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Technical Memo:

Reduction of Mismatch Losses in Solar Installations Using String Optimizers

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Date: November 2015

Mismatch Losses in Solar Installations Using String Optimizers

Solar installations are constructed using a combination of serial and parallel interconnections of multiple individual solar panels. Serial interconnections forces all modules in a string to operate at the same current and parallel strings are forced to operate at the same string voltages. This arrangement can cause individual modules to operate away from its maximum power point leading to mismatch losses in the system. Mismatch loss can be reduced using a more granular Maximum Power Point Tracking (MPPT) in the system with module level or string level optimizers. This white paper examines some common sources of mismatch loss and quantifies the loss reduction that can be achieved using string optimizers.

Throughout this paper mismatch loss is defined as:

$$\text{Mismatch Loss} = (\sum Pmaxm - Pmaxs)/\sum Pmaxm$$

Where $\sum Pmaxm$ is the sum of all individual module Pmax and Pmaxs is the total system Pmax.

It is convenient to group mismatch into three categories:

A) Current mismatch within a string.
B) Voltage mismatch between strings caused by current mismatch within a string.
C) Voltage mismatch between parallel strings

A: Current mismatch within a string

The most common causes for current mismatch within a string are; shading, uneven soiling, module manufacturing variations and uneven Isc degradation. For small to moderate (less than ~5%) current mismatch, the resulting mismatch losses are small but depend in detail on the specific module parameters. Figure 1 below shows the Power vs. Voltage curves for a string of 10 Si modules (Pmax=304W, Voc=45.5V, Isc=9A,Rsh=318 Ohm, Rs=0.4Ohm) where the Isc of one module is reduced by 1%, 2%, 3%, 4% and 5%.

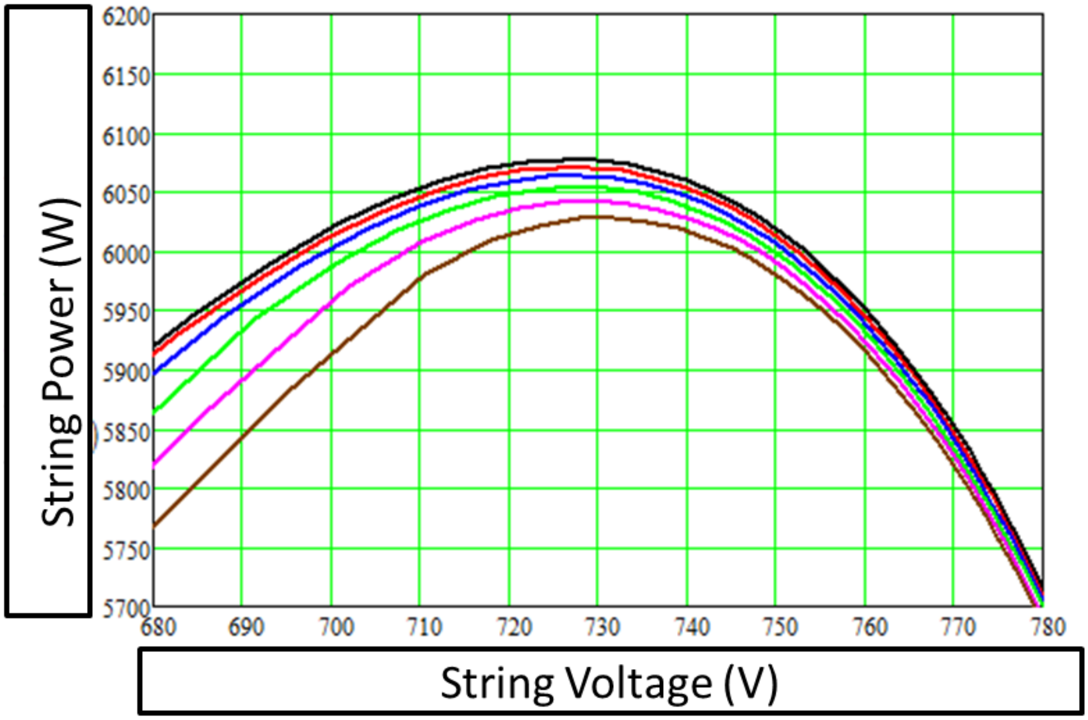

Figure 1. Power vs. string voltage when Isc of 2 of the modules in a string of 20 modules is reduced by 0%, 1%, 2%, 3%, 4%, and 5%.

