Mismatch Losses in Simulated Commercial and Utility-scale PV Arrays due to Shortened Strings

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INTRODUCTION

This work presents power loss and reverse current simulations of commercial and small utility-scale arrays with missing or mismatched modules.

- Significant avoidable energy losses in PV systems consist of faults, maintenance or failure unavailability, and mismatch losses [1].
- Reports indicate a 20 - 25% reduction in PV system output due to mismatch losses [2].
- Many operational situations force a PV array to operate with mismatch conditions, possibly resulting in measurable power losses [3-9], including periodic lab testing [10] or due to natural disasters when replacements are unavailable [11].
- When a replacement module is not available, one common industry practice is to bypass the removed module(s), thus leaving shortened string(s) [12].
- Presented work expands on our previous simulations [13].

OBJECTIVES

Understanding three behaviors:

1) the impact of mismatched strings on arrays of different sizes
2) the impact of mismatched strings at the array maximum power point under different irradiance conditions
3) the effect of mismatched strings at open circuit, such as when an array is undergoing maintenance, or the inverter has faulted

METHODS

- Simulations built of parallel strings of (12) Jinko Eagle 60 mc-Si modules, model JKM270PP-60 [14]
- Figure 1 describes nominal and shortened string behaviors for a simple two string mismatched array (blue, black curves).
  - Near I_{SC}, both strings contribute to array output
  - Near I_{MPP} of the array (red dot), shortened string contribution is reduced; beyond, it consumes.
  - At V_{OC}, zero net current is produced. Nominal strings generate and shortened strings consume.
- LTspice [15] model developed to simulate up to 900 strings with between 1 and 60 strings, shortened by 1-, 3-, or 5-modules each.
- Irradiance varied from 400 to 1000 W/m² at 50ºC
- The thermally static one-diode model is adjusted for temperature- and irradiance-dependent parameters using the technique described by Cubas [16].

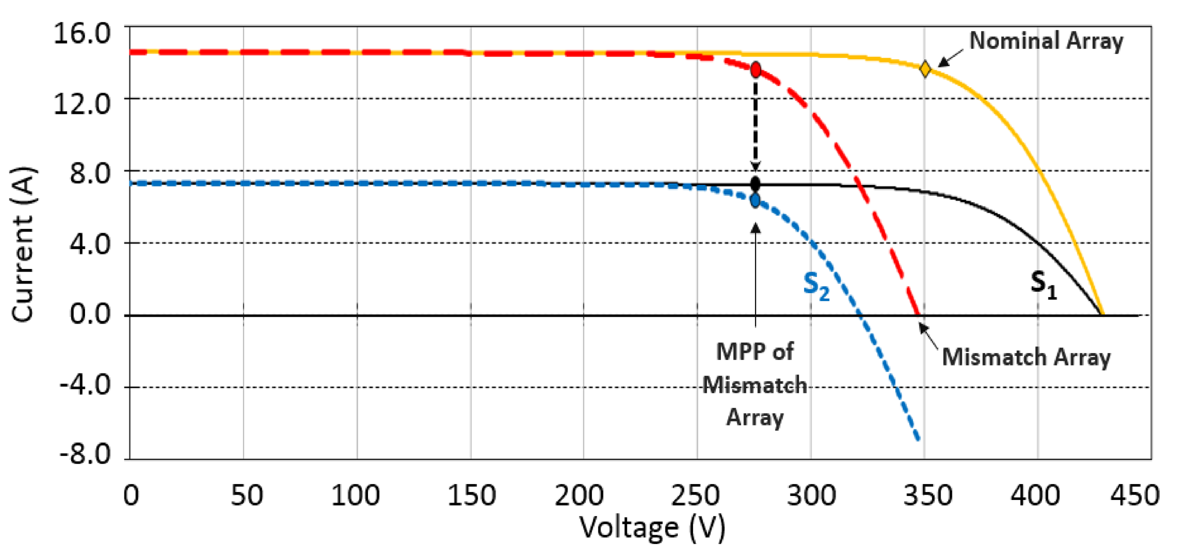

Fig. 1 Simulation of a 3-module mismatch without blocking diodes on a two-string array explains the effect of a shortened string on an array. Note that the current of the open-circuit mismatch array sums to zero but consists of both positive (S_1) and negative (S_2) components.

