PARTIALLY SHADED OPERATION OF MULTI-STRING PHOTOVOLTAIC SYSTEMS

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ABSTRACT

New shade mitigation technologies are available claiming improved performance under shaded conditions. A typical multi-string photovoltaic (PV) system was operated under partial shading conditions with and without these DC-DC converters. Power loss was attributed to low irradiance on shaded modules, current mismatch within shaded PV strings, and voltage mismatch between parallel strings. Indirect loss from voltage mismatch contributed up to 40% of the total power loss from shading. A representative residential solar installation was evaluated for potential benefit from DC-DC equipment. Detailed shading site survey information was collected and used to modify a PV production model. Using various assumptions on the severity of shade in this PV model, the application of DC-DC converters improved annual modeled power production by 5%-10% and recovered 24%-48% of the power lost due to shading.

INTRODUCTION

Power optimizers are newly available commercially, and have the stated benefit of reducing the impact of shade on the PV systems on which they are installed. Designs range from micro-inverters to DC-DC converters, with a similarity being that they will peak power track the individual PV module on which they are placed. By peak power tracking individual modules, the impact of mismatch due to shade or module degradation is reduced.

A number of National Semiconductor's Solar Magic DC-DC converters were purchased for evaluation. It is not the purpose of this study to compare one product against another, and the results of this study could fairly be applied to several other DC-DC converter products or micro-inverters. Solar Magic devices work together with a conventional string inverter to provide per-module peak power tracking. Overall string operating voltage and current are still tracked by the inverter, so Solar Magic is not a replacement for a system's inverter. With the addition of per-module peak power tracking, though, total power is improved because the output current for a string of modules is decoupled from the output current of an individual module.

To determine the effectiveness of these new products, an experiment was conducted at NREL on a 1.5 kW residential scale PV system under controlled shading conditions, both with and without the use of DC-DC converters. The size and configuration of the experiment was chosen to represent how a shaded residential system might be expected to respond to shade.

BACKGROUND AND THEORY – BYPASS DIODE

A typical crystalline silicon module will contain bypass diodes to prevent damage from reverse bias on partially shaded cells. These diodes are placed across 12-24 cells in what will be termed here a "cell substring". The bypass diode across this cell substring will begin conducting before the power dissipated into the shaded cell(s) is enough to evolve damaging temperatures [1,2]. The bypass diode allows current from non-shaded parts of the module to pass by the shaded part, dropping module voltage by an amount corresponding to the sum of cell voltages protected by the bypass diode plus the diode forward voltage.

The impact of shade on system performance depends in part on the electrical configuration of the PV modules in the system. If the modules are configured into a single series string, the effects of shade are easier to quantify. In this case, partial shading will result in bypass diode conduction on the shaded modules (with current remaining constant) and string voltage being reduced by a percentage equal to the portion of the system protected by the diode.

The situation becomes more complicated for PV systems incorporating multiple parallel strings. In the previous example of a single shaded string, the string's operating voltage is unconstrained. With multiple parallel strings, however, the string voltages must all be identical whether they are shaded or not. This voltage match consideration can result in reduced power throughout the system beyond the direct power loss due to shading. For instance, unshaded modules in series with the shaded module will tend to operate at a voltage above their peak power point to make up for the voltage lost in the shaded module. Additionally, modules in parallel with the shaded string will tend to operate at a lower voltage to attempt to match the reduced voltage of the shaded string. Because these modules are not operating at their peak power voltage Vmp, mismatch losses result.

BACKGROUND AND THEORY – SHADING

The light reaching a solar module at a given fixed tilt is made up of three independent components: sky diffuse D, beam B, and ground-reflected R [3]. The sum of these components is equal to the total global irradiance G. Under shaded conditions, B is blocked, with the other two components remaining relatively constant. The diffuse-to-global irradiance ratio D/G depends partly on atmospheric conditions and solar position, with shade or large incidence angle increasing the relative diffuse component.

The description of a shadow on a real PV system can be difficult to specify in part because of its varying opacity and irregular geometric extent across PV modules. The following simplification was therefore used in describing the extent of shade in this experiment. Assume a PV cell with a shadow across it, halving its irradiance. This case is very nearly equivalent (within 1%) to the same cell with one half of the cell entirely shaded, and the other half of the cell entirely unshaded [4]. Drawing on this principle, this experiment focused on shading PV modules by direct application of shading material (opaque masking tape) to the module surface, rather than nearby screens or shade obstructions casting irregular and not entirely opaque shadows onto the module. A higher degree of accuracy was thereby possible in measuring shade extent, with minor impact on the experimental result. It was found that directly shading a given percentage of a cell is equivalent to blocking beam irradiance making up that same percentage of the global total.

