Partial Shade Evaluation of Distributed Power Electronics for Photovoltaic Systems

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Chris Deline
National Renewable Energy Laboratory

Jenya Meydbray, Matt Donovan, and Jason Forrest
PV Evolution Labs

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Partial Shade Evaluation of Distributed Power Electronics for Photovoltaic Systems

Chris Deline
National Renewable Energy Laboratory, Golden, CO, USA

Jenya Meydbray, Matt Donovan and Jason Forrest
PV Evolution Labs, Davis, CA, USA

***Abstract* — Site survey data for several residential installations are provided, showing the extent and frequency of shade throughout the year. This background information is used to design a representative shading test that is conducted on two side-by-side 8-kW photovoltaic (PV) installations. One system is equipped with a standard string inverter, while the other is equipped with microinverters on each solar panel. Partial shade is applied to both systems in a comprehensive range of shading conditions, simulating one of three shade extents. Under light shading conditions, the microinverter system produced the equivalent of 4% annual performance improvement, relative to the string inverter system. Under moderate shading conditions, the microinverter system outperformed the string inverter system by 8%, and under heavy shading the microinverter increased relative performance by 12%. In all three cases, the percentage of performance loss that is recovered by the use of distributed power electronics is 40%–50%. Additionally, it was found that certain shading conditions can lead to additional losses in string inverters due to peak-power tracking errors and voltage limitations.**

***Index Terms* —photovoltaic systems, DC–DC power converters, microinverters, mismatch, partial shading.**

I. Introduction

Existing test protocols for inverters are designed to evaluate a number of aspects of device performance, yet there remains a need for a standardized test procedure to judge the performance of inverters, microinverters, and other power electronic devices in sub-optimal irradiance conditions such as partial shading. The design of a representative test procedure is complicated by the fact that the performance benefit from distributed power electronics will depend on the electrical configuration of the photovoltaic (PV) system in question, the extent of shade/mismatch in the system, and the type of distributed electronics under test.

A procedure has been developed that meets some of the criteria of being a representative, repeatable test of shaded performance of two side-by-side systems [1]. This test procedure uses two side-by-side PV arrays that are otherwise identical, except that the reference array is equipped with a standard string inverter, while the test array is equipped with the distributed power electronics (power optimizers, microinverters, etc.) that are to be tested. In this example application of the test procedure, Enphase M215 microinverters are used, but other devices can be evaluated in a similar fashion. Several dozen systematic shading conditions are applied to both arrays, and the AC kWh production of both systems compared under these shaded conditions. Three 'prototype' shade conditions are simulated by different weighting conditions in this test: **light** shading (7% irradiance reduction), **moderate** shading (19% irradiance reduction), and **heavy** shading (26% irradiance reduction). The resulting performance value for each shade weighting represents an annual efficiency value, reflecting additional power output produced by the device under test, relative to the string inverter system. An advantage of this weighted approach is that with the same performance data, a system owner could simply apply their specific shade conditions (determined through a shading site survey) to apply the test results specifically to their system.

II. Site Survey

Site survey information was obtained from a PV integrator in California to determine the extent of shade on 66 residential PV installations [2]. In these measurements, a panoramic view of surrounding obstructions was taken with a Solmetric Suneye tool, and the annual irradiance loss due to shade was calculated. This measurement is averaged across the installation, using multiple images taken at the corners of the PV array. The annual irradiance loss for these various sites is given in Fig. 1.

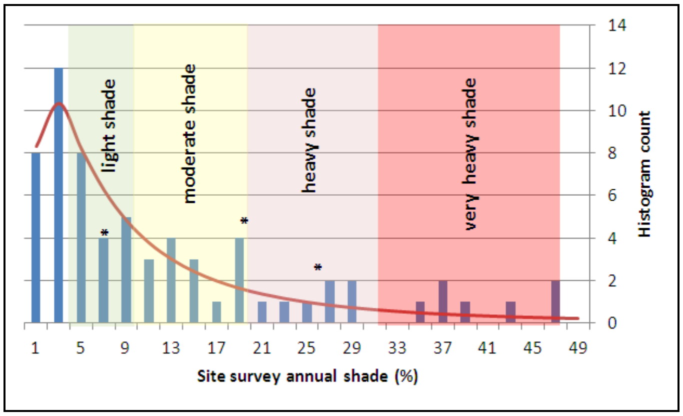

Fig. 1. Site survey details for 66 residential installations. The three asterisks * indicate the light, moderate, and heavy shade weighting conditions targeted in this test.

