NON-UNIFORM CONDITIONS AND PERFORMANCE IN PARALLEL-ONLY AND SERIES/PARALLEL ARRAY CONFIGURATIONS

A. Driesse
Photovoltaic Performance Labs Inc.
Kingston, Canada
anton.driesse@pvperformancelabs.com

B. Harris
Sustainable Energy Technologies
Calgary, Canada
brent.harris@sustainableenergy.com

ABSTRACT: As the solar industry matures, custom designed projects are giving way to standardized installation practices that expose PV arrays to a variety of non-ideal conditions. In the search for solutions, lower module prices are shifting the attention to system integration components and techniques. While the susceptibility of conventional system design to performance degradation due to module mismatch is a known limitation, the magnitude of this problem and the ability of new system integration solutions to overcome it are not yet well understood.

This paper presents the results of a side-by-side comparison of the performance of two identical PV arrays under non-ideal conditions that differ only in the details of their interconnection: one in the conventional series-parallel configuration, and the other in a parallel-only configuration. It was found that module technologies with low fill factors such as a-Si make arrays that are very tolerant to small mismatches, and that large differences in module output caused by partial shading are accommodated with virtually no mismatch loss by the parallel-only array.

Keywords: system performance, shading, mismatch losses, amorphous silicon, monitoring, PV array

1 INTRODUCTION

Guided by the market dominance of feed-in-tariff (FIT) support policies, the PV industry has become increasingly focused on economic performance. With these policies revenue is directly proportional to system performance, which depends not only on the components that make up the system, but also on how they are integrated. Non-uniform conditions at the system level can cause mismatch losses, and the potential loss of revenue justifies investment in system integration solutions to minimize those losses.

2 PROJECT OBJECTIVES

The motivation for this project is the desire to validate the hypothesis that an array consisting of shorter strings suffers lower mismatch losses than one with longer strings [1], and to quantify the difference. The principles of mismatch losses are well understood and can be dramatically demonstrated with well-chosen examples, but the long-term impact on the bottom line of an average commercial system is not so well understood.

The primary objective, therefore, is to develop a better understanding of the factors that cause mismatch conditions in a real-world context, and to assess the extent to which the mismatch causes system-wide losses. This understanding will enable us to better predict mismatch losses, plan for mitigation strategies, and weight the costs and benefits of different solutions that are available. Software and/or practical design rules will ultimately help system planners achieve better energy performance and better economic performance as well.

3 BACKGROUND

PV arrays are composed of modules connected in series and/or parallel to reach the desired power level, current rating, and operating voltage range. This electrical configuration must fit the capabilities and constraints of the chosen inverter, or alternatively an appropriate inverter must be sought to accommodate the chosen array configuration. Conventional sizing and design methods assume that the electrical output of an array of given capacity will be the same, regardless of how many modules are placed in series or parallel.

Nevertheless, it is commonly recognized that there will be losses due to module mismatch, as well as various types of soiling and shading that can be non-uniform. It is difficult to predict the magnitude of these factors, and it is even more difficult to predict the losses they cause. Long strings of cells and modules are particularly vulnerable to non-uniform conditions since the string current is limited by the poorest performers.

Mismatch between modules can arise due to a variety of factors. For example:

- Variations in STC module performance due to manufacturing tolerances and unequal degradation. [2]
- Variations in magnitude and phasing of the seasonal annealing effect for a-Si modules.
- Soiling.
- Snow.
- Partial shading.
- Variations in module installation angle.

It is not possible to change the fundamental nature of PV cells and eliminate mismatch conditions, but there are various remedies available for reducing the associated system losses:

- Bypass diodes
- Multistring inverters
- Module scale inverters
- Module scale MPPT
- All parallel wiring

All remedies involve trade-offs between potential performance gains, complexity and cost. The project reported on here focuses on the less common solution of all parallel wiring.

4 PROJECT DESCRIPTION

4.1 System Description

The experimental system has two PV arrays consisting of identical modules, but of different electrical configurations. In one case, all modules are connected in parallel; in the second case they are connected in strings of 5 modules. The modules used for this system comparison are amorphous silicon (NexPower NH-100UX-4A).