EXPERIMENT OVERVIEW

Experiments were conducted at NREL using ten 165 W PV modules (GEPV-165) mounted side by side at an elevation angle of 40^{o} and azimuth orientation of 180^{o}. A previous publication describes some initial results from this test setup, in a single-string configuration [5].

A schematic of the PV electrical configuration is shown in Figure 1. The modules are electrically connected in two series strings of five modules each. The first PV string composed of Modules 1 through 5 remains unshaded throughout the experiment, with no power optimization devices equipped to it. The second PV string is equipped with DC-DC converters, and was shaded during the experiment. The second PV string also contains a blocking diode on the positive leg, as per the manufacturer's recommendation. A two-string electrical configuration matches the manufacturer's suggested installation, and also makes up a majority of present-day residential PV installations in California [6].

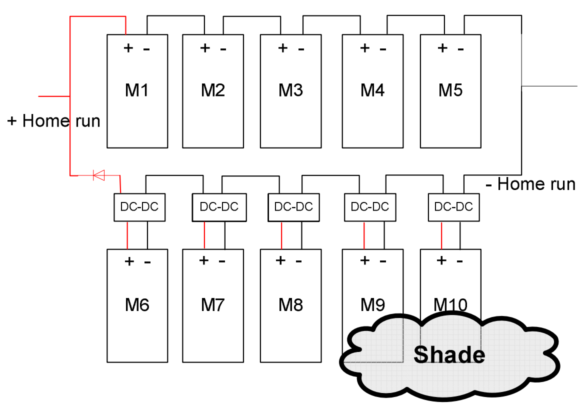

Figure 1 Electrical configuration of the ten modules used in the shade study. DC-DC devices are installed on one of the two strings.

Peak-power tracking of the PV system is provided by a custom 3 kW DC load which also provides periodic current - voltage (IV) sweep data, useful in ensuring the PV system operates at the global maximum power point (MPP). An adaptive hill-climbing algorithm [7] provides the MPP tracking logic. Auxiliary data channels monitored in this experiment include DC string currents, system DC voltage, irradiance at tilt angle (Kipp & Zonen CM-11), and module voltage and temperature.

The experimental data uses cloudless day data with irradiance in the range of 1000 ± 200 W/m^2. Shading intercomparisons use data corrected by irradiance and temperature, and compared with an unshaded reference case typically within a day of the shaded case.

Artificial shading applied

The PV system is shaded incrementally by application of black masking tape to the surface of the modules. Given a sufficient amount of shade on a single cell, the bypass diode protecting that cell will being conducting. Additional shading on that substring will not reduce power any further. The amount of shade required to turn on a sub-string bypass diode is shown in Figure 2, both with and without the use of DC-DC converters. Without DC-DC devices, the bypass diode conducts when shade covers 20%-25% of the cell's area. This result is consistent with prior results for shade on a single-string system [5], where it was found that ~30% cell coverage was required to turn on the bypass diode.

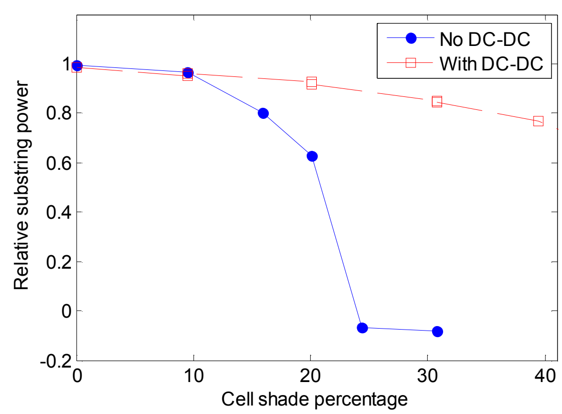

Figure 2 Impact of cell shading on a cell substring. ~25% shade on a cell causes diode conduction without DC-DC devices. With DC-DC devices (open squares), substring power loss by shading is reduced.

