String-Level (kW-Scale) IV Curves from Different Module Types under Partial Shade

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***Abstract* —Partial shade is known to cause significant de-rating for most photovoltaic (PV) systems. However, the specific de-rating due to partial shade from differently shaped objects like overhead wires is not well known. We present current-voltage (I-V) curves from three different strings containing 4 to 9 PV modules while applying various types of partial shade, including shade from electrical cables in front of the modules. We show that a 1-kW string of nine poly-Silicon modules manufactured by Sharp can have a power loss of 13% due to shading just 1% of its surface area. We verify that blocking columns of cells in a module has less impact on power loss than blocking rows. This demonstrates how the non-linear response to partial shade can depend on the placement of bypass diodes that isolate different sub-strings within each module. Furthermore, we quantify the reduction in power and I-V parameters caused by shade from wires (or PVC pipes in our experiments).**

***Index Terms* — photovoltaic systems, system performance, current-voltage characteristics.**

I. INTRODUCTION

As the adoption of distributed solar generating plants accelerates, we face new challenges for site selection. Shadows from other modules, buildings, poles, fences, trees and other obstacles are commonly found near potential PV system sites. In this paper, we quantify the reduction in performance, particularly in power, as a result of sub-optimal siting with exposure to partial shade. Furthermore, it is well-known that the power loss due to shading is not simply proportional to the shaded surface area [1]-[2]. A less well studied phenomenon is the effect on performance due to shading by wires or overhead cables. Since this has become a concern for power forecasting for utility companies and PV system installers, we address this question by reporting several experiments conducted at the Tucson Electric Power (TEP) solar test yard in Tucson, Arizona [3].

Fig. 1. Experimental set up at TEP Solar Test Yard.

Several different shading experiments were conducted. Partial shade was applied to rows or columns of modules with an opaque fabric (4% transmittance) in order to study the response of individual modules and entire strings to partial shade. To simulate shade from overhead wires, PVC pipes were used to cast shadows as shown in Fig. 1. The individual pipes were 5 cm in diameter. Typically, the shadows of two bundled PVC pipes had a width of 5.5cm.

A useful parameter for quantifying power loss due to shading is the Shade Impact Factor (SIF) [4]. It compares the fractional power loss to the shaded fraction of the module's area. SIF is defined by the equation

$$SIF = \left(\frac{P_{normal}-P_{shaded}}{P_{normal}}\right)\frac{A}{A_{shaded}} \qquad (1)$$

where P_{normal} is the system's power output without shade, P_{shaded} is the power of the system when it is shaded, A is the area of the system and A_{shaded} is the shaded area. A SIF greater than one implies more is power lost than proportional area shaded. SIF is unique to each module design and shadow type, and depends mainly on the electrical configuration of sub strings and bypass diodes within the module. We characterize the SIF for three PV strings for several types of shadows. We also document changes in several I-V curve parameters -I_{sc}, V_{oc}, I_{mp}, V_{mp}, P_{mp}- for entire strings that result from individual modules being subjected to various shadows, and also for individual modules.

A Tahara Solar Array Checker (TSC-PD01) was used to measure I-V curves, as well as irradiance. The I-V curves presented here have been corrected for irradiance using the following procedure:

$$I = I_{meas} \frac{1000\ W/m^2}{E_{meas}} \tag{2}$$

where I_{meas} is the measured current and E_{meas} is the measured POA irradiance of the non-shaded modules, and I is the current corrected for irradiance reported in the figures and tables here. All measurements were taken in January through April 2012, in Tucson, Arizona during times of day when the irradiance was greater than 900 W/m^2.

II. PV String Summary

This study was performed at the TEP solar test yard, established in 2003 and now contains 22 grid-tied PV systems [3]. We studied the effect of partial shade on three particular strings listed in Table I. The strings chosen represent a variety of flat-plate technologies.

