modules). Modules with leads attached were again used to allow various degrees of cross-tying to be explored. Current, voltage and thermocouple data were taken automatically and were recorded by a data logger. Thermocouples were attached to the backs of the modules, each one at the locations of several test cells. When these cells were not shadowed the thermocouple provided values of normal cell operating temperatures. An IR camera was again used to obtain temperatures of the hot-spot areas from the back side of the module. The data were recorded simultaneously on videotape for later computer reduction. The ambient temperature and plane-of-the-array global irradiance were also recorded.

For most of the testing a shadow mask covering one cell's width was suspended above the four parallel modules and the amount of cell area covered was varied by changing the relative angle of the shadow mask.

ARCO Solar Tests

After the Acurex and JPL field tests that used bypass diodes every 24 cells, a series of hot-spot tests was conducted at ARCO Solar's Chatsworth field site using bypass diodes around every 12 cells (one for each module). These tests used a SMUD Phase 2 (PV2) protype 9 x 16-ft panel consisting of individual laminates (frameless modules) with the same cell and circuit arrangement as those of the modules used in the Acurex and JPL tests. The panel was made up of four subpanels in series, each subpanel consisting of nine laminates in parallel with a bypass diode (Semikron SKKD 81/02). The test panel, shown in Figure 5, was mounted on a two-axis tracker with shadow masks attached directly to it. The panel was provided a four-terminal cable for I-V curve tracing and was instrumented for measurement of plane-of-the-array irradiance and cell temperature. An IR sensor was used in addition to thermocouples to measure hot-spot temperatures.

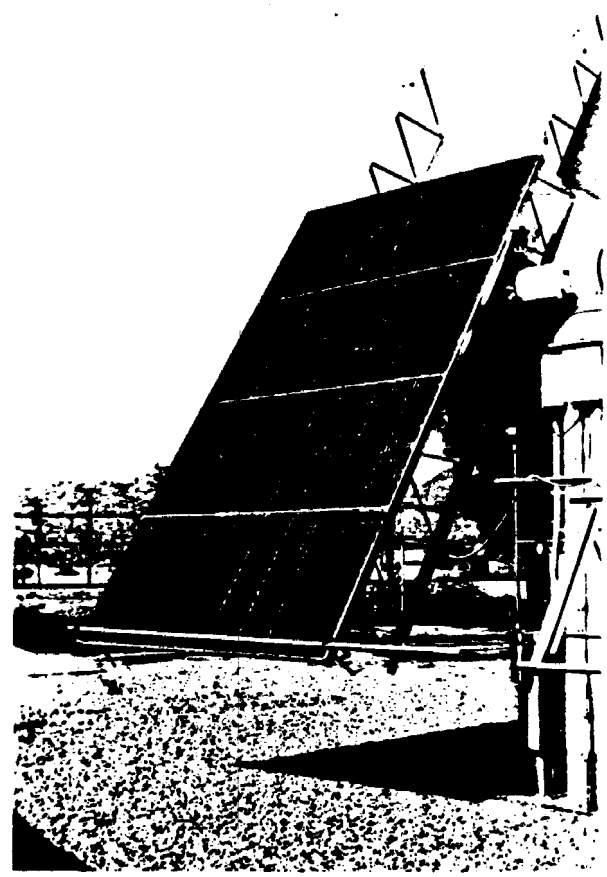

Figure 5. ARCO Solar Hot-Spot Test Array

Two groups of tests were conducted. The first was a series of short-term (20 to 60 minutes) shadowing exposures at short circuit to establish the worst-case heating conditions. The shadow conditions used were: masking of 50% of a subpanel, masking of one module, and masking of one row of cells across the panel width. The last is equivalent to the majority of the shadow configurations used in the JPL testing. This case was further broken down into hard shadows covering 100%, 75%, 50% and 25% of each cell in a shadowed row. The 25% shadow produced the highest hot-spot temperature, 91°C. The bypass diodes limited the back-bias voltage to 6.1 volts.

The second part of the ARCO tests used the same 25%, full-row shadow and exposed the panel to more than 100 hours of short-circuit operation at irradiances greater than 80 mW/cm^2. Maximum cell temperatures were consistent with the short-term test and evidence of current imbalance was not detected in this 12-cells-per-diode configuration. The shadow mask was tried on all 12 rows of the subpanel; it produced consistent cell temperatures, back-bias voltages, and currents. No attempt was made to vary the number of cross ties; however, the panel is being modified to provide for variable module cross-tying and intermodule paralleling within the diode block, for future testing.

