Quantification of System-Level Mismatch Losses using PVMismatch

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Abstract - Differences in the current-voltage characteristics of photovoltaic (PV) modules connected in series and parallel combinations lead to a loss in the system level power referred to as "electrical mismatch". As a result of electrical mismatch, the power at the maximum operating point of the PV system is less than the sum of the power outputs of the modules if they were acting independently. In this study, the PVMismatch python package was used to model PV modules from two representative flash test datasets. Randomly sampling from that dataset, a variety of PV systems configurations were simulated using the Monte Carlo technique to arrive at distributions of potential configuration-specific mismatch losses. Further, this method was extended to simulate annual energy loss due to mismatch for a sample location. The method provides a framework to quantify electrical mismatch losses for accurate performance modeling of PV systems and enables sensitivity analyses to adopt effective binning strategies for reducing system level mismatch losses.

Index Terms — PVmismatch, Photovoltaic systems, Monte Carlo analysis, DC mismatch loss, Flash test datasets

I. INTRODUCTION

Differences in the current-voltage characteristics of photovoltaic (PV) modules connected in series and parallel combinations lead to a loss in the system level power referred to as "electrical mismatch". The electrical mismatch has been studied in literature [1]–[5] primarily by using one of two methods: (1) synthesizing system level current-voltage (I-V) curves by progressively summing I-V curves of PV modules in series-parallel combinations, as per the system design requirements; and (2) estimating electrical mismatch loss in PV systems composed of modules with known or statistically-generated characteristics, as per Bucciarelli *et. al* [1], as summarized by Webber *et. al* [6]. For a PV system composed of newly fabricated cells, the system level electrical mismatch losses are estimated to be less than 0.01% [5] using Bucciarelli's model. For 1MW PV array mismatch loss is 0.501+/- 0.003% Kaplan *et. al* [7]. MacAlpine *et. al* [8] suggest the commonly used mismatch loss figure of 1-2% should have adequate accuracy for most simulations. With such a wide range of mismatch loss figures found in the literature, we find there is a need for a method to quickly estimate case specific (system size, PV module type, binning size) mismatch loss from the manufacturer flash test dataset for accurate modeling of PV systems energy production.

This study demonstrates the use of SunPower's PVMismatch python package [9]–[11] to calculate system-level mismatch losses for various PV system configurations. Mismatch losses at module level are calculated by electrical combinations of current-voltage characteristics for modules connected in series and strings of modules connected in parallel. Further, this study demonstrates how the same framework for system-level mismatch loss at Standard Test Conditions (STC) can be used to estimate annual energy mismatch loss for a given a Typical Metrological Year file.

II. PVMISMATCH OVERVIEW

Mathematical models can be effectively used to understand the effect of variation in parameters that affect the performance of PV systems. Current and voltage mismatch in the resultant electrical circuits formed by arrangement of PV modules in series and parallel in a system can be captured by modeling the PV cell using a 2-diode model and tracing the mismatch losses up to the system level. PVMismatch is a current-voltage and power-voltage curve trace calculator for PV systems which can also calculate mismatch [11]. This Python based package lets the user fully define a photovoltaic system, including the coefficients which describe a cell's response in the equivalent circuit model, the electrical circuits formed by arrangement of cells and diodes within a module, the number of modules in a string, and the number of strings in a system. Meyers *et. al* [10]. PVMismatch uses an implementation of the 5-parameter 2-diode model in a Python-based framework based on former work by King *et. al* [10], Bishop [3], and Desoto *et. al* [12].

Effects of shade on PV systems using PVMismatch have been demonstrated by Meyers *et. al*[10], including the impact of different shading geometries on a PV system using both the cell-level model and a module-level model. To demonstrate a baseline of evaluation of mismatch that is comparable to the former work, a sample shading analysis was run using PVMismatch for a 2x10 PV system (2 parallel strings of 10 series-tied modules). "Shade factor" for the purpose of this analysis is defined as the equivalent percentage reduction in incident "Suns" (where 1 Sun = 1000W/m^2 Irradiance). Fig.1 shows the impact of mismatch caused by shading one PV module in the sample PV system and the resulting change in the power-voltage characteristics. A sensitivity analysis of changing the shade factor for the same configuration yields mismatch losses of 1% and 1.4% for shade factors of 15% and 20%, respectively. This analysis demonstrates that the PVMismatch framework can effectively calculate the system-level impact of mismatch in PV systems due to partial shading on the system. This capability of PVMismatch to capture the resultant electrical characteristics from combination of imperfect characteristics of PV systems can be extended to estimate the mismatch in current-voltage characteristics resulting from module manufacturing variability and binning strategies.

a multimodal distribution of module parameters, as seen here in Fig. 3.