TABLE I
OVERVIEW OF THE PV STRINGS USED FOR THE PARTIAL SHADE EXPERIMENTS PRESENTED HERE

String #	Model	Technology	No. Modules	Module DC rating
1	Sharp NE-Q5E2U	px-Si	9	165 W
2	Sanyo HIP-G751BA2	HIT-Si	4	167 W
3	Prism Solar DA-HPC 50	Holographic CPV	8	50 W

III. Shading Rows or Columns

Before applying shade from overhead cables (simulated by PVC pipes), we studied how each of the strings responded to four different conditions: shading only the bottom row of one module in the entire string; shading only the top row of one module in the entire string, shading only one column of one module in the entire string, and shading the bottom row of the entire string. A string-level I-V curve was measured for each of the four conditions. Figs. 2 and 3 show measured I-V curves and Table II summarizes the change in the I-V curve parameters while exposed to these types of partial shading.

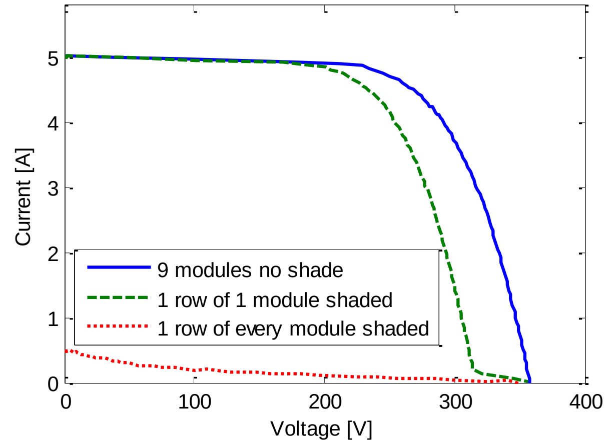

Fig. 2. I-V curves from string #1 (9 Sharp modules in series) when one row of cells in just one (out of 9) modules is shaded. The very low (red) curve corresponds to the case when the bottom row of each module in the string was shaded.

Fig. 2 shows I-V curves for string #1 with just one row of cells shaded on just one (out of 9) modules. For comparison, a string-level I-V curve with no shading is also shown. By shading one row of a module, the entire module operates in reverse bias and is effectively removed from the system operation. Shading 0.93% of the entire string reduces the power by 13% and thus demonstrates a shade impact factor (SIF) of 13.7. This result is repeatable regardless of which module in the string is shaded. When one row of every module is shaded, the resulting I-V curve demonstrates 98% power loss.

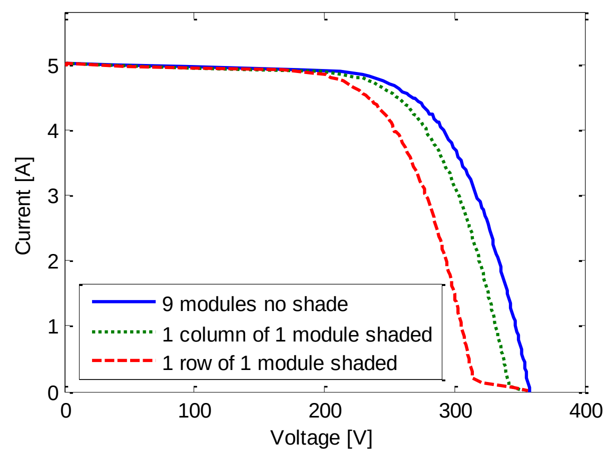

Fig. 3. I-V curves from string #1 with a column or a row shaded in just one (out of 9) modules.

Fig 3.compares the string level I-V curves (9 modules in series) while shading one row or one column of a single module from string #1. The I-V curves for the entire string of 9 modules are shown in each of these conditions. Shading rows or columns leads to shade impact factors of 13.7 and 2.3, respectively. The shade impact factor does not behave linearly compared to area shaded. This result is easily explained by the deployment of substrings and bypass diodes within the Sharp modules. It can be inferred that columns are connected in series within a module and each pair of columns share one bypass diode. This latter claim is substantiated by another brief experiment in which shading two columns was observed to make the same effect as shading just one column (provided that a correct pair of columns are chosen). As a policy recommendation, if these modules were located in an area where their rows are commonly shaded, for example by the top of an adjacent building during the winter season, then re-orienting the modules by 90° (to landscape orientation) would increase the energy yield.

TABLE II

AVERAGE PARAMETER CHANGES (IN %) COMPARED TO UNSHADED CONDITIONS DUE TO SHADING PART OF ONE MODULE IN EACH STRING. CURRENT HAS BEEN CORRECTED TO STC CONDITIONS USING (2). SHADE IMPACT FACTOR (SIF) IS DEFINED IN (1).

