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SHADOW TOLERANCE OF MODULES INCORPORATING INTEGRAL BYPASS DIODE SOLAR CELLS

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Summary

Bypass diodes have become a standard feature of solar cell arrays to improve array performance. When connected across every 12 - 15 series-connected cells in the array these diodes protect the array from the destructive effects of cell mismatch such as is caused by partial shading. However, such a connection does not provide tolerance to the disproportionate loss of array output power arising from such mismatch. This tolerance can be provided by connecting a bypass diode across each individual cell in the array or more economically by integrating the bypass diode into the structure of each cell. The tolerance to mismatch caused by shadowing of arrays incorporating such integral bypass diode solar cells is quantified experimentally and compared to the tolerance of standard arrays without bypass diode protection.

1. Introduction

Partial shading of solar cell modules can cause a disproportionate loss in module output or local overheating and module destruction. A shaded cell causes a drop in module current. Unshaded cells accommodate this drop by moving along their operating curves in the direction towards open-circuit voltage. The extra voltage generated in this way drives the voltage across the shaded cell in the opposite direction in an attempt to increase the current through it. With even small amounts of shading, the shaded cell will become reverse biased and dissipate electrical power.

The loss in module output resulting from such shading can be as high as that expected from the loss in incident solar radiation multiplied by the number of series-connected cells in the solar cell module or array. Even more importantly, in the worst case the power being dissipated in a single shaded cell can become as high as the entire generating capability of the remainder of

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the module or array. It is not surprising that this causes the rapid overheating of the cell and module destruction.

The standard technique to protect against the destructive effects of partial shading is to connect bypass diodes across every group of 12 - 15 series-connected cells [1]. This restricts the reverse bias which can be generated across any shaded cell and hence the power which can be dissipated in it. Since shading any one cell in the group of 12 - 15 cells will prevent the remainder of the group from contributing to the module output, this approach will still result in a disproportionate loss in module output because of partial shading.

An alternative technique is to incorporate bypass diodes across individual cells or more economically into the solar cell structure itself. This not only provides protection against module destruction but also minimises the loss of module power when partially shaded. Most schemes suggested in the past for integrating bypass diodes into the cell structure required relatively complicated cell processing as well as the need for additional cell interconnections [2 - 4]. The approach used in the present paper avoids these problems.

The basic concept upon which the integration is based is described elsewhere [5 - 8]. The rear junction diffusion which normally forms when the top junction is diffused is used to advantage to produce a diode connected in reverse polarity to the main body of the cell. Electrical isolation between the diode and the main cell is provided by the lateral resistance of the intervening bulk regions of the cell. Under normal operation it is possible to keep the loss in solar cell output owing to both the area of the cell devoted to the diode and the resistance of the isolation region to a few per cent [6]. Locating the bypass diode under the busbar or contact pad as in Fig. 1 further reduces such losses. Several processing techniques have been demonstrated for incorporating the bypass diode by this approach [6, 7]. The concept has been found to be particularly well suited to screen printing metallization approaches [7] where only one extra cell processing step is required for some sequences [8].

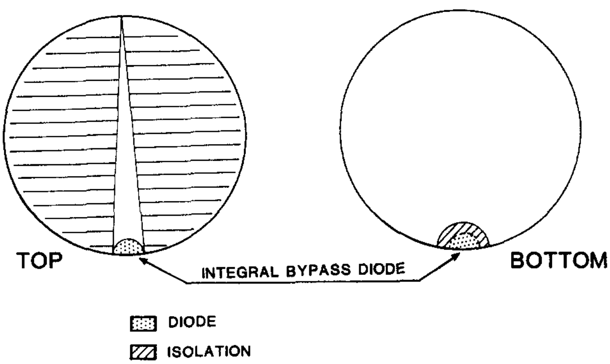

Fig. 1. Diagram showing the bypass diode incorporated under the busbar of a solar cell to reduce loss in active cell area to negligible levels.

