

Performance of Bifacial PV Modules with MLPE vs. String Inverters

Daniel Riley, Joshua Stein, and Craig Carmignani

Sandia National Laboratories, Albuquerque, NM, USA

Abstract — Sandia National Laboratories’ continued work with bifacial PV modules has found discrepancies in the capability of bifacial PV modules to generate energy depending on system design. We have also found significant nonuniformity in rear-side irradiance across strings of bifacial PV modules, thus creating electrical mismatch between modules. Module level power electronics (MLPE) that track the maximum power point of each module alleviate some of the electrical mismatch caused by nonuniform rear-side irradiance on bifacial PV modules. The bifacial gain of the bifacial PV modules can be increased significantly through MLPE, although the net energy gain may not be significant for unshaded bifacial PV systems. Here we present the results of a test between bifacial PV systems equipped with MLPE and the same systems without MLPE.

Index Terms — photovoltaic systems, solar panels, inverters

I. INTRODUCTION

Bifacial modules are photovoltaic (PV) modules that can absorb light and convert it into electricity on both their front and rear sides. This feature shows great promise to produce significantly more energy for a modest increase in cost. Furthermore, bifacial PV modules may enable unique system designs to generate energy in orientations that would not be economical for monofacial PV systems [1]. However, much of the PV market uses long rows of PV modules at a fixed tilt toward the equator.

In 2016, Sandia National Laboratories installed a test field to determine the increase in energy that could be obtained using bifacial PV modules. The test field is comprised of 8 strings (4 bifacial strings, 4 monofacial strings) at tilt angles of 15°, 25°, 35°, and 45° as shown in Fig. 1. Bifacial and monofacial PV modules are interleaved on each row to reduce spatial bias in rear side irradiance, and the current and voltage of each string are measured. The strings are held at maximum power by a centralized inverter and string voltages, currents, and module voltages are measured each minute. Additionally, string IV curves are collected periodically throughout each day by a Pordis model 140A in-situ IV tracer.

Irradiance striking the front surface is mostly uniform across large strings and inter-row shading is not present. However, the irradiance incident upon the back surface of a PV module is not uniform across the module [2]; nor is the irradiance uniform across the PV string as shown in Fig. 2. These differences in rear irradiance across the PV array can be quite large; in Fig. 2 the difference between the irradiance at the east end of the row and the middle of the row was as large as 8% of the total (front and rear) irradiance. The difference in irradiance striking the back of the modules creates mismatch in the IV curves of

modules along the row and the row is not able to produce as much power as possible if all the modules are series-connected to a typical central or string inverter. However, module level power electronics (MLPE) that individually track the maximum power point (MPP) of each module could extract more energy from bifacial PV modules, even in large-installations where direct front-side shading is not present. In large monofacial PV systems without significant shading, MLPE are not usually considered cost-effective; but in bifacial PV systems the MLPE may provide enough benefit (through mismatch mitigation) to warrant consideration in even large bifacial PV system designs.



Fig. 1. Sandia’s 4-tilt test bed. Rows are tilted between 15 and 45 degrees with rear irradiance sensors at the top and bottom of each row, near the center of the row.

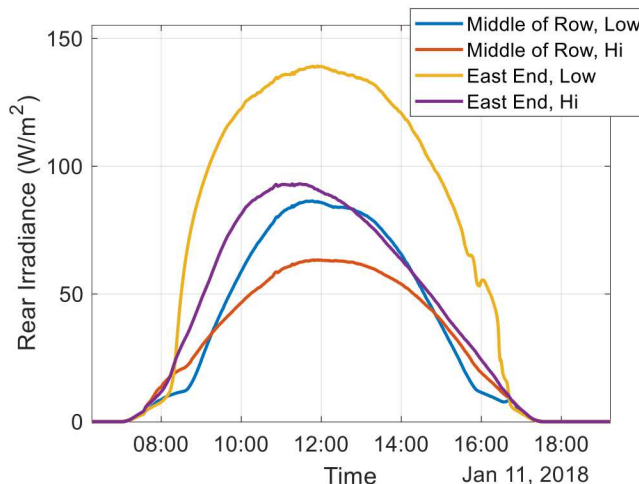


Fig. 2. Rear irradiance as measured at high and low points on the PV racking in the middle and east end of a PV array.