The resulting mismatch losses are very small and shown in the table below.

Isc mismatch	String Power (W)	Powerloss (W)	Mismatch loss (%)
0%	6077.3	0	0.00%
1%	6070.7	6.6	0.01%
2%	6063.1	14.2	0.03%
3%	6053.9	23.4	0.09%
4%	6042.2	35.1	0.18%
5%	6027.5	49.8	0.32%

Summary (A): In the case of small to modest Isc mismatch within a string, only a module level optimizer can recover the mismatch losses. However, due to the very small mismatch losses, it is doubtful if the cost of module level optimizers could be justified.

B: Isc mismatch within a string causing voltage mismatch between strings.

The situation is dramatically different when the Isc mismatch within a string is increased to the point that the module bypass diodes are activated. When the bypass

diodes are activated, the affected module is shunted and bypassed from the string and does not contribute power to the string. Module shading is the leading cause for large Isc mismatch.
The string power vs string voltage curves are shown below:

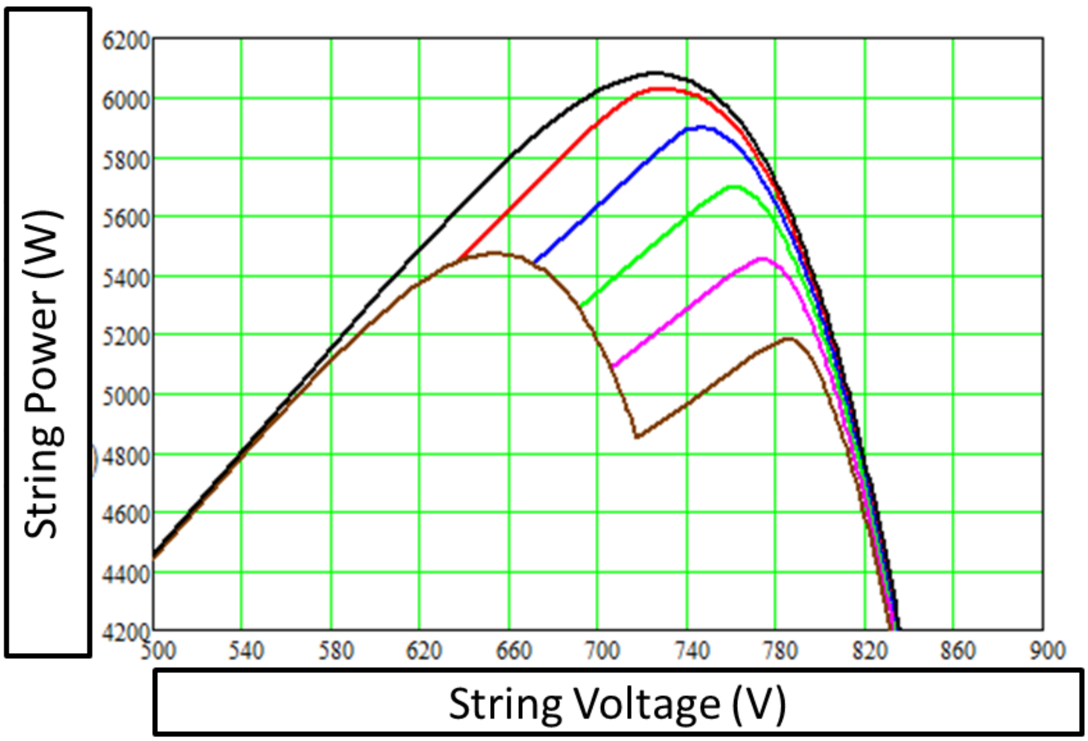

Figure 2. String power vs. string voltage for a string of 20 modules where the Isc is reduced by 0%, 5%, 10%, 15%, 20%, and 25% for 2 modules.