Including DC-DC converters on the shaded PV module improves this response, resulting in a more gradual decrease in power production and eliminates bypass diode turn-on (assuming the module is uniformly shaded). The application of per-module shade mitigation devices here allows the capture of some module power from diffuse irradiance that would not have been possible otherwise due to bypass diode turn-on. It should also be noted that an insertion loss is evident in Figure 2 with the use of DC-DC devices. With identical unshaded conditions, including DC-DC converters drops the string power by 1.7% ±0.8% due to the power draw of the active devices and the insertion loss of the blocking diode.

The values for bypass diode turn-on in Figure 2 assume that no additional shading is present in the system. Additional shaded substrings will increase the amount of shade required for bypass diode turn-on, as shown in Figure 3. This plot shows the percentage of cell shade required to turn on a substring's bypass diode assuming increasing amounts of shade on the rest of the system. To collect these data, opaque masking tape was applied to a single cell as before, but additional substrings were also completely shaded with opaque masking tape. For instance, when 20% of the modules in a string were shaded, the next shaded substring required at least 50% shade on one cell to turn on the bypass diode. These data were not collected using DC-DC devices because their use does not normally lead to diode turn-on.

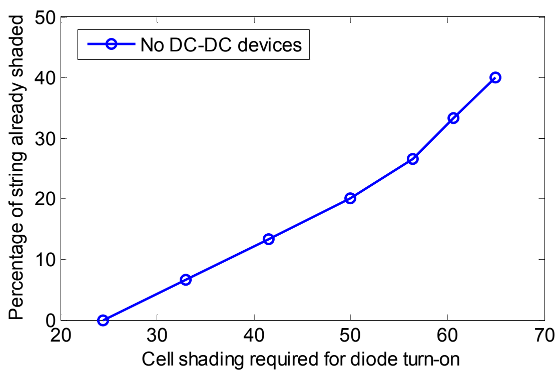

Figure 3 Diode turn-on threshold for single cell shade, given additional shaded modules in the same string.

Under most shading conditions, the impact of shade on system power is related to the number of cell substrings shaded. Module M10 was therefore shaded incrementally by masking out each of its three cell substrings in sequence. This resulted in M10's power being reduced roughly 1/3 for each substring shaded. When entirely shaded, M10's power output is actually negative due to the voltage drop and power dissipation in its three bypass diodes. The impact of shade in this parallel-string system also extends to each of the other modules in the system. As shown in Figure 4, power is reduced in each of the other modules when M10 is shaded. Modules M6 – M9, which are in series with M10, each lose 3%-4% peak power production when M10 is completely shaded. Likewise, modules M1-M5, which are in parallel, each lose 3%-9% peak power production.

The power loss in the other series or parallel modules can be understood as follows. When M10 becomes shaded, its terminal voltage is decreased as bypass diodes turn on. In a single-string system, this module voltage drop is the extent of the system impact because the operating voltage of the string is unconstrained. However, in a parallel-string configuration, the operating voltage of the parallel strings must match. Therefore, a drop in M10's voltage must be accompanied by a rise in module M6-M9's voltage, and a drop in M1-M5's voltage. If the system is peak power tracked, the voltage changes in these other modules will occur because this maximizes overall system power. This explains the 3%-4% peak power drop in modules M6-M9, because they operate at a voltage higher than Vmp when module M10 is shaded. Likewise, modules M1-M5 operate at a voltage below Vmp and experience a 3%-9% drop in power.

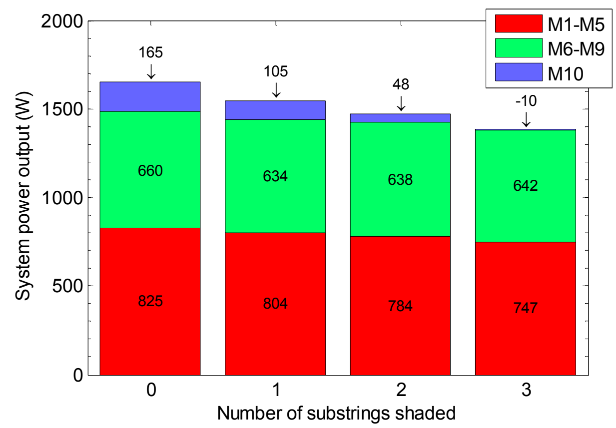

Figure 4 Total system output power under module M10 shading conditions, listed by module and string. Modules M6-M9 are in the same string as M10, and M1-M5 are in parallel.

