MODULE MISMATCH LOSS AND RECOVERABLE POWER IN UNSHADED PV INSTALLATIONS

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ABSTRACT

Distributed electronics which optimize power in PV systems have the potential to improve energy production even under unshaded conditions. This work investigates the extent to which mismatch in the unshaded electrical characteristics of PV panels causes system-level power losses, which can be recovered in arrays employing power optimizers. Of particular interest is how this potential for power recovery is affected by factors such as available light, cell temperature, panel technology, and field degradation.

A system for simultaneous collection of panel-level I-V curves over an entire array is designed. This system is used to acquire high and low light module performance data for a variety of arrays at the National Renewable Energy Laboratory (NREL) test facility. The measured data show moderately low variation in module maximum power and maximum power producing current in all of the arrays. As a group, the tested arrays do not show any strong correlations between this variation and array age, technology type, or operating conditions.

The measured data are used to create individual panel performance models for high and low light conditions. These models are then incorporated in annual hourly energy simulations for each array. Annual mismatch loss (and thus potential for increased energy capture using power optimizers) is found to be minimal, <1% for all of the sampled arrays. Due to the nature of the tested arrays, these results may or may not be indicative of typical PV array behavior; further investigation is planned over a larger group of PV installations to determine the general applicability of this study's results.

INTRODUCTION

Power optimizers, microinverters and microconverters, are types of distributed power electronics which enable power conversion and maximum power point tracking (MPPT) at the sub-array level. These devices are gaining market share in smaller photovoltaic (PV) systems that experience non-uniform operating conditions within the array. While most PV systems are designed so that they do not experience significant shading or other substantial variations in irradiance or temperature during peak generation hours, there is still a certain amount of dispersion of module electrical characteristics for any PV system. Performance differences between modules can arise from manufacturer's tolerances, defects, or field degradation, and will cause power loss in conventional grid-tied arrays, as some modules are forced to operate away from their individual maximum power points. Power optimizers allow each module to operate at its individual maximum power point, recovering the power lost from module mismatch.

$$\text{Elec. Mismatch Loss} = \text{Recoverable Power} = \frac{\sum \mathrm{P_{Module,max}}}{\mathrm{P_{System}}} - 1 \qquad (1)$$

Studies of the effect of module mismatch on output power [1,2] have examined grid-tied arrays under multiple operating conditions for a single array. Their results show a configuration and climate-dependent range of potential for power gains using per-module MPPT (0-5%), with more mismatch between modules as light levels decrease. However, there are several factors not accounted for in these studies: they do not consider the full range of operating conditions (irradiance and temperature) experienced by typical PV arrays, they do not examine arrays of different technologies, and they focus only on mismatch between new modules, while studies on degradation [3-5] show that aging increases the variance of module parameters. Furthermore, the testing in [2] is performed using an indoor light simulator, and the authors acknowledge lack of control over light uniformity, which likely positively skews their results.

This work investigates system-level power losses caused by inherent mismatch between panels in small PV systems, along with the potential for improved performance from the use of panel-level power optimizers. A portable data acquisition system is used to collect simultaneous panel-level I-V curves within PV arrays. These I-V data are recorded under ambient conditions for multiple arrays, representing a range of ages and panel technologies. Analysis of these data show a moderately low level of panel-level mismatch for all of the tested systems, and therefore a minimal potential for increased energy capture with the use of per-panel power optimizers. Further investigation with a different set of PV installations is recommended to determine whether the mismatch found in this study is typical.

METHODOLOGY

The methodology for mismatch analysis used in this study has several main components, shown in Figure 1. First, panel-level I-V data are collected for a variety of arrays under different operating conditions. These data are fitted to an I-V curve model so that mismatch can be examined over a wide variety of irradiances and cell temperatures. Resulting models of each panel are then fed into a simulation program to calculate system-level mismatch related power losses. A complete description of this process is detailed in the following sub-sections.

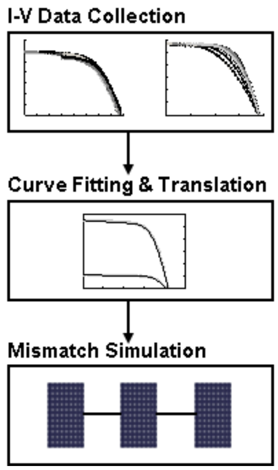

Figure 1. Overview of mismatch analysis method

Test Arrays

Five arrays from the National Renewable Energy Laboratory (NREL) outdoor test facility were chosen for I-V curve collection. This set encompasses a variety of panel technologies and system ages, as shown in Table 1. All of the arrays are 1-2kW in size, mounted at latitude tilt, arranged in groups of 6-24 panels divided into single or multiple strings.