RESULTS

Based on the three sets of experiments described above, it can be concluded that field hot-spot testing is fraught with difficulties and the phenomenon itself is complex. In general, however, the results from the tests at Acurex, JPL and ARCO were consistent and complementary. The issues listed above were illuminated, and some were quantified.

A key difficulty was finding a quantitative measure of hot-spot heating severity. Peak cell temperature is probably the best indicator in this regard, but unfortunately it is strongly dependent on the statistical variability of the cell shunt resistance level and areal distribution within each cell. Varying environmental conditions such as air temperature and wind velocity further complicate temperature interpretation.

Because severe heating often caused outgassing and blistering of the encapsulant, the accuracy of the IR camera determination of peak cell temperature was improved considerably at higher temperatures when the Tedlar back cover was removed, exposing the cell. The uncertainty in the temperature measurements, after all possible steps were taken to minimize it, ranged from 2°C at lower temperatures to 10°C at higher temperatures.

To correlate the temperatures measured in the field with those associated with the standard hot-spot test, it was necessary to correct for the different ambient temperatures. Field test conditions at the JPL site, for example, ranged from 19° to 26.8°C and 75 to 105 mW/cm^2, whereas the hot-spot test simulates conditions of 40°C and 100 mW/cm^2. To effect the correction, a stable cell with uniform temperature distribution was selected as a reference in one of the field-test modules. The cell was then electrically isolated from its circuit and subjected during each of the test runs to back-biasing similar to that of the laboratory hot-spot test. It was then subjected to the actual laboratory hot-spot test. Figure 6 is a plot of the resulting laboratory hot-spot temperature as a function of power dissipated. Measured field-test temperatures of other cells were subsequently normalized to equivalent laboratory-test values by comparing them with the reference cell's temperature under the same field conditions. The amount of adjustment was equal to the difference between the measured hot-spot temperature for the reference cell in the field and the temperature obtained in the laboratory (Figure 6) for the same power dissipation.

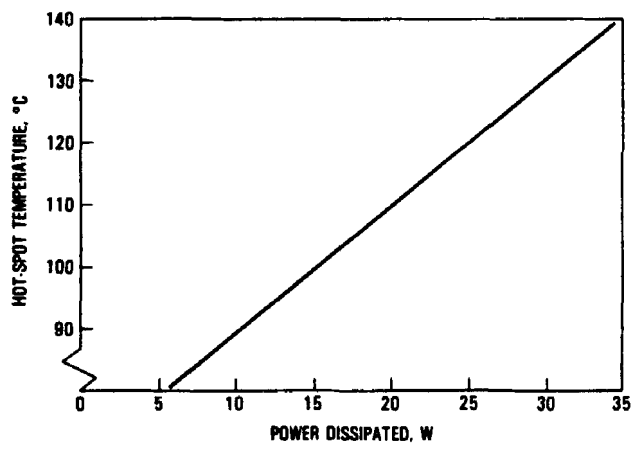

Figure 6. Reference-Cell Hot-Spot Temperature as a Function of Power Dissipated in Laboratory Hot-Spot Test

Results of the test program, with reference to the normalized field-test temperatures presented in Table 1, follow. Since a good correlation between power dissipated and hot-spot temperature could not be found, for reasons discussed above, Table 1 has been constructed and gives the bounds of the hot-spot temperatures for various ranges of each of a number of parameters to which hot-spot temperature is sensitive. The median temperature and the upper and lower extremes are given.

Levels of Current Imbalance

A key objective of the test program was to determine the conditions under which detrimental levels of current imbalance exist. In the various shadow configurations, current imbalance occurred only with 100% shadows and produced current levels in the affected cells in the range of slightly less than the cell short-circuit current to three times the cell short-circuit current (2 to 7 A).