In April 2018, Sandia added MLPE to the 15° and 25° rows of modules in the “4-tilt test bed” with MLPE applied on both

the monofacial and bifacial PV modules in each of the two rows. The MLPE track each module's MPP and allow all modules to perform optimally regardless of the differences in front or rear irradiance.

II. HISTORICAL DATA AND PERFORMANCE METRICS

In Sandia's work with bifacial PV modules, we have introduced the bifacial energy gain, BG_E , which provides a useful comparison between the energy generated by bifacial modules and co-located monofacial modules [3]:

$$BG_E = 100\% \times \left(\frac{\sum_{t=0}^{t=T} (P_{\text{bifacial}} / P_{\text{mpbifacial}})}{\sum_{t=0}^{t=T} (P_{\text{monofacial}} / P_{\text{mpmonofacial}})} - 1 \right) \quad (1)$$

where T is an arbitrary comparison duration, P_{bifacial} and $P_{\text{monofacial}}$ are measured power values (corrected to 25°C), and $P_{\text{mpbifacial}}$ and $P_{\text{mpmonofacial}}$ are front side power ratings measured on a flash tester at STC with the back of the bifacial module covered with an opaque material.

The bifacial gain is therefore an indicator of how much more (or less) energy a bifacial module may generate compared to a co-located monofacial module, relative to each of their front-side flash test ratings.

Sandia has also found [3] that bifacial modules in the four-tilt system produce bifacial gains around 7% to 11% with a central string inverter as shown in Fig. 3, but produce bifacial gains between 17 and 21% when using MLPE on a similar but smaller system. However, the difference in system size between the two systems leaves questions regarding whether the gains in energy are related to the MLPE or to the smaller, more open system design increasing the available rear irradiance.

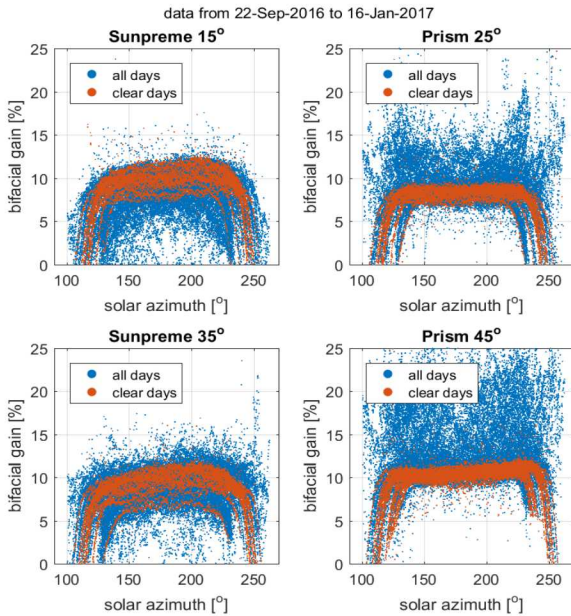


Fig. 3. Bifacial gain on each of the rows of the test field, typically between 7% and 10%.

III. RESULTS

If the reduction in bifacial energy is caused by rear-side irradiance nonuniformity, then we hypothesize that the application of MLPE could increase energy yields by between 5% and 9%.

Sandia researchers applied MLPE to the modules in early April, 2018, and these analyses present data through mid-May 2018. To make a valid comparison between the system performance with and without MLPE, we selected an identical date range from 2017 to serve as the performance data without MLPE. Thus, sun angles over the two time periods were nearly identical and seasonal ambient temperatures were similar.

Fig. 4 presents plots of the temperature-corrected DC power as a function of front irradiance. From these, it appears that MLPE do not greatly affect the power produced from either a bifacial or monofacial system that is not experiencing front-side shading. However, at low irradiance, perhaps below 400 W/m^2 , the bifacial system slightly improves in performance relative to the monofacial system as shown in Fig. 5. While Fig. 4 and 5 show the performance of the 15° systems; the bifacial systems tilted at 25° show similar performance boost at low irradiance.

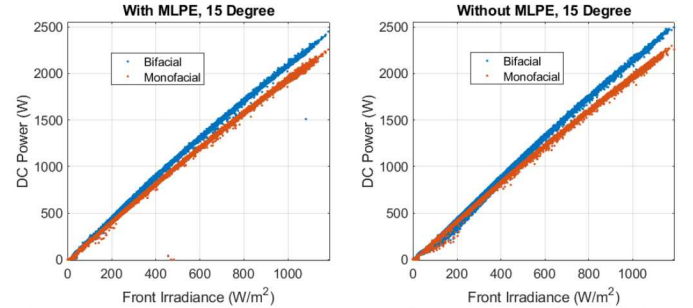


Fig. 4. Power (temperature corrected) as a function of front irradiance is largely unchanged due to MLPE. Slight low-irradiance performance increase for bifacial PV when MLPE is applied.