The distribution of shade extent in these residential systems closely follows a log-normal distribution, with $\mu = 2.025$ and $\sigma = 1.11$. This means that a majority of sites have a small amount of shading, but there are still quite a few sites with a large amount of shading. The median shading condition occurs for a system receiving 7.6% annual shade. This median shading value represents our **light shading** condition, and shade data from a representative installation with 7% annual shading will serve as the basis for the light shading analysis.

The second shading condition was chosen to represent a **moderate shading** (around the 25th percentile of Fig. 1), which corresponds to 19% annual irradiance loss due to shade. A residential system with this amount of shading was found to represent the moderate shading condition and was detailed in a prior publication [3].

Heavy shading is taken here to mean anything greater than 20% system shading, and a representative installation with 25.5% annual system shade was chosen to provide the basis for the heavy shade analysis.

Shading histograms were drawn up for the three systems, determining the annual irradiance in kWh/m^2 that occurs on the systems under different extents of shade. These details are determined by correlating TMY3 plane of array (POA) irradiance at a given date and time with the extent of system shade at that time. For the first two systems, the majority of annual irradiance falls on the array during unshaded conditions. The lightly shaded system is completely unshaded 82% of the time (on a kWh/m^2 basis), while the moderately shaded system is still unshaded 63% of the time. Fig. 2 shows close-up detail of the shaded portion of the light shading histogram, and Fig. 3 shows the entire moderate shading histogram, highlighting the amount of irradiance arriving during unshaded conditions.

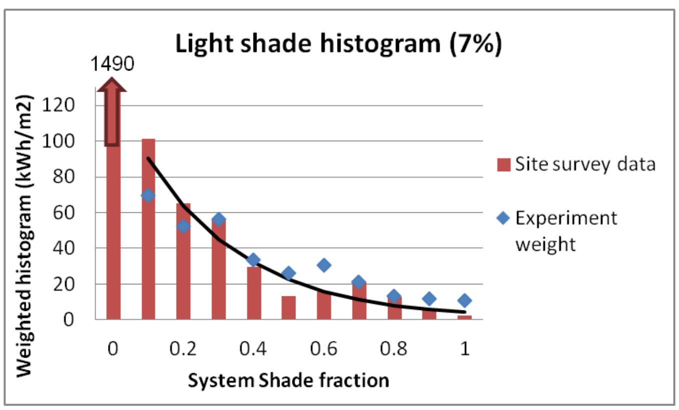

Fig. 2. Shading histogram for a lightly shaded residential installation (detail). Weighted by irradiance, the system is unshaded 82% of the time. Blue dots indicate the weight given to corresponding shade conditions during the experiment procedure.

The third heavy shading histogram shown in Fig. 4 indicates that unshaded conditions account for 48.5% of annual irradiance, with the remainder divided between the various shade conditions. These shading histograms dictate the experimental shading conditions used in this comparative test. The blue dots in Figs 2–4 indicate the relative weight given to the various shading conditions, as will be discussed below.