Each array is coupled to an inverter that is suitable for the resulting DC voltage. The parallel-only array uses a Sunergy ELV 208 inverter from Sustainable Energy Technologies nominally operating at 75Vdc, whereas the series-parallel array uses a Sunny Boy 5000U inverter from SMA nominally operating at 375Vdc.

Sensors and Data Acquisition

The quality of the measurements is a key factor for the success of the project. It is very important to identify where in the system various losses are incurred and what external factors influence those losses.

- array AC voltage, current, power, energy
- array DC voltage, current, power, energy
- individual module and string currents
- multiple module temperatures
- solar radiation

4.2 Experimental Procedures

In addition to long-term monitoring and analysis of unshaded performance, experiments are carried out to observe the response of both systems to various forms of partial shading. In short-term controlled experiments specific modules are shaded in specific amounts, whereas in long-term experiments obstructions installed that could represent obstacles typically found on commercial roof tops such as another part of a building, and the shadows evolve with the sun position and weather conditions. Initially we planned to also use smaller obstacles such as overhead wires, poles and pipes as well, but based on what we have learned so far these items will rarely cause a significant loss for these systems.

5 ASSESSMENT OF *SMALL* NON-UNIFORMITIES WITHIN THE ARRAYS

Much of the initial effort in analyzing the arrays focused on establishing a baseline for comparison. By design the arrays are identical except for the connection scheme, but in practice various small differences exist, both within the arrays and between the arrays. To isolate the effect of the connection scheme on the total performance, and thus evaluate susceptibility to mismatch losses, we have to assess the existing non-uniformities first.

5.1 Variations in module capacity

The initial output power of the modules varies within the specified range of ±5%, as confirmed by flash test data from the manufacturer. In fact most modules were within ±2%, although the average value was 0.75% below the initial specification. Based on this data the STC installed capacity of the series-parallel system was 6566 Wdc, and that of the parallel-only system was 6584 Wdc, a difference of 0.3%.

Most of the data used for analysis was collected more than 6 months after installation, and at this point the installed capacity is significantly less. An initial degradation of 24% is specified by the manufacturer. We lack the reference conditions to accurately measure the absolute degradation, but more important for us is the relative degradation. Unequal degradation could increase non-uniformity and create mismatch losses, and it could increase the difference in installed capacity between the arrays.

The parallel-only array is easiest to assess for non-uniformities since individual module currents are measured. Figure 1 compares the production per module on a sunny day to the flash test P_{mp}. The spread in the measured module production is much greater than in the initial module capacity, but is still within ±5%.

The correlation between the measurements is very poor, supporting other reports that amorphous silicon module degradation is quite variable [2]. The lack of correlation also means that the two array capacities have to be carefully checked since their difference may be greater now. This must be taken this into account in comparisons between the systems.

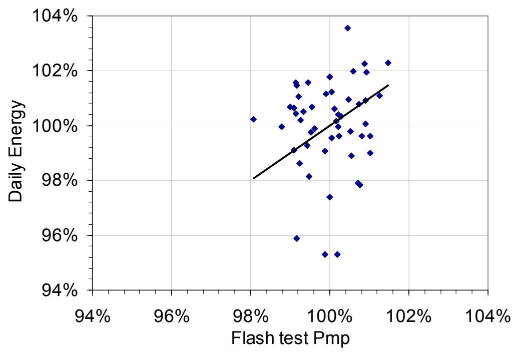

Figure 1 Energy output for a sunny day compared to factory flash test rating for 50 modules.

5.2 Soiling

Soiling became evident soon after the installation, and remains very noticeable throughout the array. With the exception of the very bottom edge, however, it is quite uniformly distributed. Due to shape and orientation of the cells – long vertical strips – any extra accumulation at the bottom edge has a minimal effect, so the overall effect of soiling on this array is essentially uniform.

During one visit we cleaned a section of each array, but the effect on power output was barely distinguishable. This was done with the sun high in the sky, and the effect might have been more pronounced at more oblique incidence angles.

5.3 Module installation angle

In many PV installations there are easily visible variations in the orientation of individual modules. This is especially true for ground-mounted systems that follow the undulations of the terrain, but also to a lesser extent for ballasted roof-mount systems such as this one, because flat roofs are not supposed to be perfectly horizontal. Lack of precision or attention to detail can create or exacerbate variations in any installation.