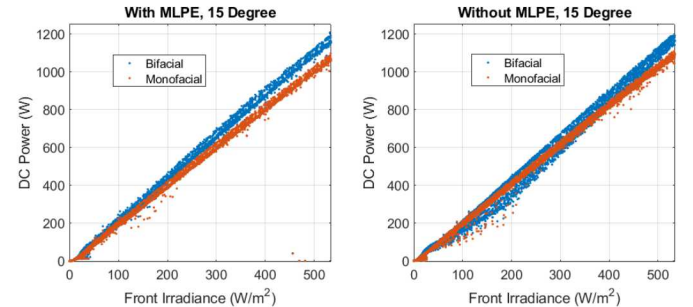


Fig. 5. Power (temperature corrected) as a function of front irradiance at the low irradiance range.

However, the slight increase in bifacial PV performance, relative to monofacial PV, is not simply due to low-irradiance conditions. Fig. 6 shows the bifacial gain as a function of solar angle of incidence (AOI) during clear-sky periods. It is apparent that there is significant increase in bifacial gain as the AOI

increases beyond 50° . At high solar AOI and clear sky conditions, the shadows cast by the PV array create highly nonuniform rear-side irradiance when we expect MLPE to most improve the performance of the bifacial modules.

We also find it interesting that for AOI greater than 65° , without MLPE the bifacial modules have a negative bifacial gain. Thus, the bifacial modules are performing worse than the monofacial modules relative to their respective front-side flash measurements.

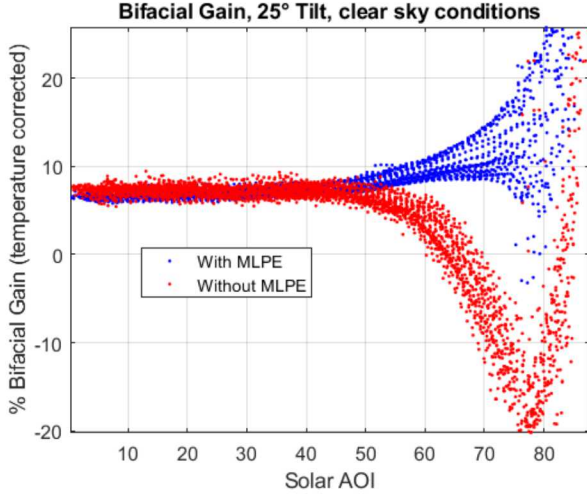


Fig. 6. Bifacial gain is significantly increased with MLPE at high solar angles of incidence.

Sandia's string-level IV curve measurements on these PV systems confirm that under clear sky conditions, rear irradiance nonuniformity can create mismatch within the bifacial PV module string and reduce the fill factor. Fig. 7 presents two IV curves for the bifacial PV string tilted at 25° , each obtained under similar front-side irradiance and prior to application of the MLPE.

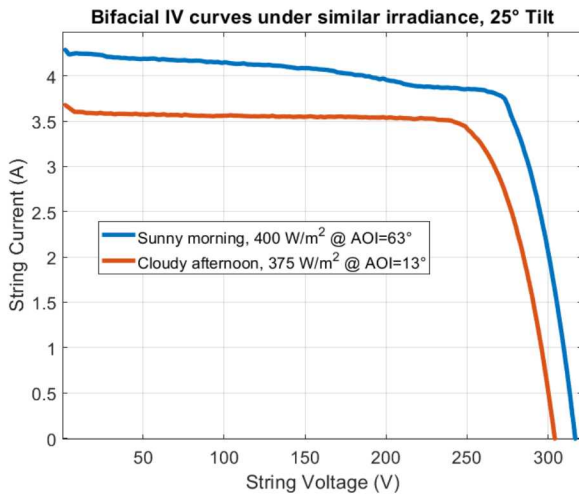


Fig. 7. Bifacial IV curves under sunny morning (high AOI) conditions show more mismatch and a lower fill factor than IV curves at similar irradiance at mid-day under cloudy conditions. Both curves without MLPE.