As seen in Figure 2, large Isc mismatch within a string is accompanied by large shifts in the maximum power operating voltage. For an installation using central inverters and a large number of parallel strings, the string voltage is essentially clamped by the undisturbed normally operating strings. Using string optimizers, the disturbed string is free to choose the string voltage giving the maximum string power. These two scenarios are shown in Figure 3 where the operating points for a central inverter and for a string optimizer are indicated by black circles and red dots respectively.

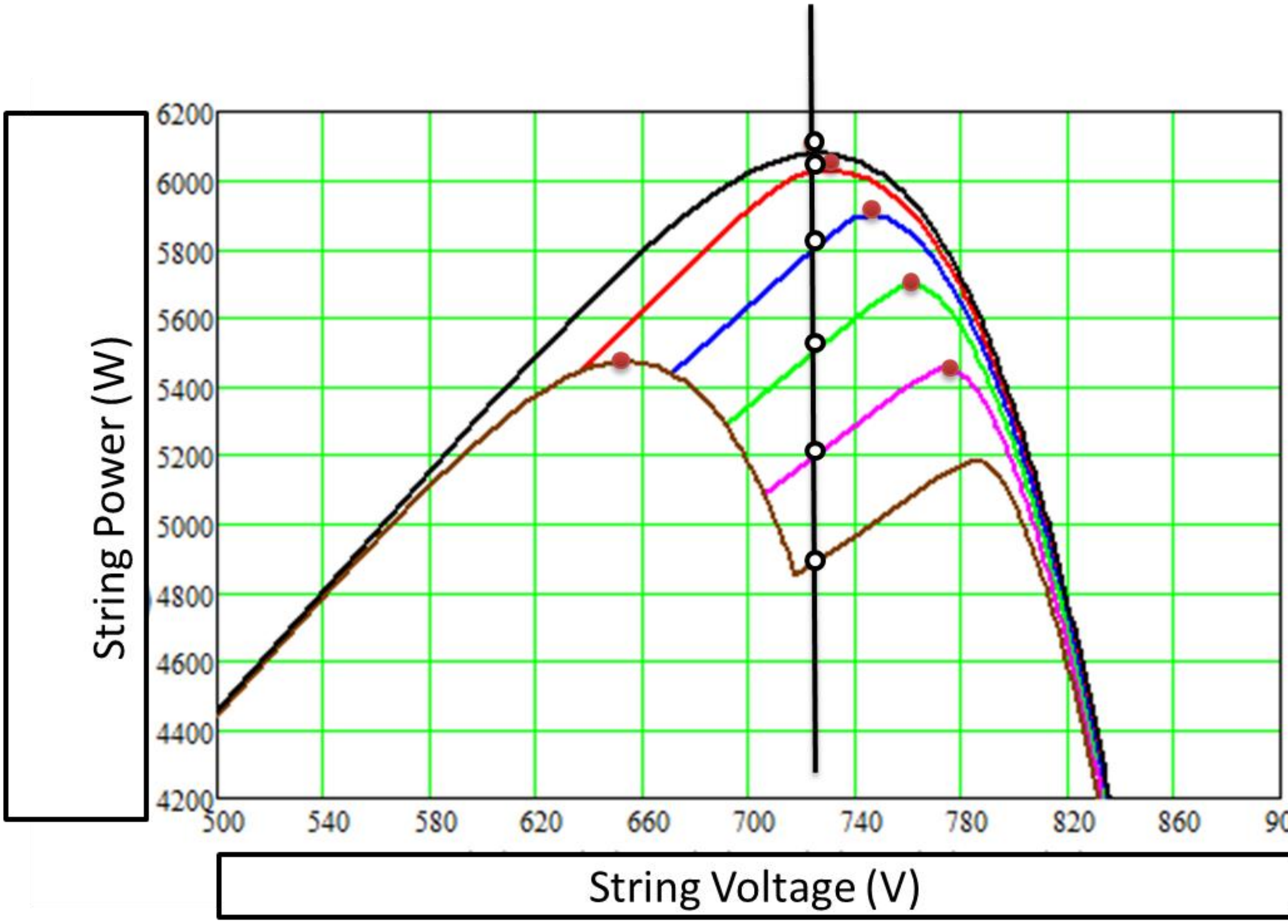

Figure 3. String operation points for a central inverter (black circles) and string optimizer (red dots).

The corresponding operating powers are shown in the table below.

Isc mismatch	Pmax string optimizer (W)	Pmax central inverter (W)	Power loss string optimizer (W)	Power loss central inverter (W)
0%	6077	6077	0	0
5%	6028	6025	49	52
10%	5899	5825	178	252
15%	5697	5530	380	547
20%	5470	5200	607	877
25%	5470	4900	607	1177

It is worth noting that when using string optimizers the string power loss is fixed at 607W (total loss of two module) for a Isc mismatch of 20% or larger. For a central inverter, however, the power loss continues to increase with increasing Isc mismatch. In figure 4 we show the mismatch losses in the two cases discussed above. It is clear that using string optimizers provides a large reduction in mismatch loss as compared to a central inverter configuration.