The slope of our array was specified to be 6.0°, but measurements on each row showed that the actual angle varied between 6.7°and 7.3°. When the sun is high in the sky this is inconsequential, but when the sun is low in the sky (early or late in the day, especially in winter) it makes a difference. The two extremes represent a difference of 16mm in the elevation of the top edge compared to the bottom edge of a module. The smaller angles were found nearer to the walls, and the overall increase in slope is consistent with roof drainage being located near the middle of the roof, and in front of the array. Because of the layout, the slopes of individual modules within strings do not vary much, and due to the nearly identical footprints the effect on total output of the two systems should be equal.

The azimuth or compass orientation of the modules appeared to be quite consistent at 40° East of South, based on the long rows parallel to the roof edge; but it was more difficult to verify since the mounting brackets allow for a certain amount of rotation of the module without affecting the slope or azimuth angles. We discovered that the height of the parking curbs that serve as ballast and mounting base varies considerably, causing a side-to-side tilt that often alternates between adjacent modules. In one case there is a 15mm difference in curb height, causing a 0.8° side-to-side slope. This translates to a difference in azimuth of 6.2° for one module compared to the array as a whole, and a difference in azimuth of 12.4° compared to an adjacent module that is tilted the other way. It was easy to locate tilted and rotated modules by the soiling pattern at the bottom of the modules as shown in Figure 2.

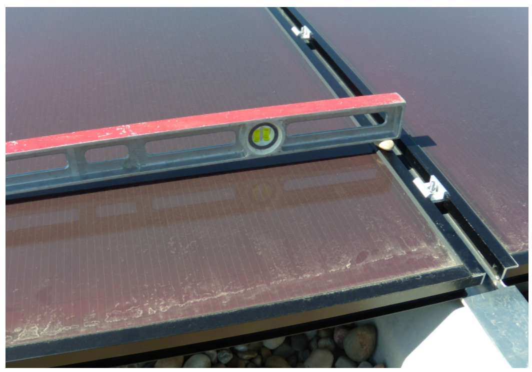

Figure 2 Soiling pattern reveals a side-to-side tilt and hints at the true azimuth.

The azimuth difference quite noticeably skews the daily production profile of individual modules. Figure 3 shows the relative output compared to the array average for two modules with opposing azimuth errors. Since opposing modules tend to be close together, they often appear in the same string, so the skewed output causes a small mismatch. At the array level the effect averages out and no skew is visible between the two array outputs.

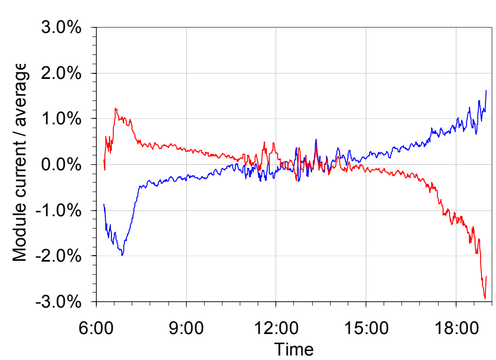

Figure 3 Relative output of two modules with opposing side-to-side tilt: red tilted East; blue tilted West.

Although this effect is relatively minor, it does complicate comparisons between individual strings and modules, because their relative output varies with the time of day. For this reason daily energy was used as a basis for section 5.1.

5.4 Module temperature

Variations in temperature are another factor we anticipated, and measure by means of thermocouples at the back of a selection of modules (in some cases 3 per module). Only a preliminary analysis of the temperature data has been done, and we observe that under clear, stable conditions differences of 5°C can exist between the warmest and coolest modules. The temperature coefficient of power for these a-Si modules is small, 0.2% per C, so this can translate to a difference in power output, and hence mismatch, of 1%. We have not yet identified a worst case for temperature-induced mismatch.

The temperature differences are maintained over time, suggesting that despite the wide spacing of the rows, the position of the modules influences how well they are cooled, but exactly which ones are better cooled depends on the direction of the wind. Since the overall footprint and internal layout of the two arrays is identical, the temperature distribution within the array should be similar under most conditions and not produce differences in the total array outputs.

6 IMPACT OF SMALL NON-UNIFORMITIES

Many of the solutions that extract maximum power from partially shaded arrays are also presented as capable of reducing the impact of smaller variations. Module mismatch is often mentioned in this context. In the previous section we described and explained various factors that lead to variations in module output power, and hence create module mismatch. However we have not yet proven that the resulting mismatch actually has an adverse effect total array power.