String #	Shaded Region	I_{sc}	P_{mp}	I_{mp}	V_{mp}	SIF
1	Bottom row	+0.4	-12.7	+0.4	-13.1	13.7
	Top row	+0.1	-12.5	+0.2	-12.6	13.4
	Column	+0.9	-4.3	+1.1	-5.3	2.3
2	Bottom row	-0.1	-26.5	-1.6	-25.3	12.7
	Top row	+0.4	-26.6	+0.7	-27.2	12.8
	Column	+1.5	-5.1	+1.7	-6.7	1.6
3	Bottom row	+1.4	-11.8	-0.6	-11.3	5.2
	Column	+0.3	-12.2	-1.2	-11.1	8.8

From Table II several findings can be discussed. Changes in current (I_{sc} and I_{mp}) are small (less than 2%) and therefore they are not as important as the other parameters. V_{mp} decreases more significantly for all cases when some area of a panel is shaded. For strings #1 and #2 the power loss was greater when a row was shaded (13% and 27% respectively) as compared to when a column was shaded (4% and 5% respectively). However, in string #3, shading rows or columns had similar effects.

For large PV systems, I_{mp} and V_{mp} are important to analyze because strings connected in parallel must operate at a common (shared) voltage which might not be V_{mp} for either of the individual strings. Strings in series operate at a common current which might not be I_{mp} for either individual string. So if these parameters change in one string, then the power output will generally be reduced for the other interconnected strings too. Hence the partial shade on just one module may lead to a situation in which none of the strings in a system work at their individual maximum power points due to the new sub-optimal current and or voltage constraints.

The most meaningful parameter to analyze when it comes to comparing the effect in power generation under shade conditions is the SIF. In the case of strings #1 and #2, SIF obtained for row shading was in the range 12 - 13, and SIF found for column shading was around 2. Hence, it can be concluded that row shading presents a higher impact on power generation compared to column shading. Still, we never observed a SIF value less than 1.6.

IV. SHADE FROM OVERHEAD WIRES

Overhead electrical wires or pipes present another geometry for partial shading studies, with a more diffuse shadow if the wires are far away. Utility companies and installers have vested interest in understanding the SIF or lost kWh due to PV systems siting under different types of overhead wires. A very common occurrence of this problem is in residential installations where the neighborhood power distribution lines may be overhead.

We separate our study into four categories of shading from overhead cables: *A*. the effect of overhead cables, *B*. the difference between merged and separated cables, *C*. the distance between wires and PV surface, and *D*. effects at string level as we have discussed in Section III. The first three categories study individual module performance based on different shading techniques and the final category looks at string performance loss due to shading on a single module.

A. Overhead Cable Shading on a Single Module

This experiment compares the electrical performance of a single module with and without shade from two PVC pipes a distance of 2 m from the PV surface as shown in Fig. 1. Table III lists the changes in I-V parameters and the SIF values for this type of shading for all three strings. This experiment was repeated for every module in these strings. The results shown in Table III are the averages for each module type. Typical I-V results are shown in Fig.4.

TABLE III

AVERAGE PARAMETER CHANGES (IN %) COMPARED TO UNSHADED CONDITIONS FOR MODULES SHADED BY TWO PVC PIPES AT A NORMAL DISTANCE OF 2 M. CURRENT HAS BEEN CORRECTED TO STC CONDITIONS USING (2). SHADE IMPACT FACTOR (SIF) IS DEFINED IN (1).

String #	I_{sc}	V_{oc}	P_{mp}	I_{mp}	V_{mp}	SIF
1	-33.9	-0.1	-24.2	-33.7	+14.8	7.6
2	-51.9	-0.2	-45.0	-52.8	+16.6	11.9
3	-70.1	-1.1	-72.3	-76.7	+19.2	8.4