Table 1. Arrays used for I-V data collection

Array	Type	# Panels	Age
A	Crystalline Silicon	20	15 years
B	Crystalline Silicon	10	7 years
C	Crystalline Silicon	6	2 years
D	Thin Film	14	7 years
E	Thin Film	24	9 years

Measurement of the NREL systems has distinct advantages, including access to different technologies and onsite weather monitoring. However, it also has some potential disadvantages which might affect mismatch results. First, the test arrays are smaller than average for even residential installations; the resulting reduced per-system panel sample size and string lengths may affect the level of mismatch relative to what is found in typical installations. Second, and perhaps more significant, the systems at NREL are research-grade arrays; it is likely that the panels were pre-screened and selected more carefully than they would be for a typical residential or commercial system, and thus may exhibit less-than-average mismatch from manufacturer's tolerances. Damaged modules are also screened and replaced, which may remove pathologically degraded modules from the sample set.

Test Conditions

Each set of panel-level array data was collected under ambient operating conditions, including both high and low irradiance. Panel temperature was not independently controlled, but did vary with incident irradiance as would be expected in real installations. High irradiance data were gathered in the hours around solar noon on sunny days, and low irradiance data were obtained either late in the day or under constant cloud cover. Plane-of-array irradiance was monitored with onsite thermopile pyranometers using minute-averaged data. Cell temperature was either directly measured or found using the Sandia temperature model [6], with site-measured ambient temperature, irradiance, and wind speed inputs.

Data Collection

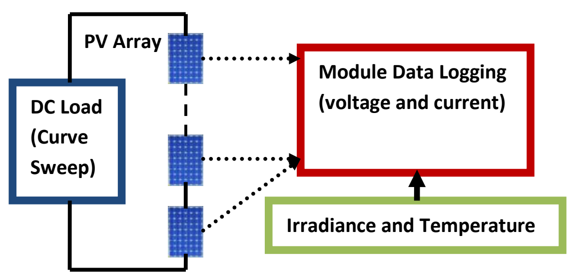

Figure 2. Test system for measuring simultaneous outdoor module I-V curves

Each test system's PV panels were connected in one or more parallel strings and attached to a programmable DC load that sweeps system-level I-V curves at low (<500 W/m^2) and high (>800 W/m^2) irradiance. During the I-V curves sweeps, panel-level voltage and current were monitored as shown in Figure 2. The plane-of-array irradiance and PV back-of-module temperature were averaged over the duration of the curve, which is less than one minute.

Data Processing

As I-V curves were collected only under specific low and high irradiance "reference" conditions, it was necessary to create a model of each panel's behavior to be translated to other operating conditions for use in annual mismatch analysis. The five parameter single diode model described in [7] was chosen for this task. It models the entire I-V curve, which is essential when examining mismatch performance with modules operating slightly off of their maximum power point, and is easy to translate fairly accurately over a range of irradiance and panel temperatures.

Previous research [8] has shown that the five-parameter model becomes less accurate as operating conditions are extrapolated from the initial reference condition. To mitigate this inaccuracy, each panel is given two separate five-parameter fits, one under high irradiance, and the other under low irradiance. This improves model accuracy over a range of operating points, and accounts for differences in mismatch between high and low irradiance conditions.

The five-parameter model takes as inputs open circuit voltage (V_{oc}), short circuit current (I_{sc}) and maximum power point voltage and current (V_{mp}, I_{mp}), as well as temperature coefficients for voltage, current, and panel power. V_{oc} was measured directly for each panel during the I-V trace, while I_{sc} was generally found using linear extrapolation. V_{mp} and I_{mp} were determined by fitting a 5th degree polynomial to the measured points around the measured maximum power (P_{mp}), as described in [9]. Finally, temperature coefficients were determined from manufacturer's specifications.

While the low and high irradiance five-parameter models often matched the panels' measured I-V characteristics, as depicted in Figure 3a, some panels showed deviations, particularly for panels exhibiting any sort of defects. An example of this is shown in one module's power vs. current curves (Figure 3b). In this case the mismatch between the model and measured data occurs near P_{mp}, with the model predicting that the module will perform more poorly than it actually does if forced to operate at a current higher than its I_{mp}. This underprediction would artificially inflate mismatch losses when using the standard five parameter model, so in cases such as these an adjusted five parameter model is used instead. Empirical modification of the model's series and shunt resistances was found to give a better overall curve fit (Figure 3c) with very minimal effect on the prediction of module maximum power.