To classify a mismatch as significant, the array maximum power point must be significantly less than the sum of the individual power points, and in more extreme cases there may be more than one array maximum power point on the curve. One of the ways to investigate these mismatch conditions is by looking at a IV curves of the array, of which we collected several dozen at different insolation levels. A sample is shown in Figure 4.

This IV curve has a very low fill factor of only 0.54, whereas the stabilized value in the spec sheet is given as 0.60. Given that the initial factory flash test average fill factor (0.71) was also below spec (0.74) this is partly anticipated. The series-parallel array had a very similar curve with a fill factor of 0.55. The most plausible interpretation is that the modules have on average degraded more than anticipated by the manufacturer, and this could be due at least in part to the cold winter that the modules experienced.

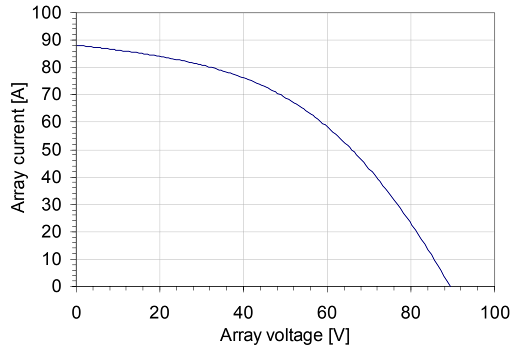

Figure 4 IV-curve of the parallel-only array.

What is importantly here, however, is not the amount of degradation but the shapes of the curves. A low fill factor means that the maximum power point is not on a very sharp peak, which further means that a relatively large change in operating voltage is required to reduce the power output. This is quite clear in the PV curve below.

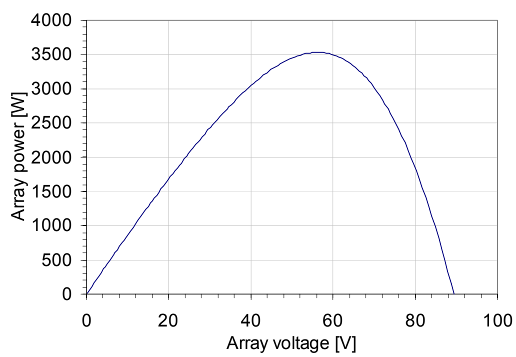

Figure 5 Power vs. voltage, parallel-only array.

In fact, as the close-up shows in Figure 6, a deviation from Vmp as large as 5% only reduces power output by 0.5%. This means that low fill factor strings or modules wired in parallel are very tolerant to voltage mismatch.

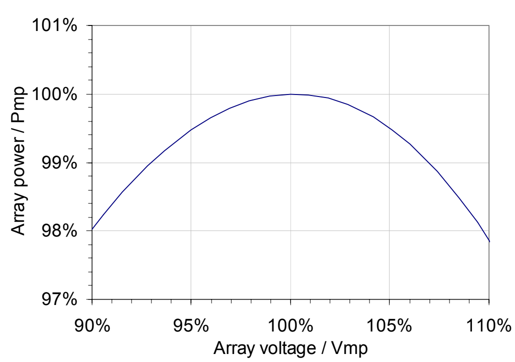

Figure 6 Power vs. voltage, close-up, parallel-only array.

Current mismatch is usually of greater concern than voltage mismatch, but a close look at the power-*current* curve demonstrates that the low fill factor offers equal robustness there. A deviation from Imp by as much as 5% still only causes a maximum reduction in power of 0.6%.

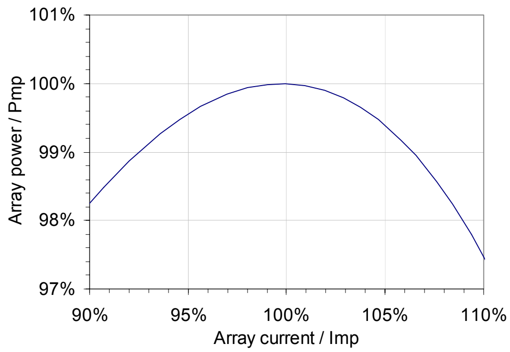

Figure 7 Power vs. current, close-up, parallel-only array

The observation regarding the IV curves and low fill factor leads to a very simple conclusion: all the small variations we observed among modules within the arrays were well within the +/- 5% range, therefore all modules must have been producing very near to their individual maximum power. This result is the same for both parallel and series-parallel configurations, and no significant improvement would be achieved using individual module MPPT of any kind. It will be useful to check the IV curves for other module technologies in the same way to see just how sensitive they are to mismatch.