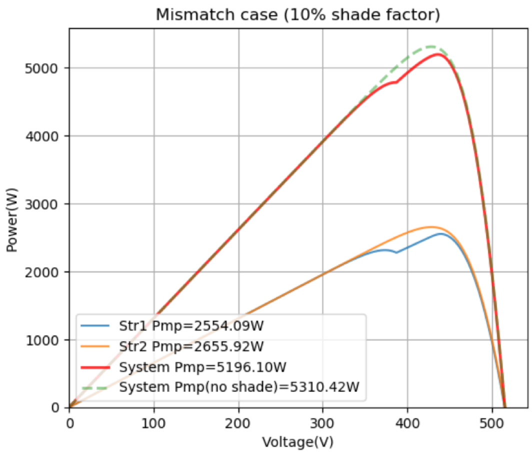

Fig. 1. Power-Voltage curve of a 2x10 PV system – 1st module in String 1 shaded 10%, shading mismatch loss = -0.4%

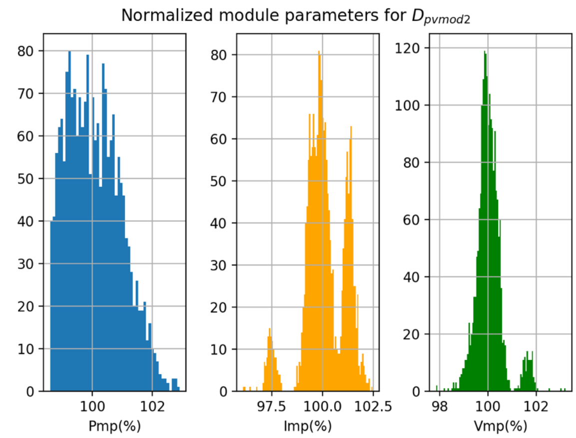

Fig. 3. Dataset D_{pvmod2} – Pmp, Imp, Vmp distributions

III. Data AND Methods

The voltage and current data behind this mismatch study were gathered from at least 1000+ unique flash tests each for two typical PV modules with different distribution of module parameters. The datasets were filtered to contain only a commercially-accepted standard bin size of maximum module power (P_{mpmod},-0%/+5%).

Using the PVMismatch model chain, the 2-diode model was fitted for each of the results from the flash test datasets. The resulting population of model PV modules are referred to as D_{pvmod1} and D_{pvmod2} in this study. These populations serve as the datasets behind the analysis presented in this study. As seen in Fig. 2, D_{pvmod1} modules follow a normal distribution of module parameters at maximum power point (MPP). D_{pvmod2} represents

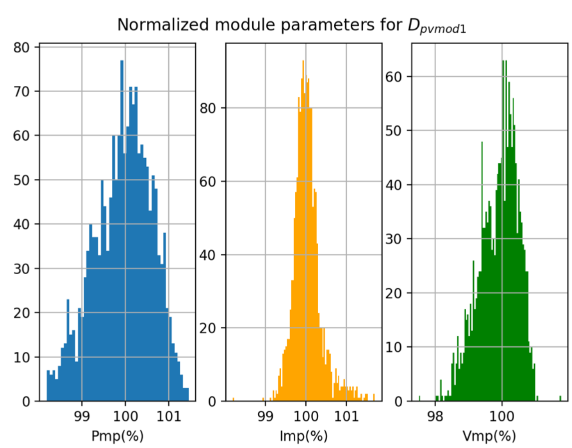

Fig. 2. Dataset D_{pvmod1} – Pmp, Imp, Vmp distributions

For each configuration of PV system, number of modules per string (N_m) were chosen to represent typical system voltage ratings: 600V, 1000V and 1500V. The number of strings (N_s) was than determined to roughly represent three different scales of PV systems: residential (≤10kW), commercial (~100kW) and utility scale (≥1MW). Equivalent N_s x N_m combinations of PV modules were sampled from the populations D_{pvmod1} and D_{pvmod2}.