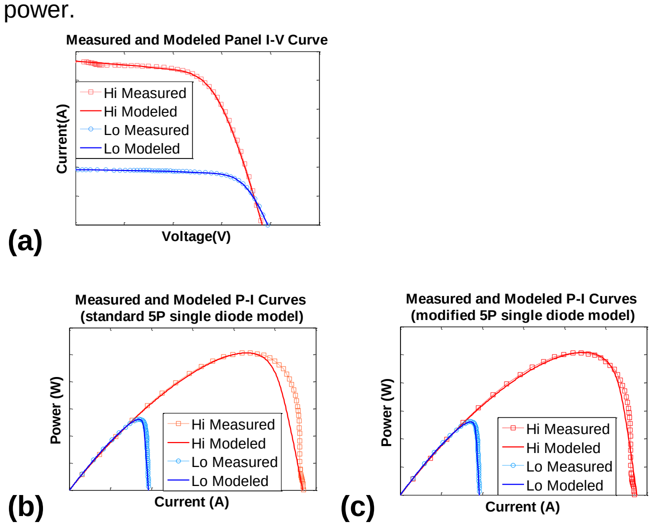

Figure 3. Fitting the five parameter model to measured curves -- a) I-V curves for a well matched module, b) P-I curves for a module with performance mispredicted by the five parameter model, and c) P-I curves for the module with the series and shunt resistances of the five parameter model adjusted for a better curve fit.

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ARRAY MISMATCH

The performance characteristics determined at high and low irradiance for each array's individual modules were used to investigate system level mismatch and the resulting mismatch-related losses and opportunity for recoverable power in arrays with power optimizers. Figures 4 and 5 show the measured power curves for modules in two different arrays, to illustrate mismatch and the way that it causes power losses.

Mismatch Illustrations

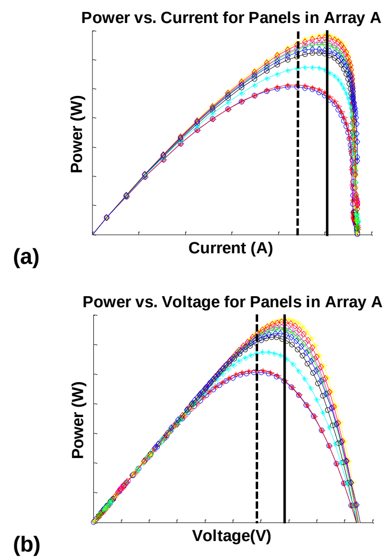

Figure 4. Power vs. current (a) and power vs. voltage (b) for modules in Array A

Figure 4a shows the power vs. current curves for one string of modules from array A. The majority of the modules in this string have similar P_{mp} and I_{mp}, shown by the solid vertical line. However, two of the panels are compromised in some way and have a P_{mp} that is ~25% lower than the good panels' output, achieved at a lower current (marked by the dashed vertical line). If the string operates at the I_{mp} of the good panels, the compromised panels lose ~10% of their maximum power output. If, however, the string operates at the I_{mp} of the compromised panels, the remaining panels will all lose ~3% of their maximum power output. This demonstrates how a fairly dramatic mismatch in current output between panels in the same series string can cause moderate system level power losses.

Figure 4b shows the power vs. voltage curves for the same modules found in 4a. V_{mp} for the good and compromised panels is again marked by the solid and dashed vertical lines, respectively. Losses similar to those noted above are predicted if the string's modules are forced to operate at the same voltage, i.e. if they were wired together in parallel. In the actual configuration of two parallel series-wired strings, the V_{mp} mismatch in the depicted string will have an impact on the other string in Array A; the other string will be forced to operate at a voltage adjusted to compensate for the behavior of the depicted string, creating more system level mismatch losses.

In contrast, Figures 5a and 5b show the power vs. current and voltage curves for modules in two strings of Array E. This array also shows a dispersion of module maximum power output, and corresponding differences in panels' I_{mp} and V_{mp} measurements. However, for this array the curve distribution is tighter and the curves are aligned so that even with the measured variation in parameters, power lost to mismatch is reduced. This behavior is typical of arrays with moderately low variation in panel characteristics.

(a)

(b)

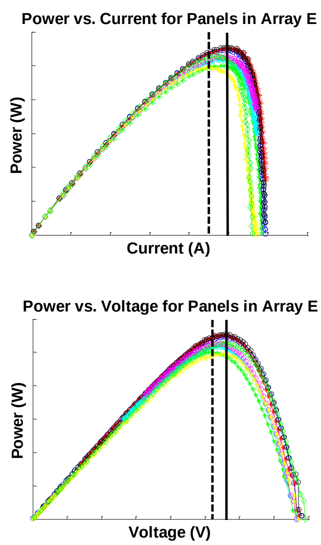

Figure 5. (a) Power vs. current and (b) power vs. voltage for modules in Array E

Array Variations and Losses

The standard deviations of relevant module parameters in each array at high and low light levels are shown in Table 2, along with losses associated with module mismatch. Variance in both P_{mp} and I_{mp} is examined, as I_{mp} variations are especially important when considering series string behavior. Mismatch loss is defined in Equation 1; it is the difference between the sum of the module maximum powers and the system's actual produced power, relative to the latter.