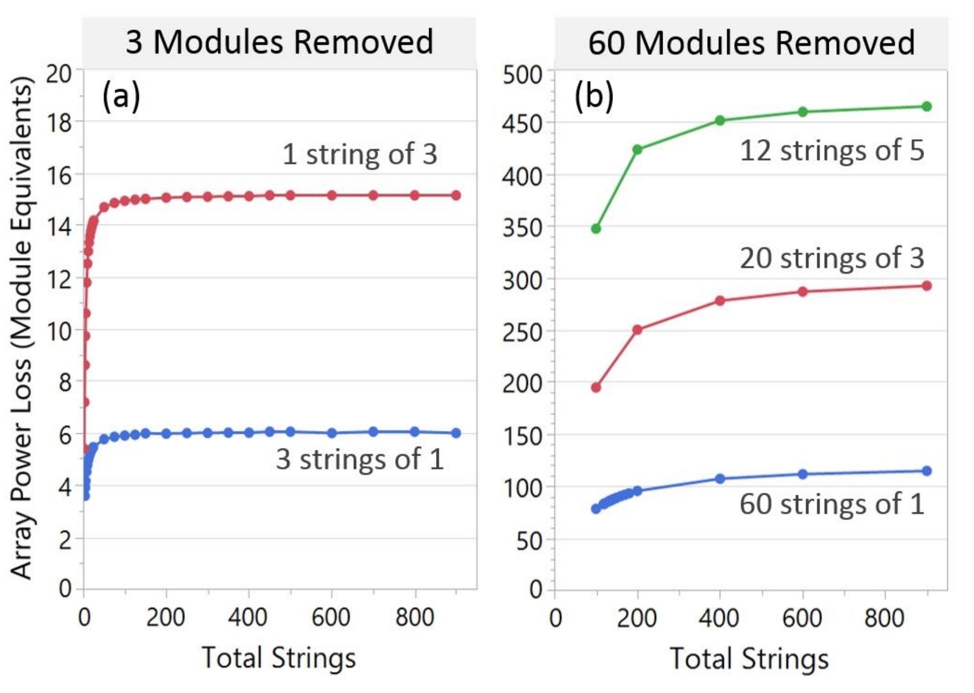

Fig. 2 Array power loss in module equivalents at 800 W/m² and 50ºC for reductions in array size of (a) 3 modules, and (b) 60 modules using several string shortening methods.

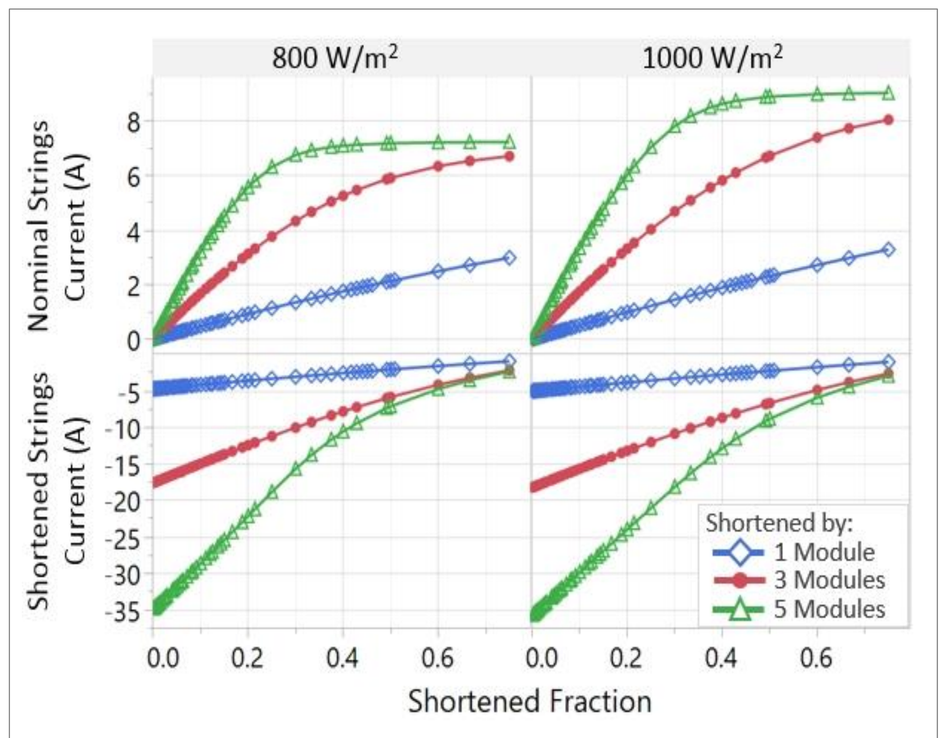

Fig. 3 Open-circuit currents in nominal and shortened strings at 800 and 1000 W/m² at 50ºC for three levels of string shortening as a function of the fraction of shortened strings within an array.