The IV curve obtained under sunny morning conditions at high AOI shows significant mismatch along the string in the form of a stepped I-V curve, producing a lower fill factor. The mid-day IV curve has a smooth current from I_{SC} to I_{MP} , indicating well-matched current throughout each module in the string.

IV. CONCLUSIONS

The rear-side irradiance available to bifacial PV modules can be highly nonuniform, especially during sunny conditions with high solar AOI. When AOI is less than 90° , but greater than perhaps 55° , the shadows cast by the bifacial PV onto the ground can provide significantly less rear-side irradiance to modules in the middle of a row than the outside of a row. These differences in irradiance create mismatch between the modules that reduce the fill factor of the string and reduce the power available to a central inverter.

Module level power electronics do mitigate the mismatch of the PV modules within a string by tracking the maximum power point of each module individually and providing the maximum power to the inverter.

Without MLPE, the bifacial PV strings suffered a severe reduction in performance at solar AOI greater than 55° , and performed worse (relative to front-side flash ratings) than their monofacial counterparts at AOI greater than 65° . Under sunny conditions and without MLPE, bifacial gain dropped from 7% to -12% between AOI of 45° and 75° . However, with MLPE applied, the bifacial gain rose about 2.5% from 7% to 9.5% over the same range of incident angles. For most PV system installations, the overall energy produced at these high incident angles in the morning and evening is typically much lower than the energy produced during low AOI periods at mid-day. Thus, while MLPE clearly mitigate losses that are caused by rear irradiance nonuniformity, the addition of MLPE may not significantly increase the overall energy production of a bifacial PV system that rarely experiences direct front-side shading.

However, there are many factors that must be considered when determining whether MLPE will provide a net gain to a bifacial PV system. In Sandia's tests, the PV modules were configured in a "portrait" orientation with a single vertical row of modules. Since the rear-side irradiance changes greatly from the top to the bottom of a tall PV row, PV systems employing multiple rows of PV module on each rack may have additional energy gain beyond that shown in Sandia's experiment. Furthermore, these results present data only from early April to mid-May. Different sun positions may greatly change the benefit from MLPE. Additionally, MLPE may provide additional benefits in systems with varying surface albedo beneath the PV, as the varying albedo increases rear-irradiance nonuniformity.

V. FUTURE WORK

Sandia continues to operate the bifacial test bed and continues to employ MLPE on the 15° and 25° tilted rows to determine if these conclusions hold true over a wider range of sun angles. Given the short test duration, determining the relative energy difference provided by MLPE in the form of a performance ratio (PR) is not yet possible, as the systems continue to produce power, a longer-term performance ratio may be possible to determine the overall energy difference provided by MLPE.

This study examined the effects of rear-side irradiance nonuniformities across a PV system, Sandia has also found the rear irradiance to be highly nonuniform across the back of each PV module as shown in Fig. 8 where rear irradiance varied by up to 50 W/m² across a module-sized 1-meter by 2-meter surface on a sunny day. Additional irradiance variation across a single bifacial module can occur when the sun is directly striking the rear side of the modules and racking members directly shade the rear of the bifacial PV modules and reduce power output [4]. MLPE cannot alleviate the mismatch between cells and cell strings within the PV module that are caused by irradiance nonuniformity on this sub-module scale. Sandia has begun investigating the possibility to further increase bifacial PV energy yields by addressing sub-module irradiance nonuniformity through sub-module level power tracking.

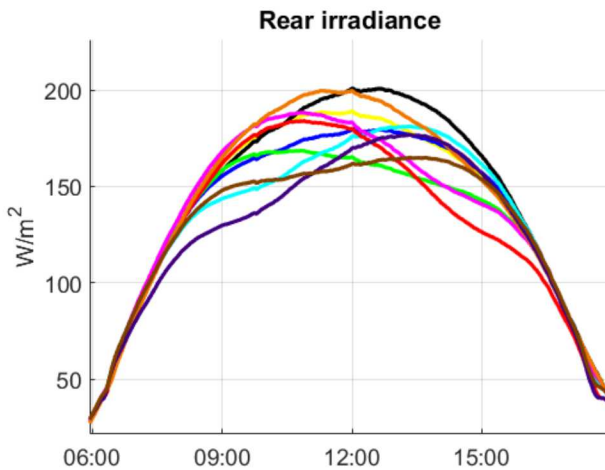


Fig. 8. Rear irradiance at 9 places on the back of a PV module at latitude tilt on a sunny day

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