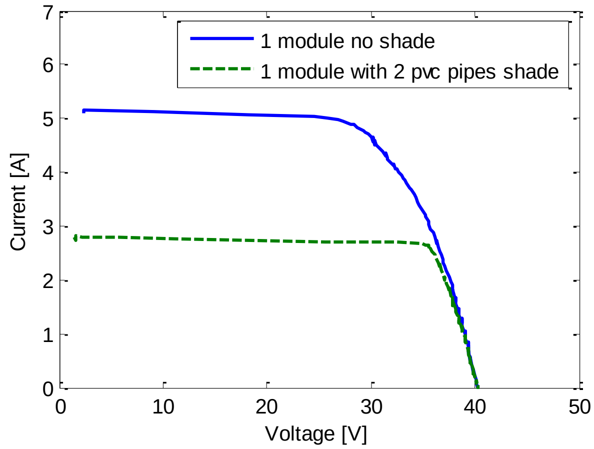

Fig. 4. I-V curves for a single Sharp module (from string #1) with shade from two bundled PVC pipes. When shaded by pipes the module's current is reduced.

As can be observed from Table III and Fig. 4, the major effect of PVC pipes shading single modules is a reduction in the I_{sc} and I_{mp} for that module's I-V curve. The reduction is large: I_{sc} is reduced by 34% to 70% depending on the module type. Due to a change in shape of the I-V curves, V_{mp} increased for all the strings (between 15% and 19%). Still, all three types of modules demonstrated SIF values considerably greater than 1 (ranging from 7.6 to 11.9).

B. Merged Cable Shading on a Single Module

This experiment analyzes whether shade from several cables that are bundled together is more or less detrimental than shade from the same number of cables being separated from each other by a certain distance. We compare the performance when three wires are separated to that when the same three wires are bundled side by side, effectively tripling the width of any one shadow. The wires in both cases were at a distance of 2 m from the module surface. Fig. 5 shows the I-V curves for string #2 under the various shading conditions. Table IV gives the I-V parameter and SIF values for each condition.

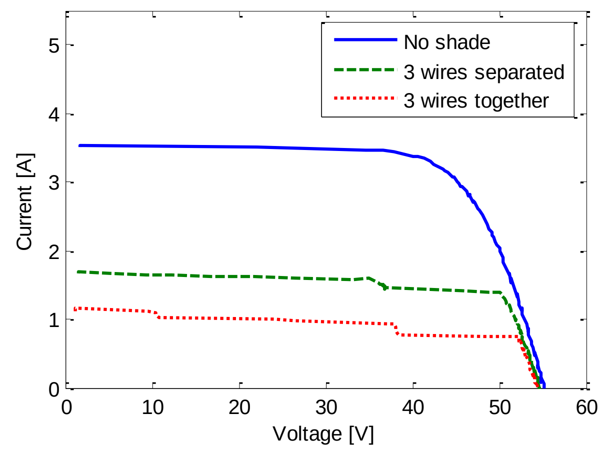

Fig. 5. I-V curves for one Sanyo module (from string #2) under the shade of three separated wires, three merged wires, and without shade.

TABLE IV

PARAMETER CHANGES (IN %) COMPARED TO UNSHADED CONDITIONS FOR OF AN INDIVIDUAL MODULE WHEN SHADED BY THREE SEPARATED OR MERGED WIRES AT A NORMAL DISTANCE OF 2 M. CURRENT HAS BEEN CORRECTED TO STC CONDITIONS USING (2).

String #	Case	I_{sc}	P_{mp}	I_{mp}	V_{mp}
1	Separate wires	-43.3	-33.3	-41.7	+14.4
	Merged wires	-54.5	-59.3	-67.1	+24.0
2	Separate wires	-52.1	-49.6	-57.9	+19.9
	Merged wires	-67.1	-71.8	-77.4	+24.9
3	Separate wires	-70.5	-75.1	-78.8	+17.3
	Merged wires	-73.4	-74.1	-77.1	+13.3

Fig. 5 and Table IV show similar results to the previous section (IV *A*). When a module is under shade from wires, the irradiance decreases on just a few cells, and this results in a dramatic reduction in I_{sc} and I_{mp} and an overall drop in power. Also similar to Section IV *A*, an increase in V_{mp} is observed, presumably because the product of series resistance (R_s) and current is reduced compared to the un-shaded case.