In this shading case, the indirect power losses due to module mismatch are substantial. For the case of shade on all three cell substrings in module M10, indirect power losses from the other series and parallel modules (not M10) account for 35% of the total system power loss from shading. It is these indirect losses that power optimizing devices are able to recapture. It should also be pointed out that the shade on module M10 only covers three cells, which account for a mere 6% of the module's total area and 0.6% of the system's total area.

A useful measure of the relative impact of shading on a system is the areal Shade Impact Factor (SIF_{area}) [8] which is a relationship between the spatial extent of shade on a module or system, and its resulting power reduction. The shade impact factor can be represented by:

$$SIF_{area} = \left[1 - \frac{P_{shade}}{P_{sys}}\right] \frac{A_{sys}}{A_{shade}} \frac{G}{B} \qquad (1)$$

where P_{sys} and A_{sys} are the nominal system power and area, A_{shade} is the shaded area, and P_{shade} is the power produced under shaded conditions. *G* and *B* are the global irradiance and beam component at the PV module's tilt angle, respectively. A high SIF_{area} indicates a large power loss from a small shaded area. SIF_{area} = 1 indicates power loss proportional to the area of the shadow, and hence, no additional losses due to voltage mismatch.

With this form of the shade impact factor, it is difficult to compare the impact of different amounts of shade because the orientation of shade can have a large effect on the power produced. For instance, a large shadow that only covers one substring would have a smaller impact than the same-sized shadow crossing three substrings. For this reason, a modification to Eq. (1) is required to look at the percentage of cell substrings shaded in a particular system. In this case, N_{sys} is the total number of substrings in a system, and N_{shade} is the number of those substrings with at least one cell completely shaded:

$$SIF = \left[1 - \frac{P_{shade}}{P_{sys}}\right] \frac{N_{sys}}{N_{shade}} \qquad (2)$$

The above formulation of SIF based on shaded vs. unshaded substrings will be used in the rest of this paper. This equation does not show dependence on B or G and assumes the substring shade is opaque enough to turn bypass diodes on. If this is not the case (as determined through current-voltage analysis) the SIF would be reduced accordingly. The B/G shading threshold for bypass diode turn-on is shown in Figure 3.

Application of DC-DC power optimizing devices

An identical shade experiment was conducted on the PV system, this time with Solar Magic devices included on modules M6-M10. Figure 5 shows comparisons of the system operating with and without shade mitigation devices for three different levels of shade: 100% coverage of a cell with opaque masking tape, 71% coverage, and 50% coverage of a single cell. The latter two conditions approximate more diffuse irradiance conditions, with the ratio of beam-to-global irradiance B/G = 0.71 and 0.50, respectively.

It is clear from Figure 5 that including DC-DC converters improved power production. The slope of the power lost to shading is equal to the SIF defined in Eq. 2. For the inclusion of DC-DC devices and 100% cell shading, SIF ≈ 0.96, meaning that there is roughly a 1:1 ratio of shade to power loss. For lower amounts of shade on a particular cell (lower shade opacity), the impact of shade is reduced.

Without DC-DC devices, the impact of shade is independent of shade opacity, as long as there is sufficient shade to turn on the substring's bypass diode (Figure 3). The inclusion of DC-DC devices allows power to be produced from diffuse irradiance. With DC-DC devices, the operating current of a module is decoupled from the operating current of the rest of the string. A shaded module can operate at a lower current than its neighbor, and still contribute power to the system. Within the 2% uncertainty of this experiment and assuming at least one PV module is shaded, the SIF for a single string equipped with Solar Magic was found to equal the beam component of the irradiance: SIF = B/G.

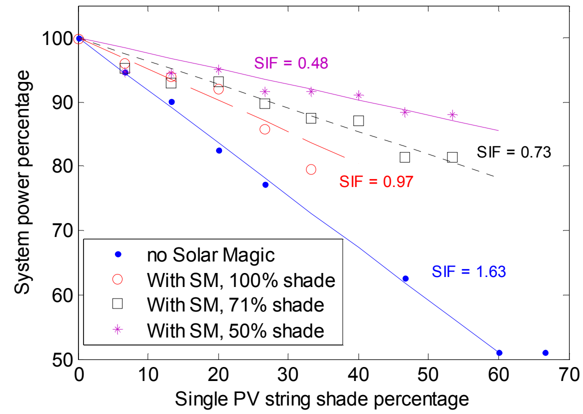

Figure 5 Performance loss due to substring shading on a single string. Uncertainty: 2%. Shade is applied to only one string in a 2-string system. Reported power loss is for the entire system.