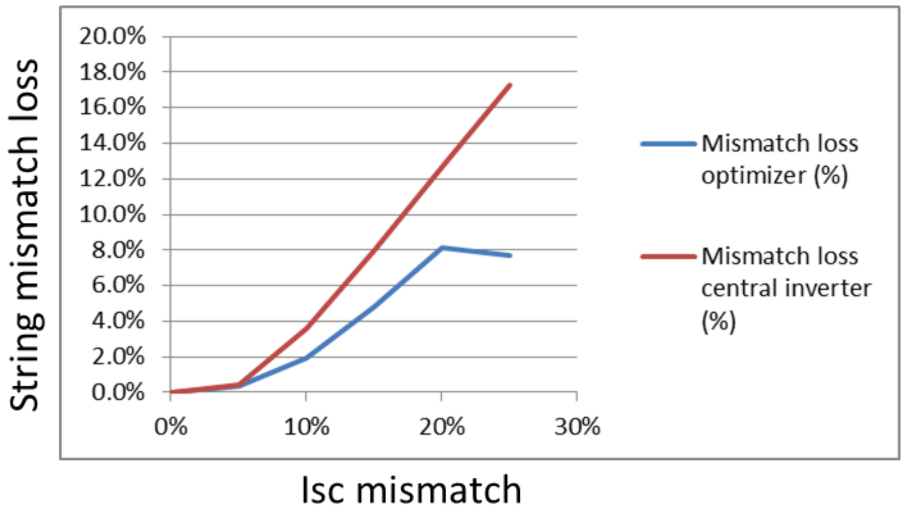

Figure 4. String mismatch loss for a 20 module string with and without string optimizer.

Summary (B): For large Isc mismatch (for example from shading) the string mismatch loss can be very large and, depending on the system details, about 50% of the mismatch loss can be recovered using string optimizers.

C: Voltage mismatch between parallel strings

There are a number of possible causes for a voltage mismatch between parallel strings; module manufacturing variations, uneven module temperatures, uneven module degradation, and varying voltage drops in homerun cabling. In a system with a central inverter without string optimizers the string voltage is clamped and equal for all strings regardless of the different optimal string voltages for each string leading to mismatch losses in the installation.
Thermal gradients: It has been reported (1) that the modules at the edge of an array can be as much as 20 deg. C cooler than modules at the center of the array. This would lead to a Vmp mismatch of approximately 9%. In figure 5, we show the Pmax vs. Vstring for voltage mismatch of 0%, 1%, 3%, 5%, and 10%.