7 DIFFERENCES BETWEEN THE ARRAYS

Although care was taken to make the two side-by-side arrays as identical as possible, in practice, there are small unavoidable differences between the outputs of the arrays. While these have little effect on the short-term experiments that are discussed in this paper, in order to be able to fairly assess the impact of mismatch losses on long term performance they must be understood and allowed for as part of long term performance comparison.

One of these factors is the degradation of the modules, which increases over time. In particular, the initial degradation of a-Si modules is significant and unpredictable as indicated in section 5.1. In addition to the mismatch losses that may result from increasingly divergent module capacity, the overall capacity of each array may also diverge over time, and this must be evaluated periodically to ensure that the mismatch losses are properly assessed.

Another factor is wiring resistance. Unlike the foregoing factors, wiring resistance is a factor that is largely predictable as part of the array design process. However, the requirements of the experimental setup resulted in higher DC wiring losses than would normally be the case. The need to avoid row-to-row and incidental shading on the roof while maintaining the symmetry of the installation spread the arrays out much wider than would otherwise have been necessary. This, combined with the need to accommodate the experimental instrumentation in the DC circuits resulted in electrical losses significantly higher than for a standard installation in both cases.

These two factors can be separated conveniently by comparing the output of the two arrays under unshaded conditions over a range of power levels. The difference between them will have a component that is proportional to irradiation, which is the due to the module capacity; and another component that is proportional to the square of the DC current, which is due to the resistive losses.

8 LARGE NON-UNIFORMITIES

Having shown that small variations in module output cannot lead to mismatch losses in our systems, we turn our attention to large variations.

8.1 Snow

Snowfall is an important loss factor in most parts of Canada. The combined factors of precipitation, wind and sun can cause uneven accumulation on an array, or uneven melting as illustrated in Figure 8. This can give rise to both small and large mismatches, and hence both direct losses and mismatch losses.

Figure 8 Non-uniform shading pattern created by snow

Given the importance of the snow factor in the Canadian market we have launched a separate study on this topic in collaboration with Queen's University, and those results will be published later.

8.2 Partial shading

With the exception of snow, there are no regular occurring causes of large variations in module output in the two arrays. This enables us to investigate partial shading under controlled conditions. Short-term tests are designed to measure the effect of specific shade patterns under specific conditions, and long-term test evaluate the effect of specific obstacles under a mix of real-world conditions.

Our main short-term test uses wood panels sized to cover 20% of the module surface. Since the PV cells are arranged in vertical strips it is possible to shade all cells in a module equally in this manner, in 20% steps from 0% to 100%. The experiment targets one set of five modules in each array, which are connected in series in one array and in parallel in the other. The placement of the wood panels is done simultaneously by two people.

Figure 9 Shade is created by wood panels in 20% increments

The first basic sequence covers the first module in steps from 20% to 80%, then the second module, and so on until all five modules are shaded at 80%. A pause between each change allows the inverters to stabilize and the data acquisition system to collect several data points.

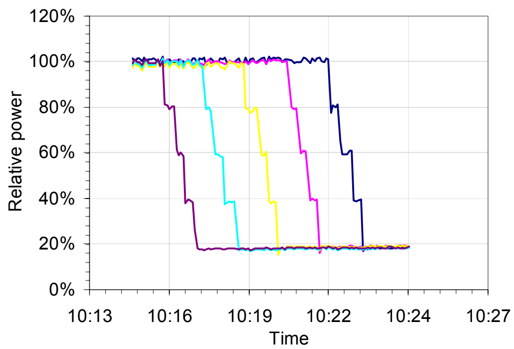

Figure 10 First shading sequence as measured on the five parallel modules

Figure 10 shows the individual module power measurements for the parallel array, which have been normalized with respect to the average value of the 45 unshaded modules. Normalization removes the effect of the gradual change in solar radiation intensity.