For string #1 and #2 more power is lost when the cables are merged. This can be explained if current in the module is limited by the least illuminated cells. With their diffuse edges and their finite size, shadows from three merged cables are simply darker than those for separated wires (especially when integrated over the size of each cell). String #3 does not show the same result. This is because of the difference in technology used: rows alternate between PV and holographic material. The impact on the power output varies depending on where the shadow falls [5] and hence this factor cannot be kept constant.

As a policy recommendation, to minimize SIF and hence minimize lost kWh, we recommend the optimal configuration for a set of cables may be to separate them rather than merging them into one large bundle.

C. Cable Distance from PV module

This experiment aims to study the power loss due to shade from overhead cables at varying distances. In order to do this, a set of cables were placed at different normal distances from the module (0.4 m to 2.7 m). The experiment was performed with two different shadow diameters, formed by either two or four merged PVC pipes.
Figs. 6 and 7 show the power loss as a function of the distance of the wires.

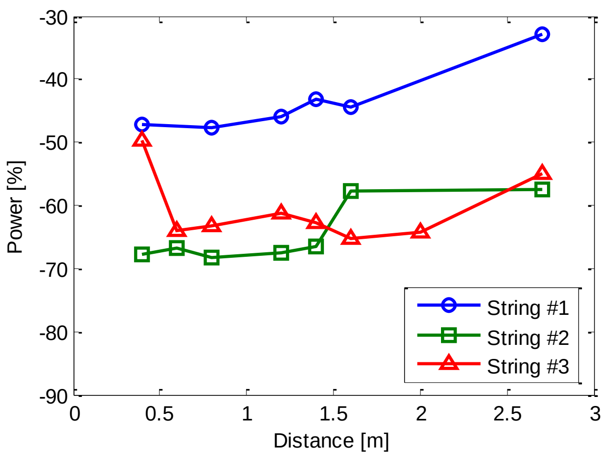

Fig. 6. Percent power loss [(P_{shaded}-P_{normal})/P_{normal}*100] vs. distance at which 2 wires are located from the surface of the module.

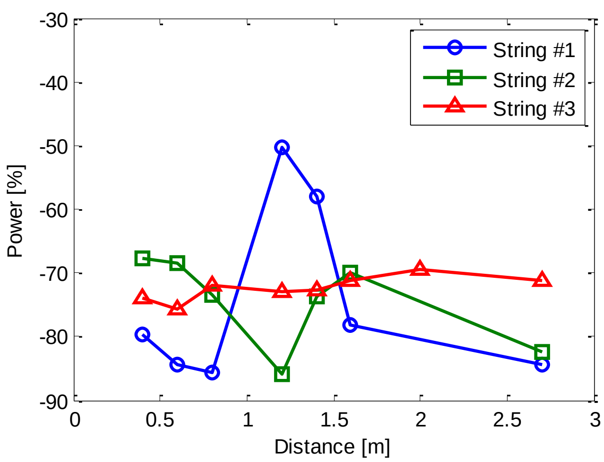

Fig. 7. Percent power loss [(P_{shaded}-P_{normal})/P_{normal}*100] vs. distance at which 4 wires are located from the surface of the module.

Fig. 6 suggests a relationship between power loss and distance: the farther away the cables are, the less the power loss. Extrapolating this relationship we predict that wires may need to be placed more than 15 m overhead in order to make the power loss as small as 10% (or SIF < 2). It is interesting to note that at a distance of approximately 12 m the angular size of the pipe bundle would be approximately half a degree, equivalent to the angular size of the sun, thus guaranteeing a diffuse shadow only. Beyond this large (12 - 15 m) distance the irradiance on any one cell would not be so much affected, i.e. every cell in the module would get at least some part of the beam component of irradiance, so we predict the SIF will trend towards unity. To verify this prediction, more experiments are needed to explore a larger distance range.

No significant trend was observed in the case of four bundled wires. Perhaps these experiments simply did not explore a large enough range of distance. Power loss observed was between 50% and 90% and our simple prediction is that the cable bundle may need to be 24 to 30 m overhead in order to make the power loss less than 10%.

D. Overhead Cable Shading on a String

The objective of this experiment is to study the effect of shade at the string level. Each string was comprised of four modules in series. With the use of two bundled PVC pipes at 2 m, three cases were studied: horizontal shade on a single module, vertical shade on a single module and horizontal shade on the entire string. Table V gives the string I-V parameter and SIF values for each condition.