Table 1. Ranges of Adjusted Hot-Spot Temperatures as a Function of the Values of the Parameters to Which the Temperature Is Sensitive

Parameter	Limits on Parameter	Hot-Spot Temp., °C
Current <100% Shadow	1.55-2.5 A	Low 86 Median 105 High 135
Current 100% Shadow	1.45-1.6 A	91-96 (3 Values)
	2-2.6 A } Occurrence of Current Imbalance	Low 95 Median 150 High 185
	4.6-7.0 A } Occurrence of Current Imbalance	Low 150 Median 220 High 310
Level of Power Dissipation <100% Shadow	12-18 W	Low 86 Median 105 High 135
Level of Power Dissipation 100% Shadow	9-19 W	Low 91 Median 150 High 185
	19-26 W	160-245 (3 Values)
	26-37 W	220-310 (5 Values)
Area Shadowed	<100%	Low 86 Median 105 High 135
	100%	Low 90 Median 155 High 310

Worst-case current imbalance occurred in tests in which a single row of parallel cells was shadowed and cross ties were introduced after each row of parallel cells. In this case, current from all three strings in the module passed through one cell. The current imbalance produced hot-spot temperatures on the order of 200°C or more and caused the encapsulant to blister and discolor severely, with gas bubbles on the front side. Little if any current imbalance was noted in modules with cross ties after every three cells.

When protective diodes were used with at least every 24 cells, current imbalance occurred only within modules, not between modules. The level of current imbalance was coupled with the total level of leakage current passed by the shadowed cells within the module. At lower current levels, 60% to 70% of the total available module current passed through the hot-spot cell, whereas at high levels (above 6.5 A) more than 90% channeled through the hot spot. The hot-spot temperatures achieved for the lower levels of current imbalance ranged from mild to severe. Although current imbalance does not necessarily lead to severe hot-spot heating, all of the cases above 4.6 A (about twice the cell short-circuit current) produced severe temperatures.

Only in the extreme-short-circuit test run at Acurex without bypass diodes was current imbalance between modules noted.

Power Dissipation

Although a plot of hot-spot temperature versus power dissipation is not possible, for reasons given above, it is advantageous to know the bounds on the temperatures achieved for a given power level, since power level can be related to diode frequency and series-parallel configuration. For a range of power dissipation between 12 and 18 W, and less than 100% shadow, there is no significant difference between the normalized temperatures obtained for the lower end of the power range and those for the higher end. For 100% shadows and power levels between 9 to 19 W, there is again no difference between the lower and upper power levels. However, the higher temperatures caused severe physical degradation. For levels in the range of 19 to 26 W, significant degradation could be expected in all cases. Power levels in the range of 26 to 37 W result in high temperatures and severe degradation.

The higher power levels, not associated with current imbalance (<19 W), led to substantial hot-spot heating, reinforcing the rule of thumb that the diode frequency should be greater than one for every 24 cells. The power levels above 19 W were associated with current inbalance and the temperatures reached indicate clearly that measures must be taken to ensure against current imbalance.

Influence of Different Shadows

In each of the tests, studies were run to assess the sensitivity of the array to various shadow configuratons. The extent of the shadow is important, in terms of the amount of individual cell area covered and in terms of the number of parallel cells or modules across which it extends. The shadow can be deep or it can be diffuse; identifying the shadows causing the most serious hot-spot problems is important in controlling hot-spot heating in central stations.

It was first observed in the tests that large shadows that cover a number of series cells in each shadowed string do not cause noticeable heating when bypass diodes are used, because the diode prevents large reverse voltages, and the voltage that is allowed is distributed among the several shadowed cells.

Significant hot-spot heating occurs when shadows are large enough to cause the diode to conduct, and when there are cell strings with one or two shadowed cells. In several tests, for example, it was verified that shadowing a portion of the array with a broad shadow and then shadowing the test module with a narrow shadow produced the same results as shadowing the entire array with a long narrow shadow. The latter simulates the shadow of a pole; the combination of broad and narrow shadows simulates something like a truck with an upright exhaust stack.

Most of the hot-spot temperatures described here were obtained with a long, narrow shadow. Two cases of shadow density were considered with this shadow: full cell coverage (100%), and partial cell coverage (less than 100%).

The hot-spot temperatures obtained with less than 100% shadowing were mostly below the marginal range of 120° to 150°C, where some form of degradation can be expected. This is consistent with the temperatures measured in the Block V hot-spot test, and with the fact that no current imbalance was noted under partial illumination.

With 100% shadows, temperatures ranged from below 100°C to above 300°C, depending on the level of cell leakage current. The temperatures above 100°C were only achieved when current imbalance existed.