For the series array we can only measure the string power, which is compared to the total power of the five parallel modules in Figure 11. The graph clearly shows the limiting effect of partial shading on the string output. Already at the first step (20% shade on one module, 4% of the area of the 5 modules) the string output drops by 9%, whereas the parallel set drops the expected 4%. At subsequent steps the mismatch effect in the string becomes more pronounced and when two modules are covered at 80% (32% of the area) the string essentially "bottoms out" with 77% losses, whereas the parallel set incurs only a 33% loss.

The operation of the bypass diodes in the string (there is one per module) is evident only when one or two modules are shaded. Initially the low fill factor of the modules permits the four unshaded modules to operate closer to their Voc while the shaded module operates closer to its Isc. But as the Isc of the shaded module drops in subsequent steps the bypass diode kicks in.

The second module also starts out by operating closer to its Isc, but when its Isc drops too far the remaining three modules are unable to provide the extra voltage to operate two bypass diodes, and the string current plummets to a level that all five modules can sustain, which is close to the minimum value of the five modules.

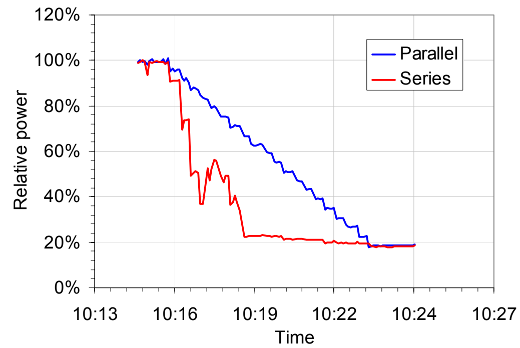

Figure 11 Total output of 5 modules during the first shading sequence

There appears to be a small gain in power as the second module in the string is being shaded. This coincides with the maximum power point tracking adjusting the overall array voltage downward. This part of the experiment was repeated more slowly, and if only the stable values are considered there is never a gain in power with increasing shade.

Another way to view these results is to plot power against insolation as in Figure 12. This clearly illustrates how the parallel configuration produces power in proportion to the available insolation whithout incurring mismatch losses.

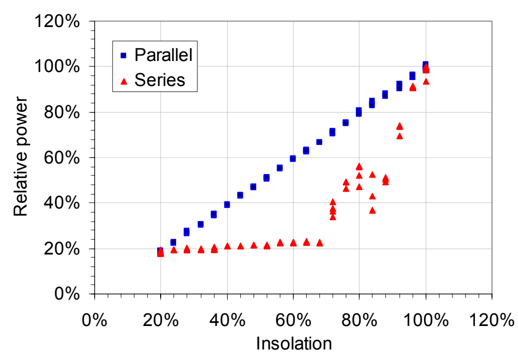

Figure 12 Output power as a function of insolation

This result shown here is not general, but valid only for the shading sequence that we used. However similar results should be expected for any shadow that moves from left to right over an array, such as the shadow of an adjacent building that is taller.

We used another sequence to simulate a shadow that moves from front to back over the array. In this sequence (executed in reverse) the modules start out all at 80% shade, then they are all taken to 60% shade, 40%, 20% and finally uncovered completely. Figure 13 shows the individual module powers in the parallel set, Figure 14 shows the relative power of the two configurations, and Figure 15 again plots power as a function of insolation.