TABLE V
CHANGES IN STRING I-V PARAMETERS (IN %) FROM THE UNSHADED CONDITION. CURRENT HAS BEEN CORRECTED TO STC CONDITIONS USING (2). SHADE IMPACT FACTOR (SIF) IS DEFINED IN (1).

String #	Shade	I_{sc}	P_{mp}	I_{mp}	V_{mp}	SIF
1	Horizontal on 1 module	+5.5	-16.5	-25.2	+11.6	15.8
	Vertical on 1 module	-1.8	-8.6	-3.0	-5.8	5.6
	Horizontal on string	-21.7	-17.5	-25.2	+10.2	4.2
2	Horizontal on 1 module	-1.8	-36.1	-9.5	-29.4	34.7
	Vertical on 1 module	-5.2	-9.8	-3.6	-6.5	6.4
	Horizontal on string	-25.2	-23.0	-31.4	+12.2	5.5
3	Horizontal on 1 module	+1.1	-29.2	-38.3	+14.7	25.4
	Vertical on 1 module	-0.1	-25.9	-3.9	-22.9	11.3
	Horizontal on string	-36.1	-35.1	-42.1	+12.2	7.7

As it can be observed from Table V, the smallest power loss occurred for all the systems when a vertical shadow (parallel to columns) was applied to just one module in a string (from 9% to 26% of power loss). This finding is consistent with the study of partial shade in section III. When horizontal shadows were applied, the observed drop in power was greater. Of higher interest is the fact that shading only one module of the string, or the entire string, does not make a substantial difference in power drop. When only one row of one module was shaded the observed power drops were 17% and 29% for strings #1and #3 respectively, and when one row of the entire string was shaded, power decreased by a similar percentage, 18% and 35%. Horizontal shade on one module has a greater SIF than shade on the whole string. With just one module shaded by pipes we observed shade impact factors as high as 25. Again, this can be explained by the fact that none of the modules work at their individual P_{mp} when they are connected in series with a module that is hindered by partial shade. Similar results were observed for string #2, the only distinct result was that V_{mp} decreased when only one row of a single module within the string was shaded, opposed to what was observed for string #1 and #3. The power curve of this case showed that there were two local power maximums, differing by only 0.3%, but the smaller local maximum V_{mp} was 9.74% higher compared to the unshaded condition, which is consistent with findings for system #1 and #3.

It is of interest to note that V_{mp} increased when horizontal shade was applied, but decreased with vertical shadows. Maximum power point tracking techniques allow for drastic changes in voltage to account for current losses.

V. CONCLUSION

The study of partial shade on PV systems is of high interest because modules under shade from trees, poles, cables, etc., can be easily found, thus accurate electric power generation forecasts become challenging. Through this research different cases were studied. The first part consisted of shading rows or columns of single modules, and then analyzing the change in I-V parameters for the entire string. For two module types (string #1 and #2) in portrait orientation, the loss in power output triggered by shading a row was much bigger than when a column was shaded. In string #1 and #2, SIF values greater than 10 were obtained when a single row of a module was shaded, as compared to SIF values smaller than 3 when a column of a module was shaded. This difference suggests that if these modules were located in an area where their rows are commonly shaded, then mounting modules in landscape orientation would increase the energy yield. These results also demonstrate the non-linear behavior of the SIF.

The second part of this paper presented a study of the change in I-V parameters due to overhead cables. Sets of PVC pipes were used in order to simulate shade coming from wires. Four experiments were performed, from which the following conclusions were obtained. Shade coming from a wire 2 m away from the module surface can cause a drop in power between 24% and 72% (with SIF between 7.6 and 11.9). Overhead cables that are separated by a small distance produce less power loss than merged cables. A possible linear relationship was observed between power loss and shade coming from different distances: the further away the cables are, the less the power loss (hence smaller SIF). Finally, the power due to one module in a string shaded by overhead wires decreases power output only slightly less than the same shadow cast on all modules in the string.

To extend this study we are making a theoretical prediction for the way power loss should depend on the distance to an overhead cable, and we recommend further experiments surveying this situation over larger distances out to 20 m. A definite correlation was seen between overhead cable shadows and PV power loss that should be considered by system designers and installers.

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