Quantifying Causes and Effects of Soft Mismatch in Solar PV Arrays

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Abstract — **Mismatch losses are an important driver of solar system performance. However, given the limitations of standard aggregate-system models, these effects have not been comprehensively documented and modeled.**

New tools are being developed that can bring a much greater understanding to these system effects. These component-based models treat each PV module and conductor as independent elements, aggregating their performance based on system designs to represent the performance characteristics of the total system.

These component-based models enable a fundamentally new way to model mismatch. They treat the mismatch factors as properties across the population of modules. For example, irradiance and temperature can be varied across modules based on probability distributions, with the effects propagated through the entire system based on the underlying physics.

With an improved ability to understand and diagnose mismatch loss behavior, system designers can improve their system design rules, refine loss assumptions, and quantify the value of energy harvest technologies.

Index Terms — **modeling, photovoltaic systems, solar energy, power conversion.**

I. INTRODUCTION

The increasing adoption of new technologies, including string- and module-level optimization, have put a spotlight on the industry's limited understanding of the dynamics behind mismatch losses. Traditional methods of defining mismatch as a loss factor ignore the fact that there are multiple drivers of these mismatch losses, including variation in available irradiance and differences in cell temperature. Furthermore, the design choices of a system, including the module choice and string length, can have secondary effects on these losses. This lack of understanding leads to poorer design choices, and provides no guidance for how various forms of MPP (central, string-level, or module-level) can improve system performance.

We propose a performance model that takes a fundamentally different approach to characterizing a PV system. Through a technique called "component-based modeling", each discrete component in the array (including each module and conductor) is treated independently, and then aggregated based on the electrical constraints of series and parallel connections. This modeling technique has traditionally been limited to small systems, because of the computational scaling problems of accounting for the myriad inter-dependencies in large systems. Very good efforts have been made to characterize the mismatch characteristics of small-scale systems [1]-[2], but they have challenges in scaling to large systems. We have developed a tool that makes use of cloud-based computation, parallel processing, and advanced simulation techniques, to enable rigorous component-based analysis of commercial and utility scale photovoltaic (PV) systems. This tool can be used to assess the true impact of mismatch between the irradiance, temperature, and voltage drop of each module within a system, and calculate the resulting energy loss to the inverter.

Results of these analyses can help inform system design choices, inform decisions on processes such as re-binning, and refine production loss estimates. We will also discuss the path for improving the treatment of these variables, including the development of empirical models that take into account module-level variation based on meteorological data and system design.

II. NEW APPROACHES FOR MODELING MODULE MISMATCH

HelioScope by Folsom Labs is a new and commercially-available performance model for solar PV systems. HelioScope is a component-based model: every module, conductor, or other component in a PV system is modeled individually, based on underlying physical properties. Industry standard methods of irradiance calculation and module characterization [3]-[6] are employed throughout the modeling process to ensure mismatch calculations are appropriately isolated from the rest of the modeling process. This approach has a number of benefits, from calculating the impact of module-level power control, to enabling rigorous parametric analysis of small changes in bank spacing or conductor size.

This component-based approach also enables a fundamentally different approach to modeling mismatch. Rather than defining mismatch losses (for example, the standard nominal de-rating of 2.0%), HelioScope can now model the sources of mismatch between modules in the array, and propagate the effects through the full system model. This approach to mismatch calculation has a number of benefits:

- Sources of mismatch can now be defined empirically – based on physical models of irradiance, temperature, and other real-world phenomena. This is a stark contrast to 'mismatch losses' as used in typical models which are based on assumptions that comingle environmental and design parameters.
- The factors are more directly related to meteorological phenomena, and therefore ranges can be developed based on specific climate zones.
- By propagating the mismatch factors through the array, secondary factors such as module fill factor or

string length can change the resulting losses due to mismatch.

III. SOURCES OF MISMATCH

We have modeled non-shaded mismatch as a function of three parameters: temperature, irradiance and module quality, each with a different distribution based on its unique properties. The model then takes these mismatch parameters as inputs into a simulation that accurately represents the electrical relationships within a field. Note that all of these random factors are considered to be independent of one another. The model also calculates the voltage drop of each string, which can cause parallel mismatch between strings.

A. Irradiance Distribution

Irradiance distribution is assumed to be a normal distribution, with the standard deviation of the distribution defined independently. Then each module is sampled from that range and is assigned a percent difference from the array mean. The use of a normal distribution provides for a small number of large outliers from the mean, corresponding to modules that are significantly impaired by soiling or other debris.Note that irradiance distribution is zero-weighted, so it will never change the average POA irradiance.

Mathematically, the adjustments will be taken directly at the POA irradiance calculations for each module.

B. Temperature Differences

Temperature mismatch is assumed to be a uniform distribution, with the overall range of temperatures used as the independent variable. Each module is sampled from that range and is assigned a percent difference from the array mean temperature. The uniform distribution is conceptually driven by the fact that there should be fewer large outliers in the temperature distribution than in the irradiance distribution.

Mathematically, the adjustments are taken right at the calculation of each module's temperature calculation, which primarily impacts the module's maximum-power-point voltage as defined by the module model's IV curves.

C. Module Binning Tolerance

Module binning is assumed to be a uniform distribution, with the upper and lower bound of the range defined independently. Each module is sampled from the defined range and assigned a percent difference from the array.

Mathematically, the adjustments are assumed to impact the baseline photocurrent of the module.

D. Mismatch from Variable Voltage Drop

Finally, an additional source of mismatch can result from differences in voltage drop between parallel strings. This is an emergent property based on the system's DC wiring layout. Modules will run at higher native voltages than the inverter's draw voltage, in order to compensate for the voltage drop on the line between the modules and the inverter.