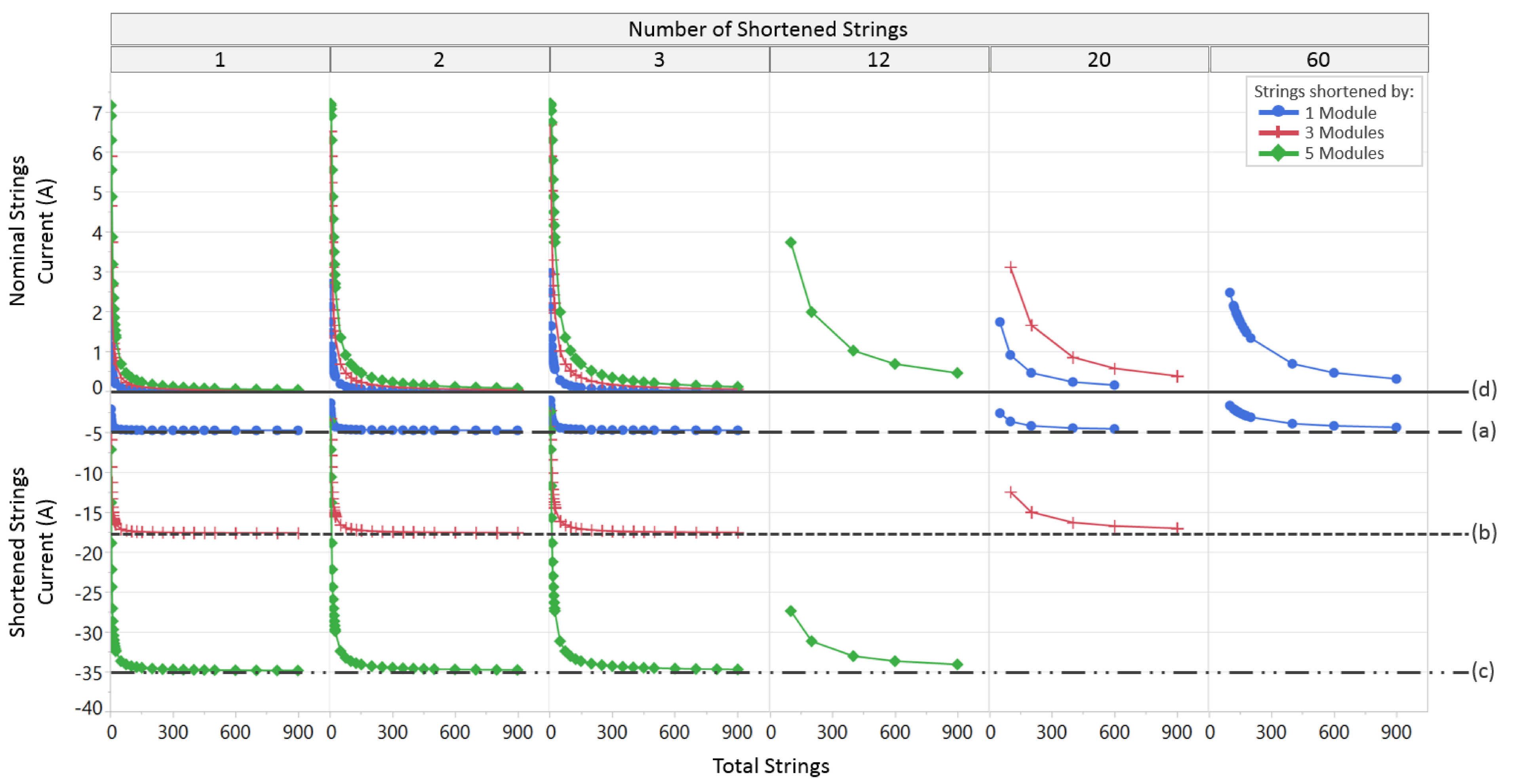

Fig. 4 Simulations at 800 W/m² and 50ºC at various degrees of string shortening show that the level of reverse current approaches a limit which is a function of the level of mismatch and not the number of shortened strings where: (a) single module shortened strings limit to approximately 4.8A, (b) three-module shortened strings limit to approximately 17.7A, and (c) five-module shortened strings limit to approximately 35A. Shown at (d), as the total number of strings increases, the nominal string contribution to current decreases to very low levels.