A. Mismatch Loss at STC

The highest level of abstraction in the PVMismatch model chain, PVsystem, was used to calculate the maximum power operating point of the PV modules connected in series and parallel (P_{mpsys}). A reference power (P_{ref}) without accounting for the mismatch losses was calculated by summing the individual P_{mpmod} as defined in equation 1.

$$P_{ref} = \sum_{0}^{(Ns*Nm)} P_{mpmod} \quad (1)$$

The mismatch loss in each system configuration at STC is calculated as shown in equation 2.

$$STC\ Mismatch\ loss = \frac{\left(P_{mpsys} - P_{ref}\right)}{P_{ref}} \times 100 \qquad (2)$$

Since the PV modules modeled in each configuration are randomly sampled from the larger population of module datasets D_{pvmod1} or D_{pvmod2}, we use a Monte Carlo approach of simulating 1000 unique scenarios of module selection to yield a distribution of potential mismatch losses for each PV system configuration.

B. Annual Energy Loss due to DC mismatch

The framework established for mismatch calculations at STC can be further extended to enable modeling of mismatch loss at arbitrary environmental conditions. The PVMismatch package offers capabilities to calculate current voltage characteristics of PV systems at varying cell temperatures and irradiance conditions. For demonstrative purposes, we chose a Typical Meteorological Year (TMY3) weather file for Tucson, AZ location. We used the normalized Plane of Array (POA) Irradiance and the Dry Bulb temperature from the TMY3 file as a proxy for setting the incident effective irradiance (Suns) and cell temperature on the model PV system, respectively. At each hourly condition in the TMY3 file, P_{ref} and P_{mpsys} were calculated. For each simulated PV system configuration, the Annual Energy Loss due to Mismatch (AELM) was calculated as shown in equation 3. For arriving at a distribution of AELM for various scenario PV systems, 200 such simulations were performed to yield a distribution of AELM.

$$AELM\ (\%) = \frac{\left(\sum_0^N P_{mpsys} - \sum_0^N P_{ref}\right)\times 100}{\sum_0^N P_{ref}} \quad (3)$$

where N = number of rows in the TMY3 weather file

IV. Results

Fig.4 shows the distribution of mismatch losses calculated at STC for three representative scales of PV systems configured from PV modules in D_{pvmod1}, each configuration simulated 1000 times. Fig. 5 shows the results calculated with the multimodal distribution D_{pvmod2}.

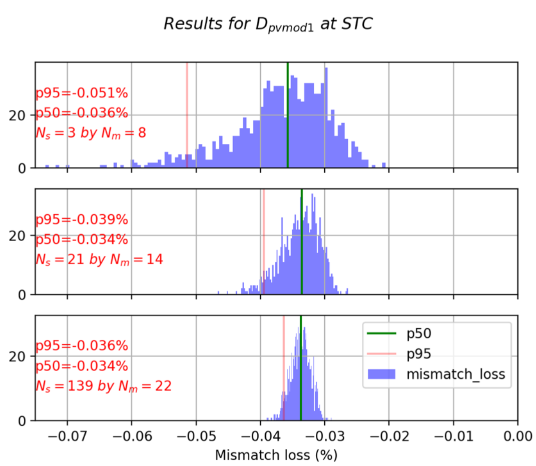

Fig. 4. Distribution of STC mismatch losses at various system scales for D_{pvmod1}