This paper experimentally quantifies the advantage to be gained in shadow tolerance by incorporating integral bypass diodes into solar cells. This is done by comparing the power output of two arrays under different shading conditions with one array having integral bypass diodes and the other not..

2. Arrays studied

Modules were fabricated under subcontract by Tideland Energy Pty. Ltd. (now BP Solar Australia) incorporating integral bypass diode cells manufactured using a screen printing sequence [7, 8]. The modules took the form of the normal commercial product of the company at that point in time. Four of these modules were connected as shown in Fig. 2 to form a nominally 24 V_{dc} array. This will be referred to in the following discussion as the Type A array. Although the efficiencies of modules with integral

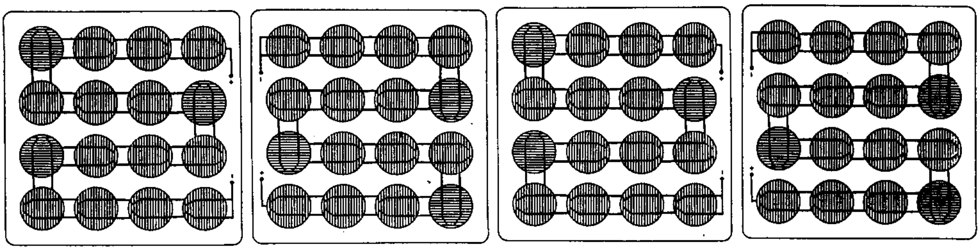

Fig. 2. Diagram of cell layout in the Type A array in which the cells incorporate integral bypass diodes. As mounted the array was actually rotated 90° clockwise from the position shown.

bypass diodes would be expected to be slightly lower as previously mentioned, the characteristics of the present modules placed them within the normal production spread of the company at that point in time with no statistical differences noted [8].

A second array of the same nominal rating was formed by connecting two commercial modules manufactured by the Applied Solar Energy Corporation as shown in Fig. 3. No bypass diodes were used in this array and it will be referred to as the Type B array.

The arrays were of approximately the same current rating but the voltage rating of the Type B array was higher because it consisted of 72 series-connected cells compared to 64 such cells in the Type A array. This placed the Type A array at a disadvantage when comparing shadowing performance at nominal rated voltage although it is still seen to be superior in performance. The efficiency of the Type A array based on its entire area was approximately 6.6% under typical operating conditions while that of the Type B array was slightly higher at 9.6%. The difference is mainly because of the increased cell packing factor in the latter and the use of fine,

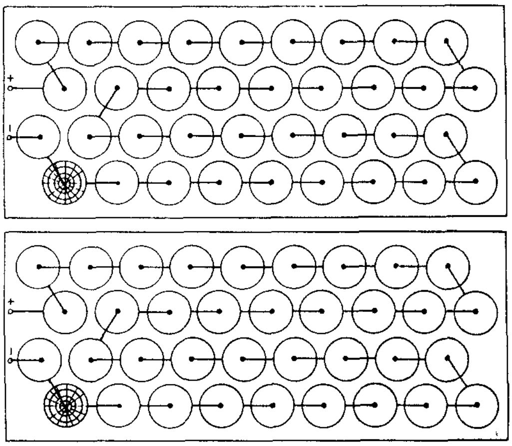

Fig. 3. Diagram of cell layout in the Type B array where no bypass diodes were used. As mounted the array was rotated 90° clockwise from the position shown.

photolithographically defined metallization fingers. The different geometrical arrangement of the cells within the two arrays will also affect the comparison of array performance under any given shading condition as noted where appropriate.

3. Single cell shading

The simplest shading studies conducted upon the arrays was the effect of shading a single cell in the array. This simulates conditions such as those caused by falling leaves, bird droppings or cracked cells.