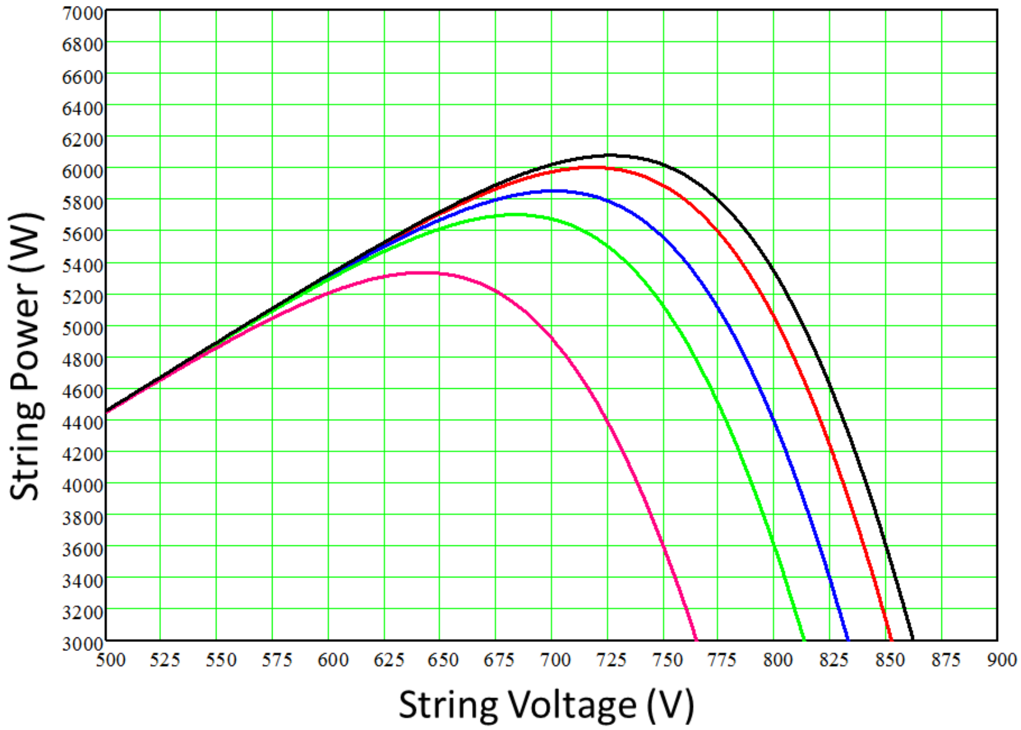

Figure 5. String power vs string voltage for a 20 module string with voltage mismatch of 0%, 1%, 3%, 5%, and 10%.

For a central inverter system where the string voltage is clamped at the undisturbed Vmax (735 V) the corresponding Pmax and mismatch loss for the string would be:

Voc mismatch	Pmax string optimizer (W)	Pmax central inverter (W)	Mismatch loss central inverter	Mismatch loss string optimizer
0%	6077	6077	0.0%	0
1%	6002	5988	0.2%	0
3%	5851	5759	1.6%	0
5%	5700	5443	4.5%	0
10%	5334	4248	20.4%	0

Using string optimizers will, of course, remove all mismatch losses as each string would be operating at its own maximum power voltage. The above case is a worst case scenario and in most cases the system voltage would be slightly pulled down by the low-voltage strings thus reducing the mismatch losses. Taking this effect into account we show in figure 6 the net overall system wide mismatch loss as function of Voc non-uniformity with the percentage of the array being affected as parameter.