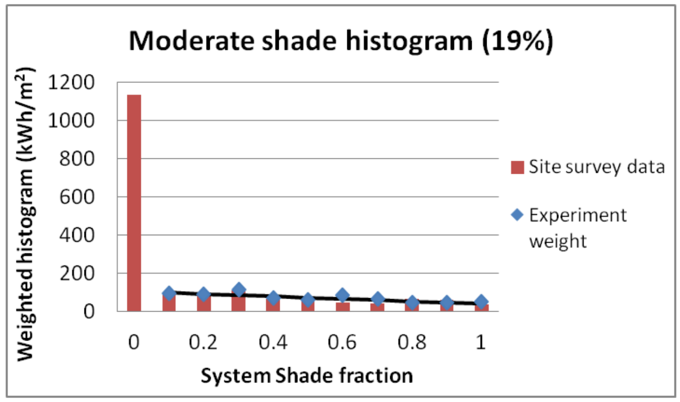

Fig. 3. Histogram for a moderately shaded residential installation. 63% of the annual irradiance occurs during unshaded conditions, with the remainder divided between the various shade conditions.

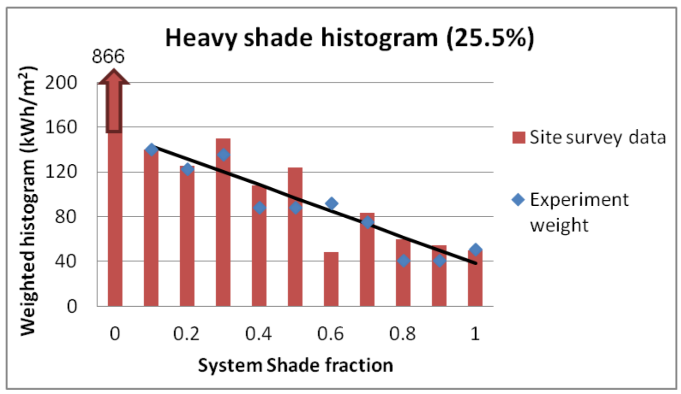

Fig. 4. Histogram for a heavily shaded residential installation (detail). Close-up is shown of the shaded conditions. Unshaded conditions account for 48.5% of the annual irradiance.

II. EXPERIMENT CONFIGURATION

An experiment replicating these shading conditions was conducted at PV Evolution Labs in Davis, California. The test ran from August to October, 2011, with the intent of assessing the performance of Enphase M215 microinverters relative to a string inverter (Fronius IG Plus 11.4).

Two PV arrays were used, each consisting of three parallel strings of 12 modules. The 72 Sharp NU-U235 modules used in the test were flash tested and distributed between the two arrays, such that each array had the same average rated power and distribution. The panels assigned to the Enphase array had a total STC power rating of 8494 W, and the panels assigned to the Fronius array had a total STC power rating of 8502 W.

The standard deviation of per-panel STC rating is 1 W for both arrays. The panels are oriented at 20 degree latitude tilt, south facing and divided between six successive rows.

Per-panel shading is applied to the two systems using a black, 50% open vinyl/polyester fabric with average measured transmittance of 37% and uniform spectral response (Fig. 5).

The main performance metric studied here was AC energy production, which is monitored for each array with a revenue grade (0.2% accuracy) Shark 100T power transducer. This data is logged on a Campbell Scientific CR1000 datalogger, along with meteorological data such as POA irradiance using a silicon reference cell, and module temperature using thermocouples. DC performance characteristics of the reference array were also recorded but not reported here.

Fig. 5. Shading fabric with 37% transmittance, drawn across the test array.

A series of shade conditions are applied to the two PV systems. The shading fabric is drawn across the three parallel strings in each system. Modules are mounted in the portrait direction, and shading is drawn across the modules from right to left, in units of 1/3 of a module (= 1 **submodule**), as the modules contain three bypass diodes. There are six separate direct shading tests for these systems with three parallel strings. If the shading is represented in a vector format, with N[1:0:0] representing shading that is placed on N submodules of one of the three strings, and N[1:1:1] representing uniform shading covering N submodules on all three strings, the six shade vectors are given in Table I. An illustration of the N[3:2:1] shading configuration is also shown in Fig. 6.