Table 2. Parameter variation and resulting mismatch losses for tested arrays

Array	Stdev Pmax		Stdev Imax		Mismatch Loss	
	high light	low light	high light	low light	high light	low light
A	8.9%	1.3%	3.9%	0.6%	1.0%	0.2%
B	1.7%	2.2%	2.2%	2.6%	<0.1%	0.2%
C	1.9%	1.4%	0.5%	1.3%	<0.1%	0.3%
D	1.5%	3.7%	1.2%	1.9%	0.1%	0.2%
E	6.1%	5.6%	5.5%	5.3%	0.2%	0.5%

As expected, module performance variation tends to be the highest for the two oldest arrays (A and E), but the array sample set and differences are small enough that no conclusions can be drawn regarding mismatch and array degradation in other systems of this age or technology. Distribution in P_{mp} and I_{mp} for the arrays in this study do not appear to be strongly influenced by panel technology type or array operating conditions. Further study of a larger group of arrays would be required to determine what, if any, trends may be related to array age, technology type, or operating conditions.

Mismatch losses in these arrays are similar at both high and low irradiance, never exceeding 1% regardless of the measured panel variation. There is slightly more loss at low irradiance, percentage-wise, for all of the arrays except Array A, which has 2-3 panels showing reduced performance under bright sun and high module temperature conditions. However, given the low losses and their small differences in magnitude, no trends relating mismatch losses to array age, panel type, or operating conditions are determined for this set of tested arrays.

ANNUAL ENERGY SIMULATION

Annual, hourly energy simulations were run to determine panel-level power optimizers' potential to increase energy capture by recovering mismatch-related losses in unshaded PV systems. In these simulations, each hour's unshaded operating conditions were calculated using weather data from the TMY3 database for Denver, Colorado. Irradiance was found using the HDKR anisotropic sky model [7] and panel temperature was computed using the Sandia temperature model [6]. The arrays were oriented due south with a 22.6 degree tilt corresponding to a standard 5:12 roof pitch. Maximum power point tracking was assumed to be ideal at either the central inverter (no optimizers) or panel (optimizers) level. Each panel had its hourly performance individually determined using five parameter models calculated from its measured high and low irradiance performance; high irradiance models were used for light > 500 W'm^2 and low irradiance models were used for lower light conditions. The arrays were assumed to be configured in strings as listed in Table 3.

Table 3. Annual mismatch loss (potential energy gain) for unshaded arrays in Denver, CO

Array	Configuration	Annual Mismatch Loss
A	multiple strings	0.70%
B	multiple strings	0.10%
C	single string	0.15%
D	multiple strings	0.15%
E	multiple strings	0.35%

Table 3 also shows the simulated results for the percent annual mismatch loss (and thus potential for increased energy capture) for each of the tested arrays. As expected, these results fall within the ranges of loss at high and low irradiance listed in Table 2. The potential for increased energy capture in these arrays is quite low, less than 1% in all cases. These results are in good agreement with those found in [1] when the authors removed the most mismatched panel from their simulated system. It is clear that in systems with relatively little mismatch between panel characteristics, there is very little power to be recovered with panel-level power optimizers.

However, as previously mentioned, there is a possibility that the arrays measured and simulated in this study are not fully representative of standard PV installations. The arrays are smaller than most residential systems, which leads to a smaller sample of panels per array and shorter series strings. Also, the individual panels are likely to have undergone a more rigorous screening process prior to installation, and receive better maintenance once deployed than your typical system. For these reasons the results here, showing little power recovery potential available to power optimizers from mismatch-related losses, may not be representative of typical PV installations. Further work is planned to use the methodology presented here to investigate mismatch losses in a larger and more diverse set of PV systems.

SUMMARY

This study explores the potential impact of power optimizers in PV arrays that are not subject to shading or other obvious non-uniform operating conditions. In these arrays, the opportunities for power recovery come from system-level power losses caused by mismatches between modules' electrical performance characteristics.

A method of measuring PV panel mismatch and estimating annual performance loss is described. Simultaneous, panel-level I-V curves are recorded for a variety of field arrays of different technologies operating under high and low light conditions. Each panel's measured data are fitted to the single diode PV generator model at both high and low irradiance, and the models are modified as necessary to match non-ideal curves.

Analysis of the measured data show a moderately low level of panel-level mismatch for all of the tested systems, independent of system age, technology, or operating conditions. This translates to minimal potential for increased energy capture, less than 1% annually, when using panel-level power optimizers to recover mismatch-related losses. It is noted, however, that the arrays tested here may have panel selection bias which could reduce their mismatch relative to typical PV systems. Further investigation over a wider breadth of PV installations is recommended to determine whether the mismatch and associated losses found in this study are typical.

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