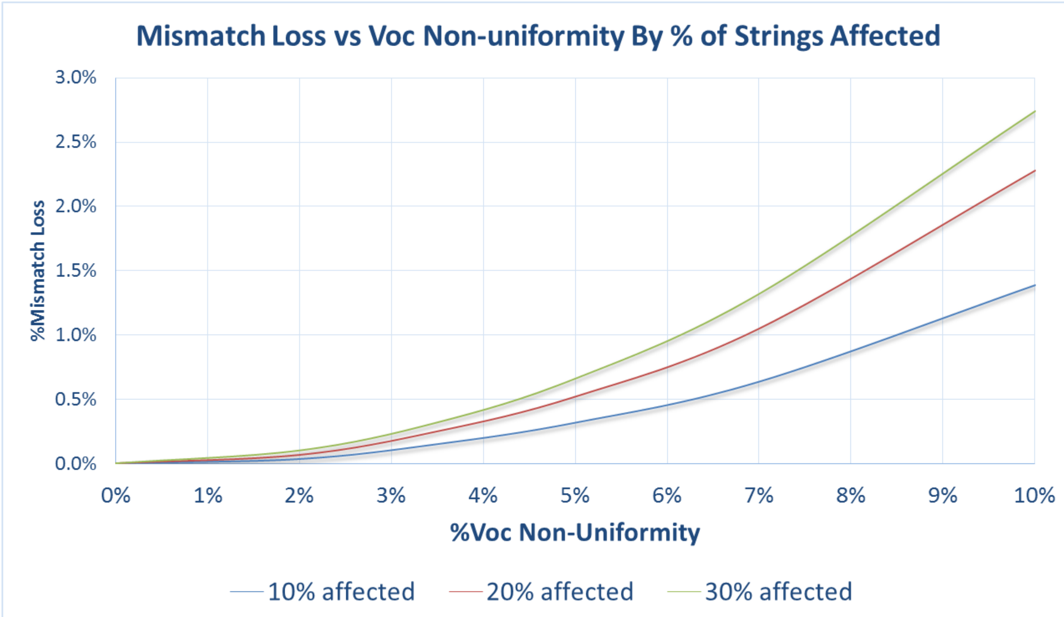

Figure 6. Total system mismatch loss as function of string Voc mismatch with percentage of strings affected as parameter.

The mismatch loss will reach a maximum when approximately 40% of the strings are affected. Figure 7 shows the total system mismatch loss as function of percentage of strings affected for a voltage mismatch of 10%.

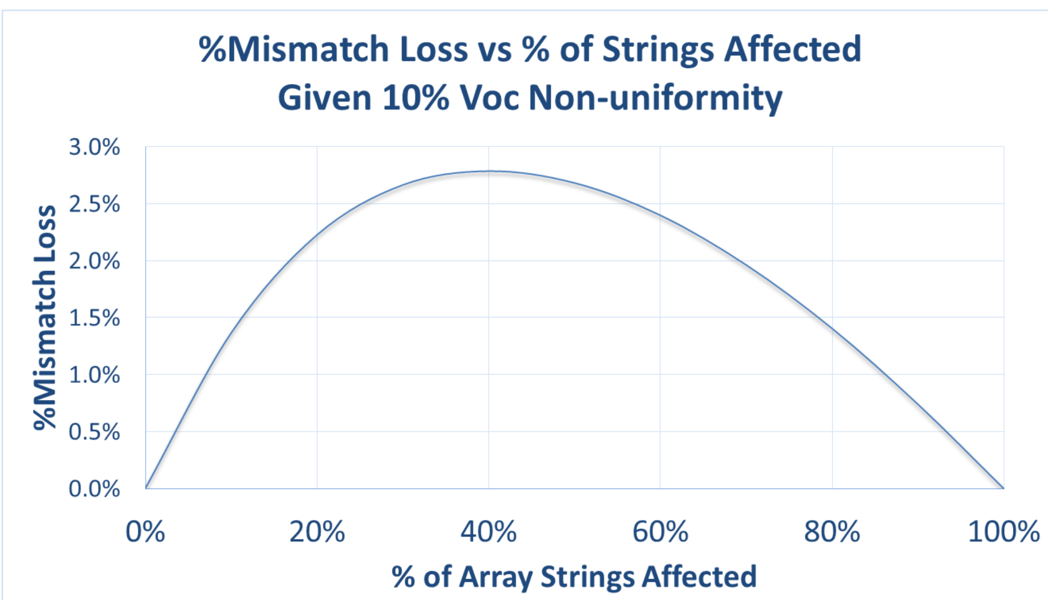

Figure 7. Total system mismatch loss as function of strings affected for a central inverter system without string optimizers.