TABLE I
RELATIVE SHADE VECTORS USED IN THE EXPERIMENT

Each vector is multiplied by N submodules out of 36 possible/string

String 1 shading	String 2 shading	String 3 shading
1	0	0
1	1	0
1	1	1
2	1	0
2	1	1
3	2	1

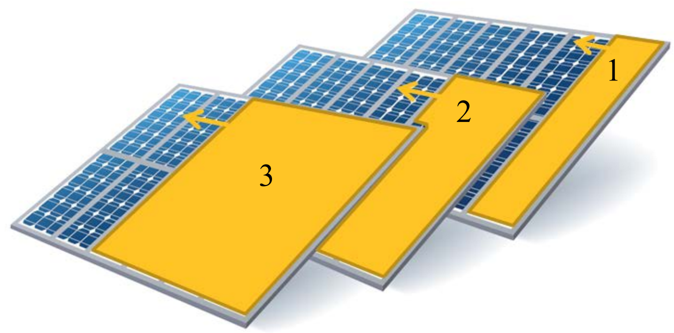

Fig. 6. Three parallel strings showing a N[3:2:1] shading ratio

For each of the shading conditions considered, a minimum 15-minute measurement interval is required taking 1-minute average data of AC kWh production. Data is only collected under clear-sky conditions with POA irradiance > 500 W/m^2. For each shade condition, the value of shade efficiency is recorded:

$$\eta_{shade,n} = \frac{Wh_{AC(DUT,n)}}{WH_{AC(ref,n)}} \frac{1}{C_{1-2}} \qquad (1)$$

where $Wh_{AC(DUT,n)}$ is the AC watt-hours produced by the array equipped with the device under test during shade condition n, $Wh_{AC(REF,n)}$ is the AC watt-hours produced by the reference array during shade condition n, and C_{1-2} is a correction term to account for differences in nominal array performance. Because of the close matching of the two arrays, $C_{1-2} = 1$.

Unshaded production of the systems is monitored throughout an entire sunny day. This provides a relative unshaded efficiency value, equal to the ratio of unshaded production from the array equipped with the device under test to the unshaded production of the reference array:

$$\eta_{unshaded} = \frac{Wh_{AC(DUT,unshaded)}}{WH_{AC(ref,unshaded)}} \qquad (2)$$

In addition to comparing the performance of the two systems to each other, a comparison is also made between shaded and unshaded operation of each system. This is made possible by the above unshaded measurements collected over a full sunny day. Subsequent shaded conditions are referenced to the unshaded production at the same time of day, after correcting both the shaded and unshaded data for temperature and irradiance [4]. Additional detail is provided on the above experimental process in the full report in [1].

III. EXPERIMENT RESULTS

A comparison of unshaded power production was conducted for the two arrays over a period of four days, totaling 22 kWh/m^2 irradiance exposure. The microinverter array produced on average 0.5% more power during this period, due in part to the Enphase M215 inverter's higher rated efficiency (96% vs 95.2% for the Fronius IG Plus 100V-2). Therefore, $\eta_{unshaded} = 1.005$.

During the shaded part of the experiment, the shade conditions in Table 1 were carried out for both PV arrays, out to N = 18/36 substrings shaded per string. Shading screens are deployed in different extents on the three parallel strings. Each shade condition is maintained for at least 15 minutes under sunny skies with irradiance greater than 500 W/m^2 and solar incidence angle less than 50 degrees. In this experiment, data are not recorded before 9:15 AM (PST) or after 3:45 PM (PST) to maintain these irradiance requirements.

After applying a correction for temperature and irradiance [4] the relative performance of each system can be compared with its own unshaded performance, as shown in Fig. 7. The microinverter system showed better performance under shaded conditions, losing roughly half as much performance as the string inverter.