A final note: the difference between a shadow produced by a mask a foot above the surface and a deep shadow produced by placing the mask directly on the surface was found to be insignificant.

RECOMMENDATIONS

It is possible to make tentative recommendations for the circuit design and testing of central-station arrays, based on these results.

Circuit-Design Options

The best circuit-design option to ameliorate hot-spot problems is the use of bypass diodes to limit the maximum reverse voltage. In addition, in source circuits involving parallel solar cells, it is important to minimize the chance of current imbalance by controlling the frequency of cell cross ties. As the number of cells per substring decreases, there is a greater risk of one string having a significantly lower shunt resistance; as the number of cells increases, the shunt resistances of the various substrings average out, becoming equivalent. For two or three parallel strings per module, cross ties should be no more frequent than every three cells; for four to six, no more frequent than every six cells. For more than six parallel strings, cross ties should be no more frequent than every 10 to 12 cells. In addition, there should be at least one bypass diode for every 12 to 18 cells (more if the above guidelines are exceeded). The ratio of the power increase with current imbalance to that without it must be equated with the number of parallel strings; therefore, the voltage must be reduced by the same factor. In the tests described, with one diode per 24 cells, stressful heating was obtained without current imbalance and severe heating with imbalance. When one diode per 12 series cells was used, acceptable heating levels were achieved.

Hot-Spot Test Options

The results of the field hot-spot test indicate that the laboratory test for module hot-spot susceptibility gives an adequate indication of what to expect in the field if there is no current imbalance. However, when current imbalance is possible, certain changes in the test procedure are recommended. Based on the results of the test program, it is first concluded that the procedure is correct as it is for high-shunt-resistance (type A) cells because these cells do not participate in current imbalance.

Low-shunt-resistance (type B) cells are subject to current imbalance and require modification of the test procedure: it is recommended that the test current (I_L) be increased to the short-circuit current level of the module under conditions of 100 mW/cm^2, NOCT. This current limit was equal to the cell short-circuit current, which is still correct for cases with no current imbalance.

Field Test Options

Because the hot-spot heating test as modified above allows worst-case current imbalance, it is useful to conduct hot-spot heating tests in the field under actual current-imbalance conditions. Although the specifications and procedures for this type of test are yet to be developed, the long-duration field test, defined in the SMUD PV2 photovoltaic panel procurement specifications by Acurex and implemented by ARCO, provides an excellent starting point.

The results of the field testing performed and described also suggest guidelines for the development of a field hot-spot test. It was observed, for example, that the shunt resistances of some of the cells changed as a result of the tests. This was more frequently observed in cells that had sustained excessive heating levels. As time went on, the magnitude of their response to hot-spot heating increased. Another interesting effect noted in one of the test modules was the switching of the current path between one parallel cell and another when changes such as altering the shadowing were made. Therefore, any field testing to determine the existence and effect of current imbalance should involve a test duration on the order of 100 hours, the same as the laboratory test. The test should also be performed when the irradiance in the plane of the array is 80 mW/cm^2 or more and the air temperature is higher than 20°C. This means that in many parts of the country the test may not be possible for six months of the year. When conditions are generally acceptable, a tracking array would allow the test to be performed in two weeks of good weather. A fixed array would probably require a month of good weather.

The test array should contain as many parallel modules as a source circuit in the central station and as many series modules as would be protected by a diode. Test cells from several of the test modules should be selected in the same way as in the laboratory test except that at least five low-shunt-resistance cells (type B) involving at least three separate modules should be selected. The test should be performed with a shadow mask

covering the entire area of one row of parallel cells. Unless the orientation of the shadow mask can be changed continuously to keep the area covered constant, the mask should be clamped directly to the array. Alternatively, if a sufficiently representative sample of cells cannot be located in a single geometric row across the array, individual cells could be masked if each of the parallel substrings within the series block in the module contains one shadowed cell and all substrings across the full array width within the diode block are shadowed. After the test is completed, the test modules should be evaluated in the same way as those in the laboratory test.

CONCLUDING REMARKS

The results presented here provide guidelines for the selection of module series-parallel configurations and the frequency of use of diodes. The multiple testing described here is believed to bracket the possible protection options, from no bypass diodes, to a use frequency slightly lower than the guidelines, to one within the guidelines. The issue of current imbalance has been addressed; results indicate that future hot-spot testing must take it into account.

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