Variable Degradation Rates-

Degradation rates may also vary across an array. Typical degradation rates are reported as -0.5% to -1% per year. Since that degradation could be in either current (Isc and Imp) and/or voltage (Voc and Vmp), then the mismatch losses due to voltage non-uniformity will increase over time. Using the commonly reported acceleration factor of 0.7 eV (2) and a baseline operating temperature of 45C, we can compute that for every 10C increase in operating temperature, the degradation rate roughly doubles causing the voltage non-uniformity due to the thermal gradient effect mentioned above to be compounded over time.

The degradation rates for modules operating at 45C, 50C, 55C, 60C using an acceleration factor of 0.7eV are shown below. It is not unlikely, given the thermal gradient data collected on operational systems that modules/strings will be degrading at a rate associated with both the 45C (blue) line as well as the 55C (green) line within the same system.

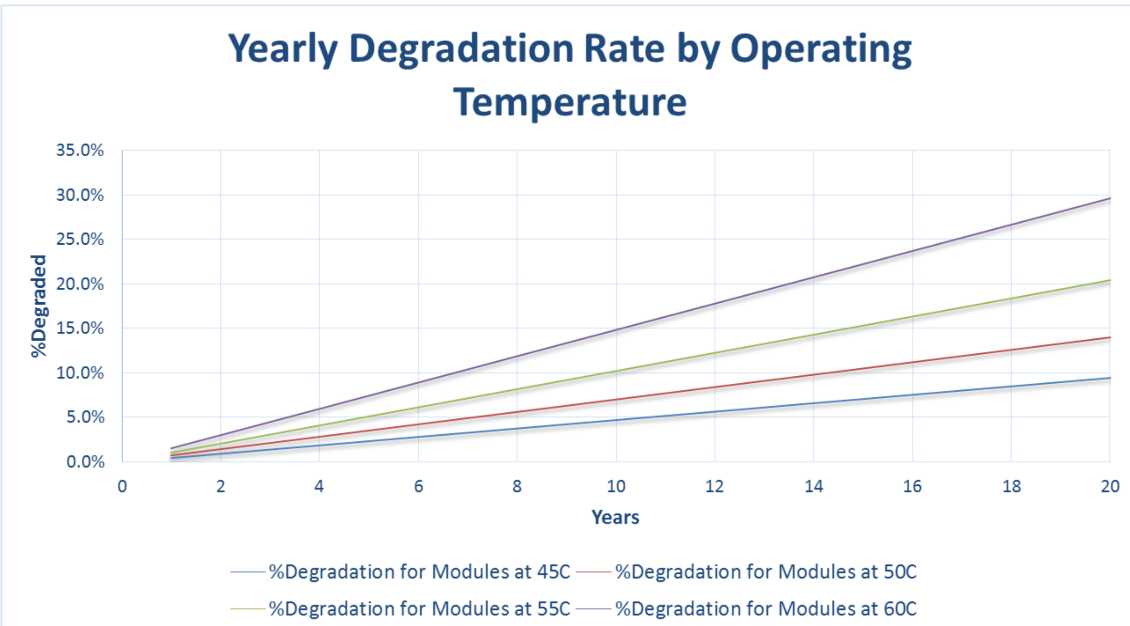

Figure 8. % degraded per year for varying operating temperatures

To properly account for the energy loss due to mismatch over the life of a system, a consideration for the thermal gradient as well as the variable degradation rate needs to be taken. The impact of variable degradation rates due to measured thermal gradients on voltage non-uniformity are shown below. Using a 10C thermal gradient, the year 1 Voltage non-uniformity is only 0.8% which results in a negligible mismatch loss of -0.003%. However, this voltage non-uniformity increases to 8% by year 10 which results in a mismatch loss of -1.8%.