Figure 4(a) shows the effect of shading a single cell upon the Type B array. Similar curves were obtained for modules produced by other manufacturers. At voltages approaching open-circuit there is a region where current is approximately constant with a value determined by the degree of shading. As short-circuit is approached this current decreases owing to a "soft" breakdown of the shaded cell as the reverse bias across it increases. The shading of the single cell causes a disproportionate increase in module output. For the 25% shading condition the loss in module output is 20 - 25 times larger than that expected from the loss in total radiation onto the cells in the module. This factor increases to 55 - 60 times larger for the other three shading conditions (50%, 75% and 100%).

More importantly, Fig. 4(a) shows that, when the Type B array is short-circuited, over 40 W can be dissipated in the shaded cell. This would be more than sufficient to cause the destruction of the shaded cell module had the shading been maintained for any prolonged period.

Figure 4(b) shows the corresponding results for the Type A array with integral bypass diode cells. The main loss because of shading in this case is a loss in module voltage of about 1.4 V. This is the voltage lost owing to the

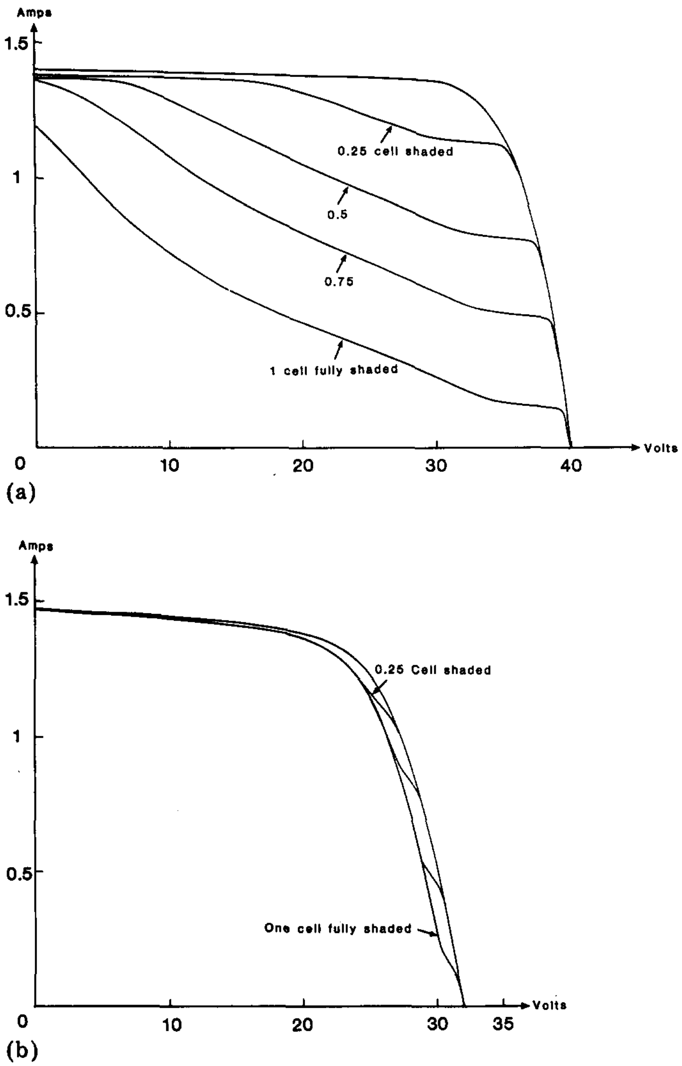

Fig. 4. Output current–voltage curves when a single cell in the array is shaded to different degrees: (a) Type B array (no bypass diodes); (b) Type A array (with integral bypass diodes).

loss in output from the shaded cell combined with the voltage needed to reverse bias the bypass diode across this cell. The loss in module output because of shading is about 10 - 11 times larger than that expected from reduced solar input for the 25% shading condition. This factor decreases proportionally to only 2 - 3 times larger than expected for the 100% shading condition.

Owing to the presence of the bypass diode the power dissipated in the shaded cell is limited to only 1.2 W.