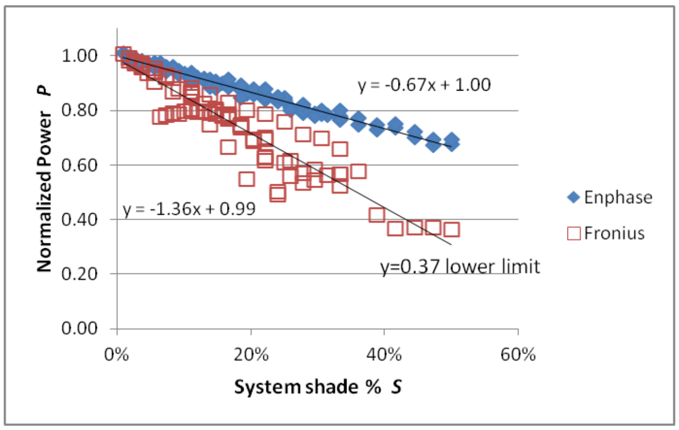

Fig. 7. Normalized production P of the Enphase microinverter system (blue diamond) and Fronius string inverter (red square) vs. extent of shade S.

Fig. 7 shows a linear best fit of power with respect to shade extent S for the two systems. The normalized production P of the microinverter system follows the linear fit $P = 1 - 0.67S$, where the slope is nearly equal to the opacity of the shading screen (opacity = 1-0.37 = > 63%). This means that the microinverter system is recovering almost all the irradiance filtering through the shade screen under these test conditions.

Performance loss of the string inverter system is also shown in Fig. 7. The slope of power loss vs. shade extent for the string inverter system is greater, owing to mismatch losses within the module strings and between parallel strings. For the string inverter system, a single linear fit is taken through all the various shading conditions, resulting in a linear fit of $P = 0.99 - 1.36S$. Even though a single linear fit is taken through the data, there is differentiation among the different shading conditions, which was not seen in the microinverter system. This can be seen in different extents of performance loss vs. S, shown in Fig. 8. For instance, the isolated shade condition N[1:0:0] results in a steeper slope than uniform shade N[1:1:1] conditions, but the performance loss levels off sooner, reaching a minimum at $P = 0.80$.

For uniform N[1:1:1] shading of the string inverter system, the power loss seems to level out near $P = 0.37$, with normalized power remaining constant with increased S. This plateau coincides exactly with the transmittance of the shading screen $\%T = 0.37$. It is thought that here, the standard string inverter system is operating at a different high-voltage, low-current peak operating point with this shade extent and beyond. This behavior is consistent with prior shade modeling analysis detailed in [5]. The modeled behavior of the Fronius system vs shade is taken to be $P = 0.99 - 1.36S$ with a minimum of $P = 0.37$, based on the linear fit in Fig. 7.

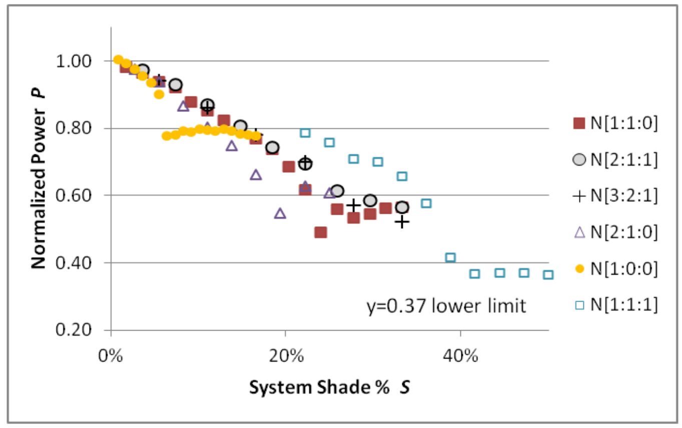

Fig. 8. Normalized production of the string inverter system vs. system shade extent for shade proportions given in Table 1.

Along with the linear estimate of P vs. S for the two systems, the shading histograms in Figs 2–4 are used to determine shading losses for the three reference residential installations. These shade losses are detailed in Table 2:

TABLE II

CALCULATION OF ANNUAL SYSTEM PRODUCTION [KWH/M^2] AND RELATIVE PERFORMANCE FOR 3 SHADING HISTOGRAMS.