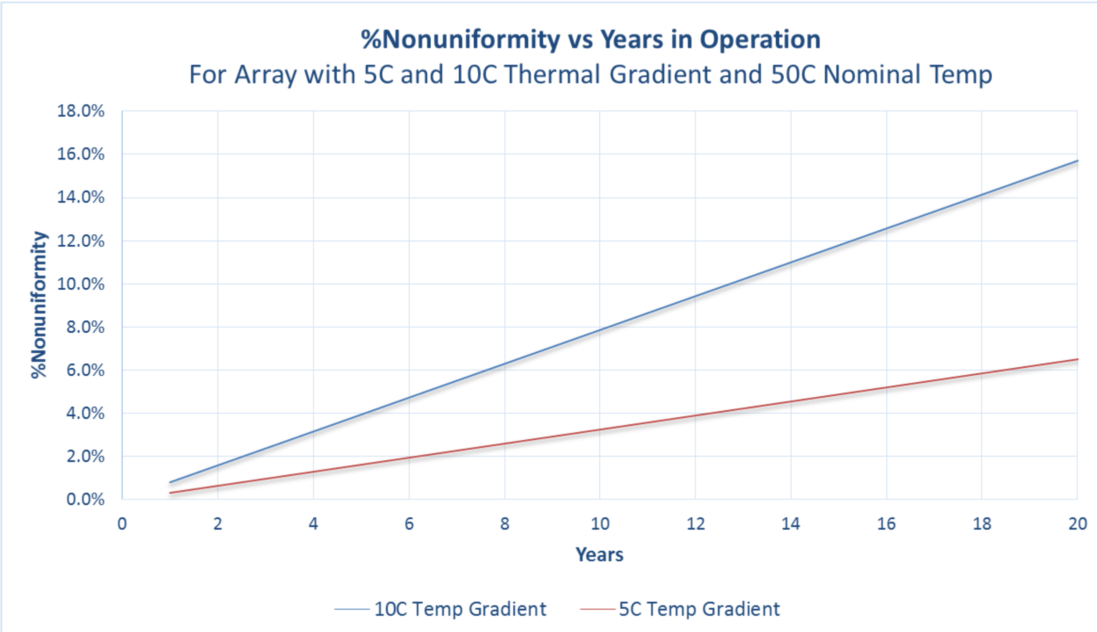

Figure 9. %Non-uniformity vs years for 10C and 5C thermal gradient

Variable degradation rates can also be inherent to the modules, although this should be quite small. The degradation rates discussed here are only those due to the compounding thermal gradients.

Summary (C): Voltage mismatch between strings caused for example by manufacturing variations, temperature gradients, and module degradation can be substantial and probably increases over time. This type of mismatch loss is completely eliminated by using string optimizers.

Discussion:

The table below summarizes the reduction in mismatch losses that can be achieved with string optimizers.

Mismatch loss type	Plausible values for total system mismatch loss	Fraction recoverable with string optimizers
(A) Isc mismatch within a string	0.2% to 4%	0%
(B) Voltage mismatch between strings caused by Isc mismatch within a string	0% to 10%	~50%
(C) Voltage mismatch between strings	0.5% to 5%	100%

It is not possible to make a universally applicable calculation of the mismatch losses in solar installations. Each installation will have its own specifics depending on module selection, array layout, string configuration, climate etc. It is, however, highly unlikely that there are no mismatch losses and that must be taken into account when doing proper PVSYST modeling. In this white paper we have shown examples of module and string non-uniformities and the resulting mismatch losses. Using plausible assumption about the system, mismatch losses can easily amount to several % of total output power and is likely to increase over time. Depending on the type of mismatch losses that are present in a system, the use of string optimizers can decrease these losses by an average of 50%.

References:

1. Trina Solar, “Module Mismatch in Commercial Arrays”

2. Peter Hacke et.al. ,Testing and Analysis for Lifetime Prediction of Crystaline Silicon PV Modules Undergoing Degradation by System Voltage Stress” 2012 IEEE Photovoltaics Specialists Conference.