The effects of shading of a single cell upon the normalized power output of the arrays are summarized in Table 1. For small degrees of shading

TABLE 1

Effect of partially shading a single cell upon the normalised power output of the Type A array with integral bypass diode cells and the Type B array without bypass diodes

Fractional shading (%)	*Normalised output power (%)*	
	Type A array (integral diodes)	*Type B array (no bypass diodes)*
0	100	100
25	96	92
50	96	60
75	96	41
100	96	22

(less than about 10%) the two systems perform similarly. As the degree of shading increases, the Type A array becomes quickly superior. For example, with 50% shading of a single cell there is a 4% loss in output in the Type A array compared with a 40% loss in output for the Type B array. This represents a 10 times increase in shadow tolerance. With 100% shading of a single cell the shadow tolerance of the Type A array is 20 times that of the Type B array.

4. Multiple cell shading

4.1. Shading patterns

The effects of larger area shadows covering a significant fraction of the array were also investigated. Such large area shadows may be caused by sources such as adjacent buildings or trees or by cloud edge effects. Eight shading patterns as shown in Fig. 5 were investigated with the degree of shading of the array ranging from 5% to 25% in each case with 5% increments. The nomenclature used to describe the shading condition is also defined in Fig. 5.

4.2. Vertical shading

The output of the Type B array under the first type of shading (WE) is shown in Fig. 6(a). This type of shading causes a larger reduction in power output than that expected from the reduced radiation on to the array by a factor of about six for the Type B array. Hence, once more than 15% of the array is shaded its output is negligibly small.

Figure 6(b) shows the corresponding results for the Type A array with integral bypass diodes. As the shading increases from 0% to 25% the characteristics shift from the normal unshaded curve to one shifted about 20 V along the voltage axis towards short-circuit. This 20 V shift corresponds to the switching in of the bypass diodes of the 16 cells lying along the shaded edge. As the shading increases there is a local maximum in the power output

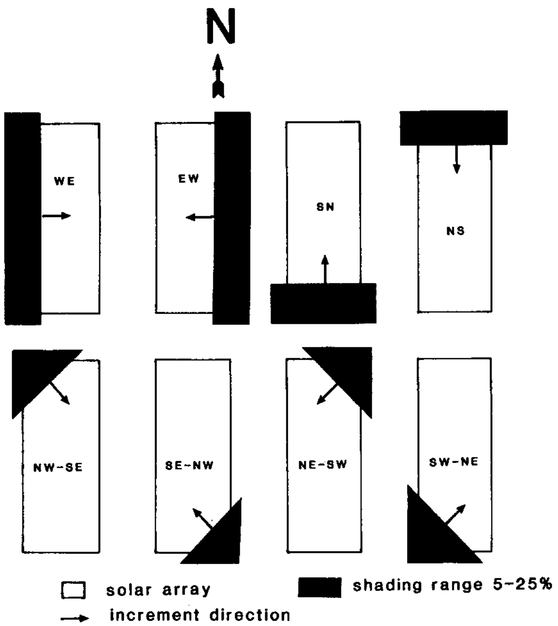

Fig. 5. The eight shading patterns studied and the corresponding nomenclature.

of the array at a voltage below 10 V as well as around 30 V. Since some systems would not be able to take advantage of power at the lower voltage, both maximum power output and power at nominally rated voltage (24 V) were measured for the arrays.