IV. RESULTS OF THE ANALYSIS

A: Baseline Mismatch Losses

The default system assumptions are a 5% standard deviation in irradiance, 4 degree range in temperature, and a module tolerance range of -2.5% to +2.5%. These generally correspond to mismatch losses of approximately 2-3%. All analysis uses a 55kWdc array using 280-watt crystalline modules in strings of 12, feeding a 50kW inverter.

B: Sensitivities

The first factor, standard deviation in irradiance, leads to significant marginal changes in system mismatch losses.

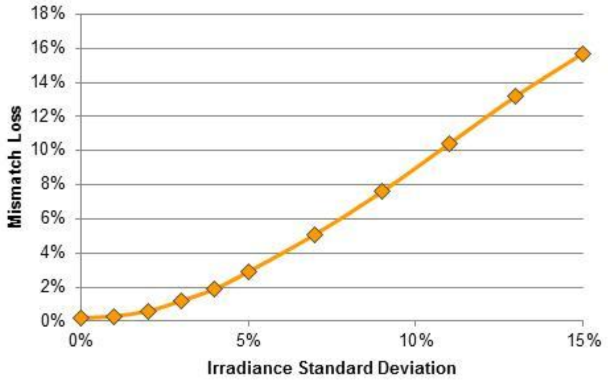

Fig. 1. Sensitivity of System Mismatch Losses to Irradiance Standard Deviation

This only breaks down on the low end of the distribution, where the first few percent of standard deviation do not lead to mismatch losses. The module's power curve is relatively flat in the local area near the peak power point.

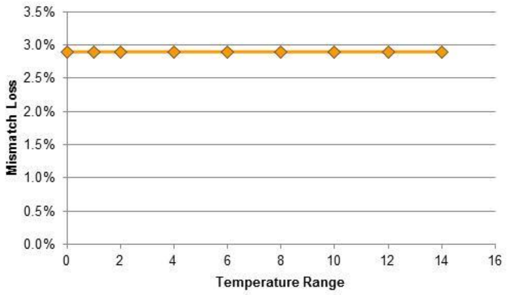

Fig. 2. Sensitivity of System Mismatch Losses to Temperature Range

Modifying the temperature range has almost no effect on losses. This can be explained by the fact that temperature changes result in changes to voltage, not current. So they do not cause series mismatch, and the parallel mismatch is muted by the fact that 12 modules are in each string.

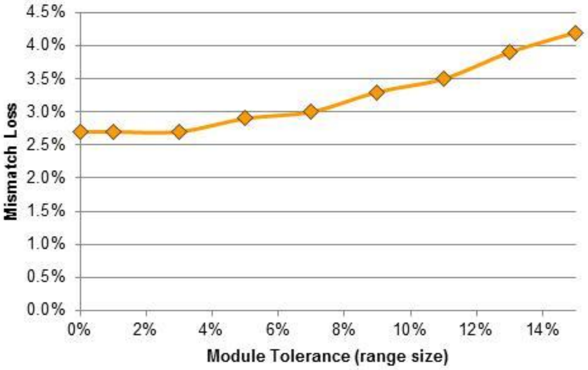

Fig. 3. Sensitivity of System Mismatch Losses to Module Binning Ranges

Changes in module binning range have a small positive effect on mismatch losses. The uniform distribution of module binning means that there are fewer extreme outliers, and thus the overall energy impact is far less than the normally distributed differences in module irradiance.

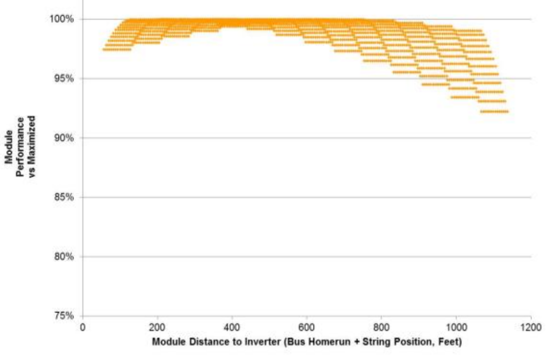

Fig. 4. Module Power Distribution Based on Differences in Voltage Drop

Mismatch due to voltage drop can occur, as the inverter will pick a draw voltage that is optimal for modules in the middle of the distribution. However, the absolute power lost due to this factor will often remain low.

C: Weather and Design Sensitivities

We can also modify secondary system design choices, such as module type, string size, and weather location. These will slightly change the mismatch losses compared to the baseline array. Further detail and implications will be shared in the full report.

V. SUMMARY AND PATH FORWARD

The three direct sources of mismatch have dramatically different effects on mismatch losses. Irradiance differences drive the vast majority of the mismatch losses, while module binning has a smaller effect, and temperature differences have close to no effect.

All three of these mismatch factors are first-order approximations – they can and will be improved based on further research. Irradiance distributions should not be defined as a normal distribution, but should rather have a negative skew, such that there are more negative outliers than positive ones. Soiling is, after all, a one-way bias. Additionally, temperature mismatch should have a spatial component, since the modules on the edges of the array should run cooler. This would lead to more mismatch between strings, and higher parallel mismatch in voltage.

There is also a need for more empirical data to inform these variables' absolute values. There are anecdotes of module temperatures differing by 10°C [7], and analysis from a data set published by NREL shows average standard deviation (weighted by power) of 15.4% [8]. However, these data need to be more systematically analyzed, in order to understand values and any relevant differences based on climate areas.

On all of these fronts, the team at Folsom Labs looks forward to working with partners from the research and development community to develop commonly-accepted frameworks and data ranges.

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