Light shading: (1812 kWh/m^2 unshaded production)

Enphase production	Fronius production	Fronius loss	Enphase score (l)	Enphase shade derate
1753	1691	-6.7%	**1.037**	**0.967**

Moderate shade: (1894 kWh/m^2 unshaded production)

Enphase production	Fronius production	Fronius loss	Enphase score (m)	Enphase shade derate
1690	1568	-17.2%	**1.078**	**0.892**

Heavy shading: (1784 kWh/m^2 unshaded production)

Enphase production	Fronius production	Fronius loss	Enphase score (h)	Enphase shade derate
1532	1365	-23.5%	**1.123**	**0.859**

The results of Table 2 indicate that the light shading scenario shows an annual performance improvement of 3.7% for the use of microinverters (the performance improvement score). The moderate shading scenario shows a performance improvement of 8% for the use of microinverters, and heavy shading results in a 12% performance improvement. In all cases, the percentage of performance loss that is recovered by the use of distributed power electronics is 40%–50%, relative to the estimated extent of shade in the system. Note that when the performance loss due to shade is multiplied by the shade mitigation score, the overall derate including shade is not greater than one—shade mitigation devices only recover a percentage of the annual power lost due to shade; they don't increase production above what the system would produce without mismatch or partial shading losses.

A. Additional Analysis

The above fit of the experimental data allows an extrapolation of the performance improvement score to other environmental or shading conditions. For instance, the slope of the normalized production *P* vs. *S* graph in Fig. 7 indicates that the microinverter production is related to the ratio of diffuse irradiance to global irradiance: *D/G*. This fact has previously been demonstrated for module-level power electronics in general [3]. If the normalized production of the microinverter system is assumed to be related to the diffuse irradiance fraction by: $P = 1 - (1\text{-D/G})\, S$, the performance of the microinverter system can be determined for arbitrary *D/G* ratio. Likewise, the normalized production of the reference string inverter system in Fig. 7 indicates that a production minimum exists when P = D/G. Other than this limit condition, the slope of the production from the string inverter is assumed to be constant with *D/G*—an assumption consistent with previously modeled shade impact on PV systems [5].

Given the above equations for modeled performance of the two systems, additional performance scores for 13 different solar installations with varying shade extent are created. These 13 additional shading conditions are drawn from some of the site surveys included in Fig. 1. Results are shown in Fig. 9 assuming five different *D/G* ratios: 0.15, 0.37, 0.5, 0.75, and 0.9. It can be seen that *D/G* ratios less than or equal to 0.5 give nearly identical results. For these three lowest *D/G* ratios, performance scores follow a slope of 0.5 times shade extent.

Put another way, 50% of the lost power due to shade is recovered by the use of the microinverters. At higher diffuse fractions, however, this performance benefit is reduced to something closer to 30% at *D/G* = 0.75, and 15% at *D/G* = 0.9. The fact that performance results are relatively consistent for any simulated diffuse ratio below 0.5 supports the use of shading materials with at least 50% opacity in this experiment.

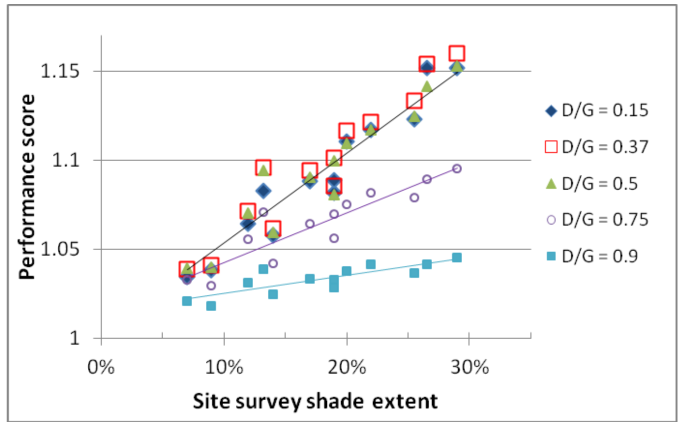

Fig. 9. Performance score of the microinverter system for different shade conditions and diffuse irradiance ratios (D/G). Results are based on modeled behavior of both microinverter and string inverter systems.