Table 2 compares the normalized power output of the arrays as the shaded fraction increases. The shadow tolerance of the Type A array is clearly superior being able to tolerate more than twice the amount of shading

TABLE 2

Effect of vertical shading (WE in Fig. 5) upon the normalised power output of the Type A array with integral bypass diodes and the Type B array without bypass diodes. The effect upon the maximum power output of the module and the power output at 24 V_{dc} (nominal operating voltage) are shown

Fractional shading (%)	*Normalised output power (%)*			
	Type A array (integral diodes)		*Type B array (no bypass diodes)*	
	Maximum power point	*Power at 24 V*	*Maximum power point*	*Power at 24 V*
0	100	100	100	100
5	97	97	72	64
10	84	83	25	25
15	57	57	2	2
20	29	25	1	1
25	26	9	1	1

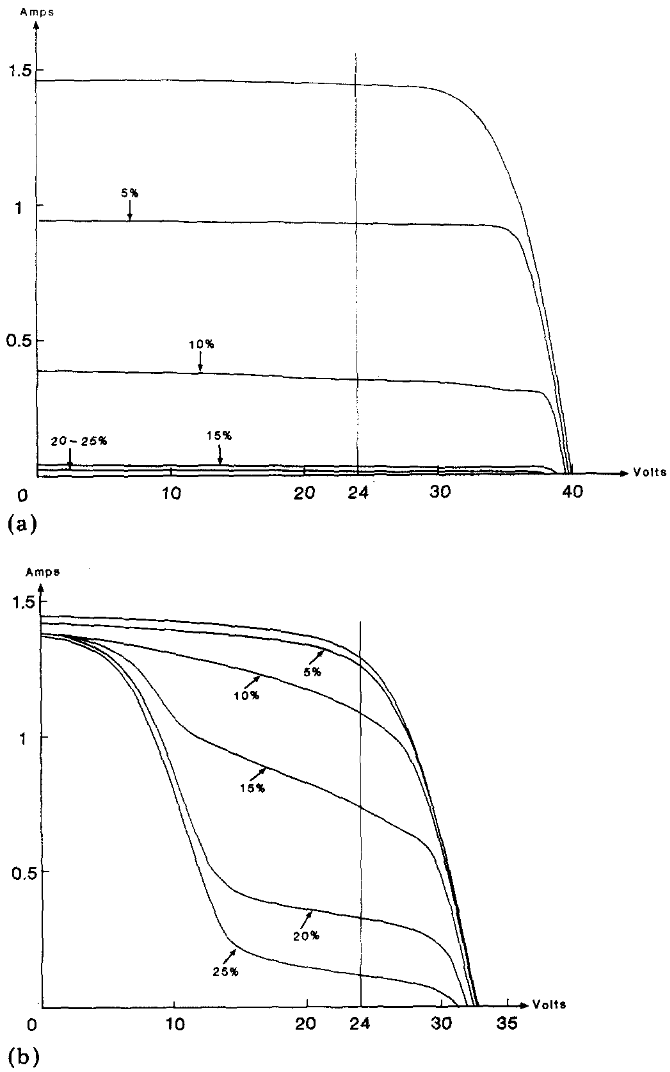

Fig. 6. Output current–voltage characteristics when shaded to different degrees in the vertical direction (WE in Fig. 5): (a) Type B array (no bypass diodes); (b) Type A array (with integral bypass diodes).

for a given reduction in power output. For shading in the 15% - 20% range the Type A array produces between 25% and 60% of its rated power while the Type B array is producing less than 3%.

4.3. Horizontal shading

Figure 7(a) shows the effects of NS shading upon the Type B array. The effects are similar to those of vertical shading although slightly more severe. With the given orientation of the modules (Fig. 3) this shading direction will cause more severe shading of a smaller number of cells at small