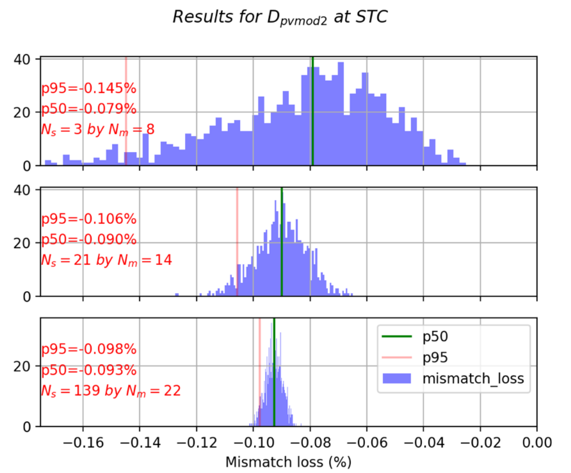

Fig. 5. Distribution of STC mismatch losses at various system scales for D_{pvmod2}

Comparison of the results in Fig. 3 and Fig. 4 show that the multimodal distribution of the PV module characteristics leads to higher mismatch loss in PV systems of all scales. It is noteworthy that the P50 value of the STC mismatch losses for all the cases simulated doesn't change significantly across system scales but the P95 value shows a distinct decreasing trend. The P95 values of losses were observed to be decreasing with the increasing scale of the system for both the PV module distributions studied.

Fig. 6 shows the distribution of the annual energy loss for an example PV system configuration (3 strings of 8 modules) using the distribution Dpvmod1.

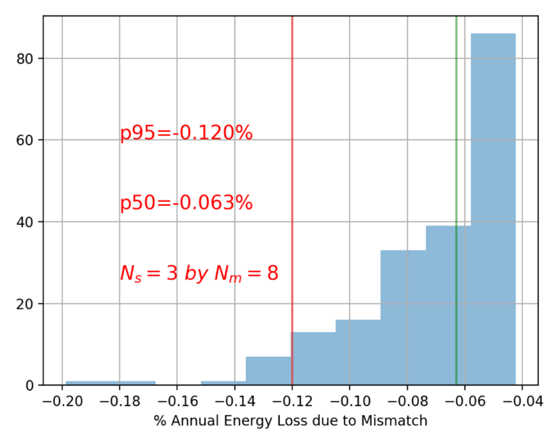

Fig. 6. Example of distribution of Annual Energy Loss due to Mismatch for a typical N_s=3 by N_m=8 using dataset D_{pvmod1}

The results for annual energy loss due to mismatch are consistent with the expectation that mismatch will be higher at non STC. The P50 case of the distribution of annual energy loss is -0.063% and the mode of distribution -0.04%, compared to the P50 STC mismatch loss at -0.036%. The annual energy mismatch loss was only calculated for one PV system configuration for demonstrative purposes as they are highly computationally intensive and time-consuming simulations to run.

V. Discussion

Table I summarizes the results of several scenarios simulated during the course of this study. Results indicate that for larger systems the P95 mismatch loss typically decreases. Also, the annual energy loss is higher than the STC mismatch loss. The results presented in this study indicate that the mismatch loss is significantly lower than the 1-2% guidelines as found in the literature also a widely used industry practice.

TABLE I

System configurations		Mismatch loss (%)							
		D_{pvmod1}				D_{pvmod2}			
		STC		Annual		STC		Annual	
N_s	N_m	P50	P95	P50	P95	P50	P95	P50	P95
3	8	-0.04	-0.05	-0.06	-0.12	-0.08	-0.14		
21	14	-0.03	-0.04			-0.09	-0.11		
139	22	-0.03	-0.04			-0.09	-0.10		

VI. Conclusion

Accurately determining mismatch losses in PV systems is crucial for evaluating total system losses as they directly impact the levelized cost of energy (LCOE). Measuring the DC mismatch loss in the field would be an extremely difficult task given the vast number of possible PV system configurations and the dynamic factors that affect the performance of PV systems. Using the PVMismatch framework with flash test data and the Monte Carlo technique, we present a method to calculate the mismatch loss at STC and annual energy loss due to mismatch with several example scenarios.

This method can also be extended to model other prominent factors that introduce DC mismatch loss in PV systems. The future scope of this study would be to quantify the effect of mismatch loss introduced by varying DC feeder lengths, module temperature non-uniformity across the PV array, and non-uniform cell and module degradation over lifetime.

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