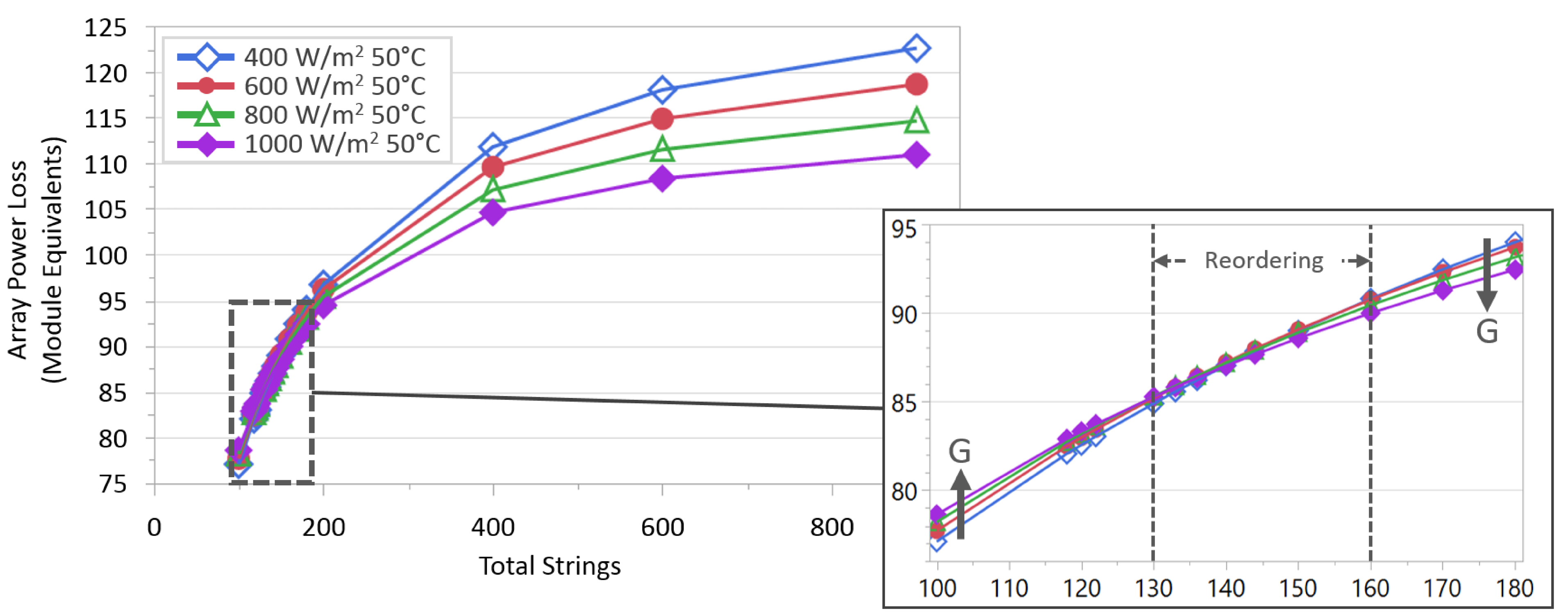

Fig. 5 Power loss in module equivalents as a function of irradiance at 50ºC for a 60-module array size reduction.

RESULTS AND DISCUSSION

EFFECT OF ARRAY SIZE

The more severe the level of shortening, the more substantial the impact on relative array output.

- Simulations varied the total number of paralleled strings, the number of shortened strings, and the severity of shortening (by 1-, 3-, or 5-modules).
- Removal of modules from an array may be accomplished by removing single modules from multiple strings, or by removing multiple modules from fewer (Figure 2).
- Power losses must be normalized to equivalent modules for comparison.

REVERSE CURRENT AT OPEN CIRCUIT

Shortening should be limited to single modules per string to limit reverse current. 3- and 5- module shortened string reverse currents may exceed the series fuse ratings and pose safety and reliability concerns.

- For any given number of shortened strings, as the overall size of the array increases, the current generated by the nominal strings decreases and the current consumed within the shortened strings increases (Figure 4).
- Single module shortening displays a linear relationship to shortened fraction while 3- and 5-module shortening shows non-linear behaviors. Flattening occurs near I_{SC} limit (Figure 3).

IRRADIANCE IMPACT ON POWER LOSS AT P_{MPP}

The impact of irradiance level depends on the ratio of impacted strings to array size.

- Array power loss increases as the total number of strings increases (Figure 5).
- For large arrays, the impact is more substantial at low irradiance than high; relationship reverses in arrays of a low total number of strings (Figure 5 inset).
- The ratio of impacted strings to array size provides context. An increasing impact with irradiance is observed above a ratio of 0.462 (60 of 130 strings). The reverse relationship is observed below a ratio of 0.375 (60 of 160 strings).
- It is unclear if the ratios calculated are applicable to other conditions.

CONCLUSIONS

- For any quantity of removed modules, the more severe the level of shortening, the more substantial the impact on array output.
  - Limit string shortening to single modules over multiple strings versus multiple modules per string.
- Arrays with low shortened string ratios experience higher relative losses at low irradiance than at high irradiance.
- Shortened strings in an open-circuited array experience a reverse current.
  - 3- and 5-module shortening reverse currents may exceed series fuse rating (safety concern)

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