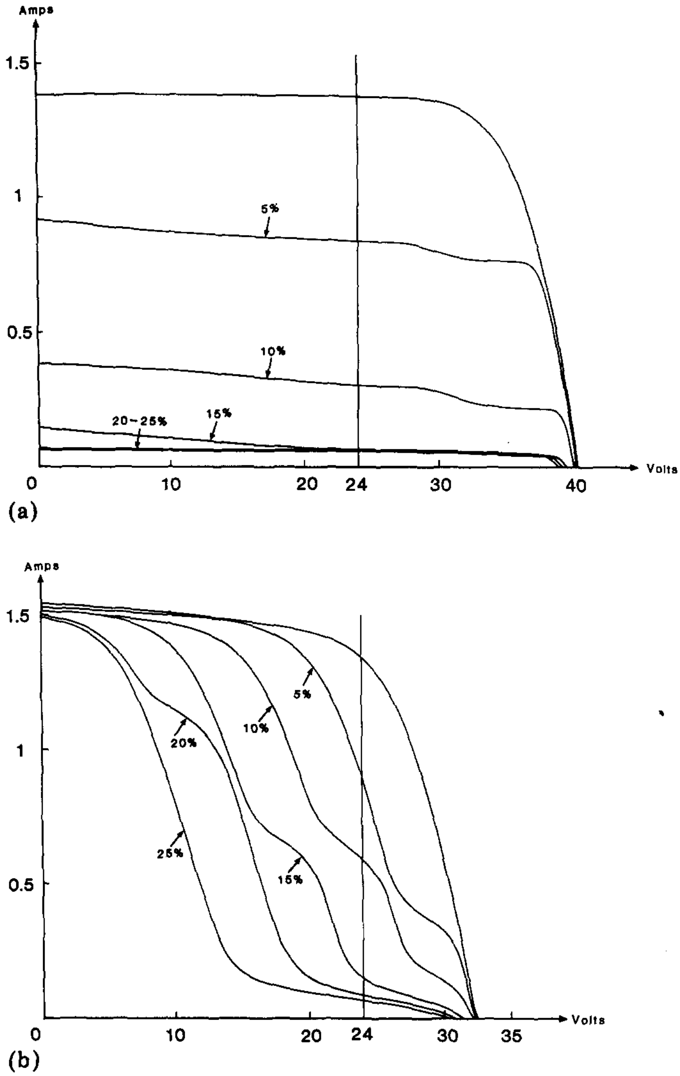

Fig. 7. Output current–voltage curves when shaded to different degrees in the NS horizontal direction: (a) Type B array (no bypass diodes); (b) Type A array (with integral bypass diodes).

shading levels. This fact also explains the additional structure apparent in the curves around 30 V. Again 15% shading reduces the module output to low levels.

For the Type A array, the characteristics shown in Fig. 7(b) are dominated by approximately 5 V shifts as successive rows of 4 bypass diodes are switched in. As shown by the data of Table 3 the difference between the maximum power output of the module and the power at rated voltage is larger than in the vertical shading case.

TABLE 3

Effect of horizontal shading (NS in Fig. 5) upon the normalised power output of the Type A and Type B arrays. The effect upon both the maximum power output of the module and the power output at nominal operating voltage (24 V) are shown

Fractional shading (%)	*Normalised output power (%)*			
	Type A array (integral diodes)		*Type B array (no bypass diodes)*	
	Maximum power point	*Power at 24 V*	*Maximum power point*	*Power at 24 V*
0	100	100	100	100
5	82	65	65	61
10	63	43	20	22
15	45	11	4	6
20	40	7	3	4
25	27	5	3	4

Table 3 shows that the maximum power output of the Type A array is again more tolerant to shading than that of the Type B array. However, the advantage at the nominal rated voltage of the module (24 V) is less pronounced.

4.4. *Diagonal shading*

Figure 8(a) shows the effect of diagonal shading (SW–NE) on the output of the Type B array. The effect is particularly severe since this shading condition will quickly cause almost complete coverage of a small number of cells with even smaller shading fractions. With only 5% shading the array output is very low.

As opposed to this, the tolerance of the Type A array was much better. The characteristics shown in Fig. 8(b) are more complicated than the previous case owing to the less coordinated switching in of the bypass diodes. As shown in Table 4 the tolerance to shading of the power output at nominal voltage of the Type A array was about 4 times higher than that of the Type B array. The tolerance of the maximum power output was very much higher.