These performance improvements from DC-DC devices stem from reduction in current mismatch within a series string. It is also important to consider the mismatch of voltage between two parallel PV strings. With the inclusion of these devices, there actually is no string voltage mismatch between parallel strings. Because Solar Magic consists of a two-stage buck-boost converter, both the input and output voltages are set arbitrarily, within input and output DC voltage limits. The output voltage of the Solar Magic units is set by the peak power tracking algorithm of the string inverter connected to it, which in turn is driven by the peak power operating voltage of the unshaded string. The operating voltage of the system is unchanged by the amount of shade on the shaded string, resulting in no voltage mismatch between the two strings.

Without DC-DC devices however, additional losses arise in the system due to voltage mismatch between the parallel strings. Under the condition of unbalanced shade in a 2-string system, the shade impact factor without DC-DC devices was found to be SIF ≈ 1.63. This experimentally determined SIF arises from two summed components: SIF due to current mismatch of SIF_I = 1 and SIF due to voltage mismatch of SIF_V = 0.63. The current mismatch SIF_I = 1 means that shade on a single substring reduces the power contributed by that substring by 100% because the bypass diode is turned on. The voltage mismatch SIF_V = 0.63 means that the shade on that substring also produces additional power loss equal to 63% of a substring due to voltage mismatch between the parallel strings.

Note that these values are not related to the size of the shadow, but rather to the number of substrings shaded. The areal shade impact factor (SIF_{area}, Eq. 1) is much greater for substring shade that only covers a single cell. Also note that in Figure 5 the linear fit through the data is better for large shade percentages than small (< 1 module) shade percentage. Assuming a linear fit for SIF in Figure 5 was found to introduce less than 0.5% error in the subsequent analysis.

Uniform shade on parallel strings

The previous shade experiment assumed that one of the PV strings was shaded, and the other parallel PV string was unshaded. This may or may not be the case for a real shading situation, depending on the orientation of shade to the PV system. If the amount of shade on both strings is the same, power losses due to string voltage mismatch are eliminated. In this case, the string voltage is reduced uniformly, and $SIF_V \approx 0$. The shade impact from current mismatch SIF_I is unchanged.

Because SIF_V is already zero for the case with DC-DC conversion, having uniform shade on parallel strings would primarily impact the power produced without the DC-DC devices. We found that these devices provide benefit under uniform conditions due to the reduction in current mismatch, but no additional gains from voltage mismatch mitigation. The performance benefit of power optimization devices should therefore be greater in multi-string PV systems experiencing shade primarily on one string versus a system that is uniformly shaded or consisting of a single string. PV systems that include modules at different tilt or orientation would also benefit from DC-DC devices. These conditions will be investigated further in follow-on experiments.

APPLICATION - TYPICAL RESIDENTIAL CASE STUDY

The above experimental results can be applied to a typical residential PV installation (Figure 6) to estimate the annual performance benefit from using DC-DC devices. As previously noted, the benefits of DC-DC equipment depend greatly on the electrical configuration of the PV system, and the orientation of shade to the modules.

Figure 6 View of the "typical residential installation".

The residential PV system chosen for this representative study is a 3 kW PV system consisting of 14 crystalline silicon PV modules in two parallel strings. One aspect of this system that makes it a good candidate for study is that it experiences what could be described as "typical" shade conditions. Other large surveys of shading in residential neighborhoods have shown that power lost to shading typically peak within 2-4 hours of sunrise or sunset, and total irradiance losses due to mature tree shading is 10%-15% [9]. The shade conditions in our representative residential system can be seen in Figure 7. A shade site survey was conducted over the whole system with a Solmetric SunEye, showing that annual irradiance loss due to shade is around 20%, peaking prior to 10 AM and after 2 PM. The shade experienced by this PV system is therefore somewhat more extensive than average.