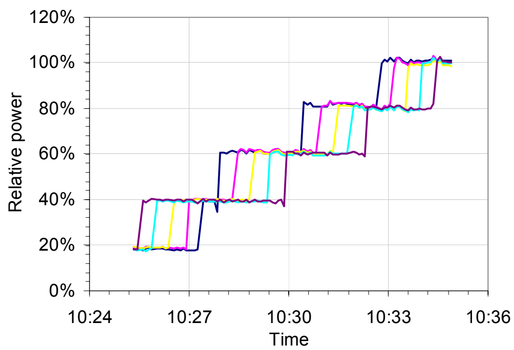

Figure 13 Second shading sequence as measured on the five parallel modules

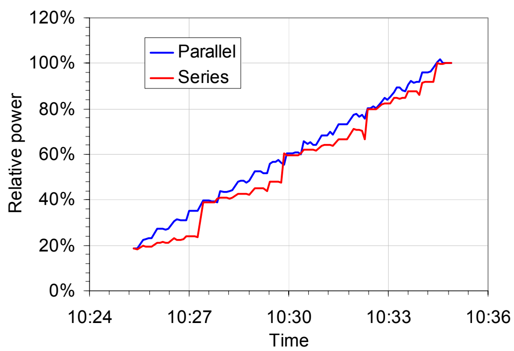

Figure 14 Total output of 5 modules during the second shading sequence

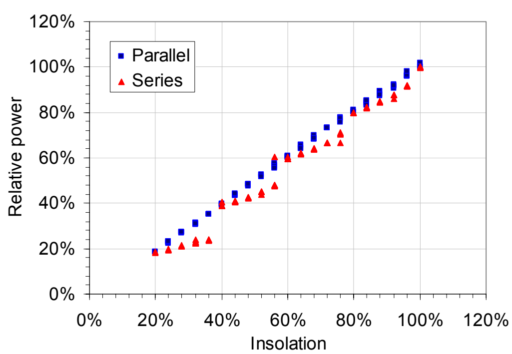

Figure 15 Output power as a function of insolation

Clearly the mismatch losses for the string are not nearly as great with this shading sequence. A major diagonal shadow moving across the array would have an effect somewhere between these two results.

8.3 Module fault

Modules can fail in different ways. One possible outcome is that the module no longer produces current, and as long as the bypass diode remains intact this has the same effect as blocking all light. We have simulated faulty modules in a string, therefore, by covering them completely, one at a time.

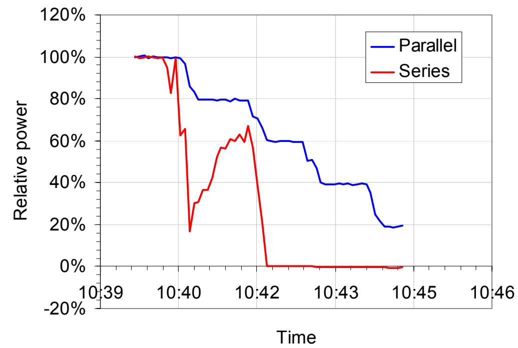

Figure 16 Total output of 5 modules with one, two, three and four modules covered completely

As seen in Figure 16, the first module is covered at 10:40 and the second at 10:42, and so on. The parallel connected set of modules suffers a loss of 20% each time, which is the output of one module. There is no additional mismatch loss. The series set suffers an initial loss of 80% but recovers half of that gradually as the MPPT algorithm adjusts the array voltage downward. This is a relatively small adjustment that does not substantially affect the output of the other strings. (See discussion insection 6). The bypass diode in the "defective" module is now active. When the second module in the series set becomes "defective" also, the remaining three modules are unable to produce any power.

9 CONCLUSIONS

The data and observations collected during the first year of operation, both in normal operation and in experiments, permit us to draw the following conclusions:

1. Module technologies with low fill factors such as a-Si make arrays that are very tolerant to small mismatches. For a fill factor around 0.55, as long as the mismatch in the Vmp or Imp of a module is within ±5% of the rest of the array, the resulting mismatch *loss* for the module will be less than 0.5%.

2. Module technologies with long thin cells resist certain types of shading better than round or square cells. Soiling that accumulates near the bottom edge of modules affects all cells equally, and shadows from relatively thin obstacles such as poles and wires very rarely affect one cell more than the others.

3. Large differences in module output caused by our partial shading experiments are accommodated with virtually no mismatch loss by the parallel-only array.

The series-parallel array incurs mismatch losses whenever at least one module is shaded 20% more than the others. The mismatch loss increases the shading loss by a factor of two or more when just one or two modules are shaded and the remaining ones unshaded.

All things considered, the combination of low fill factor modules with long narrow cells and a parallel array configuration—which is made possible by a low-voltage inverter—is demonstrated to be very effective at avoiding all kinds of mismatch losses. For planning purposes this means the parallel system has a shading impact factor of 1.0. The susceptibility of series strings to mismatch losses is also demonstrated in this comparison, and through long-term monitoring we expect to be able to provide realistic estimates of annual mismatch losses in future reports so that a full cost-benefit analysis of the available options can be done.

10 ACKNOWLEGEMENTS

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Figure 17 View of the complete installation looking from the North-East