4.5. *Extreme cases*

Tables 5 and 6 summarize the best and worst performance of the Type A and Type B arrays at a given fractional shading for the eight shading conditions of Fig. 5. Table 5 shows the dependence of the maximum power output while Table 6 shows that of the power output at the nominal rated voltage of the system (24 V).

Table 5 shows that the effect of diagonal shading is more severe for both arrays than horizontal or vertical shading. However the Type A array with the integral bypass diode cells is clearly superior. Even in the best case any shading greater than 10% of the array without bypass diodes will cause the power output to drop to negligible levels. As opposed to this the array

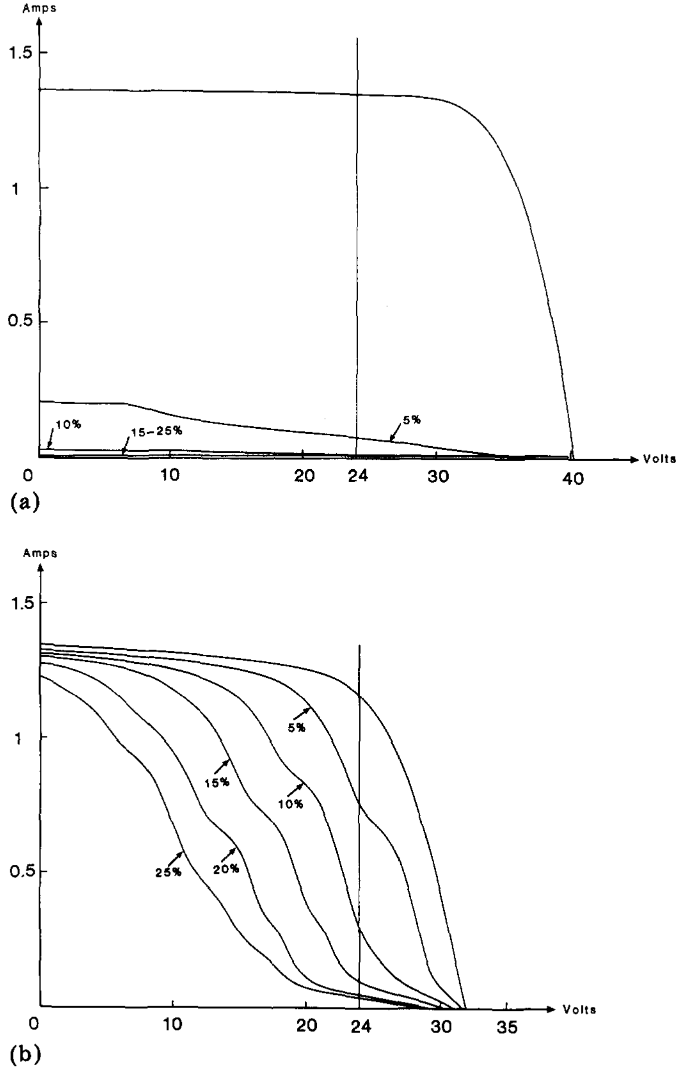

Fig. 8. Output current–voltage curves when shaded to different degrees in the SW–NE diagonal direction: (a) Type B array (no bypass diodes); (b) Type A array (with integral bypass diodes).

with integral bypass diodes gives about 25% of its peak output with 25% shading of its area.

Table 6 shows that the Type A arrays still have a pronounced advantage in terms of power output at nominal rated voltage although less pronounced than above. Some of this difference is because of the smaller number of cells in the Type A array as noted in Section 2. Nonetheless, its performance under the worst possible diagonal shading conditions is comparable to that of the Type B array under the best possible non-diagonal shading conditions. In the best case the Type B module output drops below 10% of

TABLE 4

Effect of diagonal shading (SW–NE in Fig. 5) upon the normalised power output of the Type A and Type B arrays. The effect upon both the maximum power output of the module and the power output at nominal operating voltage (24 V) are shown