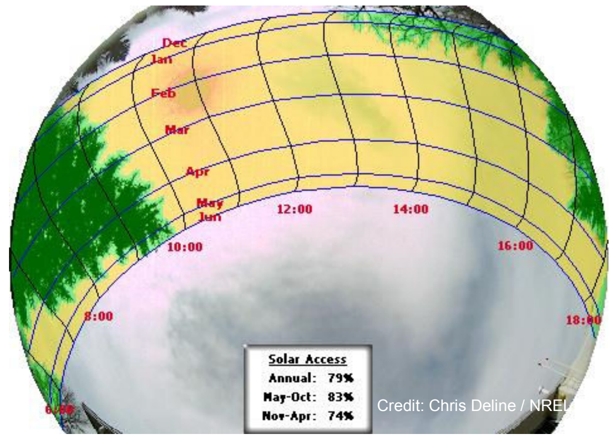

Figure 7 Site survey showing surrounding obstructions. Annual insolation reduction by shade is 20%, averaged over the system.

A shading site survey was conducted, with a shade image taken for each substring in the system, 42 images in total. This measurement frequency does not provide shade data on a per-cell basis, but it does provide shade estimation data with high enough resolution to calculate the number of module substrings experiencing shade within a 15-minute time window. These substring shade data translate to system power reduction using the empirical SIF results summarized in Table 1.

No DC-DC:	SIF_I =1	SIF_V = 0.63	Total SIF= 1.63
With DC-DC	SIF_I = B/G	SIF_V = 0	Total SIF = B/G

Table 1 Shade Impact Factor (Eq. 2) with and without DC-DC devices. Linear fit to data in Figure 5.

Once an estimate of system shade percentage is collected, a detailed PV power production model can be used to translate these shade power losses to annual power production. The basis of this analysis is NREL's PVWatts V1 code, which has a publicly accessible Web interface [10,11]. This program uses average TMY meteorological data to calculate PV system production, given modeling assumptions such as PV and inverter parameters. The existing version of PVWatts does not have the capability to take shade data as an input, so only the numerical core of the software was used. A power derating based on hourly shading and *B*/*G* irradiance conditions was applied to the hourly DC power output of the PVWatts core software.

Several different system assumptions were used in this analysis. All simulations include a Fronius 3.8 kW inverter, fourteen 208 W Sharp PV modules at 18.5^o tilt angle, and TMY3 weather data from Boulder, CO. An overall DC-to-AC derating of 0.79 was used. In simulations using DC-DC devices, an additional 0.75% insertion loss is included to account for the DC power draw and losses from one string worth of this equipment. Shade coverage over the two PV strings is determined from the detailed site survey described above. The impact of shade on power production was conducted in two different ways. The first method assumed that one PV string was entirely unshaded, and shade occurs only on a single string. This scenario provides the most beneficial results for DC-DC devices, since mismatch losses are greatest under these conditions. This artificial case represents a PV system arranged in such a way that shade is predominantly cast over one string than another, which may be true for some systems. The second simulation method used the second PV string's shade data as measured. Both simulations assumed linear SIF values given in Table 1.

The results of the power production analysis are shown in Table 2. Single string shading results assume shading data is applied only to one string. Two string shading results use the actual shade data measured on the test installation.

	Annual power produced	Power lost to shade	Improvement by DC-DC devices (%)
Unshaded annual power production			
	4424 kWh	**0**	
Single string shading, 2nd string unshaded			
-No DC-DC	3681 kWh	-17%	
-With DC-DC	4038 kWh	-9%	**10%**
Both strings shaded			
-No DC-DC	3465 kWh	-22%	
-With DC-DC	3710 kWh	-16%	**7%**

Table 2 PVWatts simulation results using site survey data for a two-string PV system.

The results of the full simulation show that there would be a roughly 7% improvement in performance from the inclusion of DC-DC devices on a single string of this "typical" residential installation. However, a residential system that saw shading on only one of its two PV strings would see a much improved benefit – up to a 10% production improvement. This further underscores the importance of understanding what sort of systems would benefit most from DC-DC devices. From this study, we found that multi-string PV systems would have an increased benefit, assuming non-uniform shading was present on one string. For systems with multiple parallel strings that experience persistent shade on a few modules in one string, particularly if that shade occurs during the high irradiance times of day (10 AM - 2 PM), DC-DC devices could make good economic sense. In addition, the impact of module fill factor on the effectiveness of DC-DC devices was not addressed here. It is expected that higher fill-factor modules experience greater mismatch loss, and would thus see greater benefit from the inclusion of Solar Magic devices. An additional point is that the improvement in voltage mismatch (SIF_V) requires Solar Magic units to be placed on each module in a single string. Selective placement of Solar Magic units on only a few shaded modules would only provide the benefit of improved SIF_I current mismatch.

ACKNOWLEDGEMENT

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