B. Inverter MPPT Errors

During the course of this experiment, it was found that certain shading conditions led to additional performance losses from the reference string inverter. This was associated with the inverter incorrectly operating at a point that was not the global maximum. This effect is illustrated in Fig. 10 for an example shading condition. In this case, there are two local peaks in the power vs. voltage curve. The higher voltage peak also happens to be the global maximum, but this is not always the case. Under certain shading conditions, the lower voltage peak is the true global maximum. Depending on how quickly the shading condition is changed, the inverter might be left behind, and not track the real maximum power point.

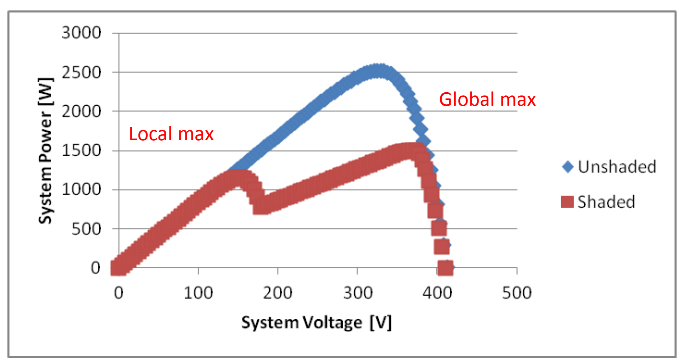

Fig. 10. Power vs. voltage curve for a partially shaded PV system. Partial shading results in multiple local maxima, which may confuse the peak-power-tracking algorithm of the inverter.

A number of measurements were retaken for the N[1:1:1] uniform shading condition, as this shade condition was most likely to result in peak-power tracking errors from the string inverter in our test case. To help minimize tracking errors, the reference system was started up in a shade-free condition, and then slowly placed into a shaded condition by incrementally shading additional submodules.

The impact of these inaccuracies on a real system is debatable. However, for this experiment, by allowing the inverter to inaccurately track the maximum power point, the reference system would have received an additional performance loss of 2%, when weighted by the moderate shade conditions in Fig. 3. For this comparative test, the reference inverter had to be monitored to ensure it was accurately tracking the maximum power point, which will reduce variability from one shading condition to another.

IV. Conclusion

A test method is illustrated here, aimed at providing a repeatable and representative performance analysis of distributed power electronics. The comparison here was between a microinverter-equipped system and a string-inverter-equipped system. The test methodology is based on directly shading two side-by-side systems and comparing the relative output of the two systems. Three shading conditions are identified to illustrate the performance benefit of the test device under different representative conditions, relative to a string inverter. By applying temperature and irradiance corrections to the same shading data, a comparison can be made between the device performance under shaded and unshaded conditions. This provides additional details of how the distributed power electronics behave under different shade conditions, and allows a model of shade response to be proposed.

Annual performance improvement scores were determined for the microinverter system of 4% for light shading conditions, 8% for moderate shade conditions, and 12%–13% for heavy shade conditions. Each of these scores indicates a recovery of around half of the overall performance loss due to shade, as predicted by the shading loss site survey.

For further information the reader is encouraged to read the full NREL technical report. It is hoped that the test methodology can be duplicated for a variety of microinverter and shade mitigation products, as well as for string inverters with novel maximum-power-point-tracking algorithms.

Acknowledgement

Test data for this experiment were collected under a test service agreement between PV Evolution Laboratory and Enphase Energy Inc. The testing method was developed and data analysis was independently conducted by the National Renewable Energy Laboratory under Contract No. DOE-AC36-08GO28308 with the Department of Energy. A number of individuals also contributed important reviews and contributions to this work, including Jeff Newmiller, David Briggs, Sara MacAlpine, and Solar Works, Inc. Testing was conducted at PV Evolution Labs by Rajeev Singh, Filiberto Alex Pineda, and Dang H. Dang.

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