Fractional shading (%)	*Normalised output power (%)*			
	Type A array (integral diodes)		*Type B array (no bypass diodes)*	
	Maximum power point	*Power at 24 V*	*Maximum power point*	*Power at 24 V*
0	100	100	100	100
5	88	64	3	5
10	62	24	0.7	0.7
15	49	8	0.6	0.7
20	34	4	0.6	0.7
25	26	3	0.6	0.7

TABLE 5

Summary of the most extreme effects observed for the eight shading patterns of Fig. 5 on the normalised power output of the Type A and B arrays at the maximum power point. The orientations corresponding to these extremes are shown in parentheses

Fractional shading (%)	*Normalised output power (%)*			
	Type A array (integral diodes)		*Type B array (no bypass diodes)*	
	Best case	*Worst case*	*Best case*	*Worst case*
0	100	100	100	100
5	97(WE)	73(NW–SE)	79(SN)	3(SW–NE)
10	84(WE)	56(SE–NW)	29(EW)	0.7(SW–NE)
15	57(WE)	42(SE–NW)	4(NS)	0.6(SW–NE)
20	42(SN)	27(EW)	3(NS)	0.5(NW–SE)
25	27(NS)	24(NW–SE)	3(NS)	0.5(NW–SE)

its non-shaded value when 10% - 15% of its area is shaded while the Type A array stays above this value until the shading is greater than 25%. This factor-of-two advantage in shadow tolerance increases to above three for the more severe diagonal shading conditions.

5. Conclusion

The advantage in the shadow tolerance of solar cell arrays with integral bypass diode solar cells have been experimentally quantified by studying the performance of two nominally 24 V arrays consisting of 64 and 72 series-connected cells. With less than about 10% shading of a single cell in the array there is little advantage in having integral bypass diodes. However, with any

TABLE 6

Summary of the most extreme effects observed for the eight shading patterns of Fig. 5 on the normalised power output at nominal voltage (24 V) of the Type A and B arrays. The orientations corresponding to these extremes are shown in parentheses

Fractional shading (%)	*Normalised output power (%)*			
	Type A array (integral diodes)		*Type B array (no bypass diodes)*	
	Best case	*Worst case*	*Best case*	*Worst case*
0	100	100	100	100
5	97(WE)	59(SE–NW)	72(SN)	5(SW–NE)
10	83(WE)	22(SE–NW)	25(EW)	0.7(SW–NE)
15	57(WE)	7(NE–SW)	6(NS)	0.7(SW–NE)
20	25(WE)	4(NE–SW)	4(NS)	0.7(SW–NE)
25	11(EW)	3(NE–SW)	4(NS)	0.7(SW–NE)

higher shading levels the advantage quickly increases. With 100% shading of a single cell the loss in power output in the array with integral bypass diodes was only one twentieth of that of the array without bypass diodes.

Eight multiple cell shading patterns were also examined in some detail. Diagonal shading was found to be more severe than horizontal or vertical shading for arrays with and without bypass diodes. Even with the former less severe shading patterns, the power output of the array without bypass diodes dropped to negligible levels if any more than 10% of the module area was shaded. The performance of the array with bypass diodes was far superior. Even under the most severe diagonal shading, about 25% of the unshaded array output was obtained with 25% of the array shaded. Since this power was obtained at voltages below the nominal rated voltage of the array and could not be used by some systems, the tolerance at this voltage (24 V) was also studied. The advantage of integral bypass diodes was also apparent in this case although not as pronounced as above. For the less severe non-diagonal shading case, the array with these diodes could tolerate about twice as much shading as the array without them for any given relative power output. This advantage increased for the more severe diagonal shading conditions.

In related work [9] it has been shown that the series resistance unavoidably incorporated with the integral bypass diode in the present approach serves a useful function in preventing "current hogging" when modules are connected in parallel. The integral bypass diode presently described not only provides a simple technique for improving the tolerance of solar cell arrays to shadowing but also protects against thermal instabilities in both small and large systems.

Acknowledgments

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