# AN-2120 Power Optimizers Partial Deployment for Single String Systems

**ABSTRACT**

The SolarMagic power optimizers allow for greater flexibility when designing a photovoltaic array compared to the traditional series connected panels in a string with parallel connected strings to form an array. The default configuration for a SolarMagic assisted string is to have all of the panels connected to a SolarMagic DC/DC power optimizer (Figure 2). Assisted strings with SolarMagic are optimized for mismatches between panels and between strings, maximizing the system efficiency by re-capturing the energy that would have been lost caused by the mismatch.

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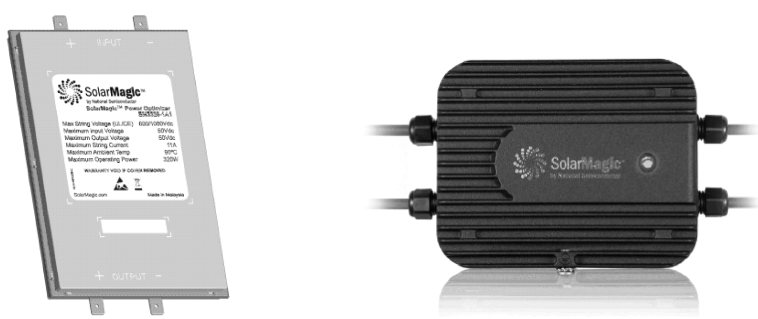
## 1 Introduction

The SolarMagic power optimizers allow for greater flexibility when designing a photovoltaic array compared to the traditional series connected panels in a string with parallel connected strings to form an array. The default configuration for a SolarMagic assisted string is to have all of the panels connected to a SolarMagic DC/DC power optimizer (Figure 2). Assisted strings with SolarMagic are optimized for mismatches between panels and between strings, maximizing the system efficiency by re-capturing the energy that would have been lost caused by the mismatch.

If you build a system which has a Central Inverter (hereinafter called “C/I”) with its own Maximum Power Point Tracking (“MPPT”) control connected with a single string which has a SolarMagic unit on each panel in the string, it’s possible that the power may not be sufficiently harvested under certain situations which would cause a voltage mismatch between strings. This is caused by the interaction between the MPPT of the C/I and the MPPT of SolarMagic. To address this, there is a configuration, as shown in Figure 3, which is a design of a single string applying SolarMagic power optimizer units partially, not on every panel, within the string. This configuration eliminates interference between MPPT controls and maximizes the array power output.

## 2 SolarMagic Power Optimizers

There are two series of SolarMagic power optimizers, the first generation SM1230 series and the second generation SM3320 series as shown in Figure 1 with the appropriate electrical specifications. Both power optimizer series of products can utilize partial string implementation as long as the string design is based on the SolarMagic power optimizer input and output specifications.



SM3320-xAx SM1230-xAx/xBX

**Figure 1. Variation of the SolarMagic Power Optimizers**

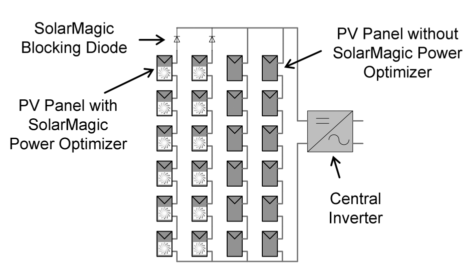



**Figure 2. Example of Basic Configuration**
**6 Panels x 4 Strings (with 2 assisted strings)**

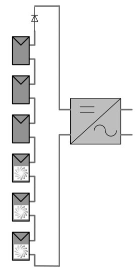


**Figure 3. Example of Single-String Configuration 6 Panels (with 3 assisted panels)**

**Table 1. Input Specifications**

| | **SM1230-xAx** | **SM1230-xBx** | **SM3320-xAx<br>xBx<br>xSx<br>xFx** |
|---|---|---|---|
| $V_{MPP}$ max | 40V | 80V | 40V<br>42V<br>50V<br>70V |
| $I_{MPP}$ max | 8.5A | 5.5A | 11A<br>9A<br>9A<br>9A |
| $V_{OC}$ max | 50V | 100V | 50V<br>80V<br>80V<br>100V |
| $I_{SC}$ range | 9.2A to 10.4A | 5.9A to 6.4A | 11A<br>9A<br>9A<br>9A |

**Table 2. Output Specifications**

| | **SM1230-xAx** | **SM1230-xBx** | **SM3320-xAx<br>xBx<br>xSx<br>xFx** |
|---|---|---|---|
| $V_{OUT}$ max | 43V | 80V | 43V<br>46V<br>53V<br>74V |
| $I_{OUT}$ max | 8.5A | 5.5A | 12.5A<br>10A<br>10A<br>10A |

## 3 Principle of Operation

The main function of SolarMagic power optimizers is distributed panel-level MPPT control. In more concrete terms, in the input stage of the power optimizer, this control always tracks the Maximum Power Point (“MPP”) of the PV panel, maximizing power generated from the solar insolation. While, on the other hand, in the output stage, the output power is kept approximately equal to the amount of power at the input stage so that the output current is adjusted to the common string current. The output voltage is also determined as a result of the power and the current.

When a string in a basic multiple-string configuration is assisted by SolarMagic power optimizers, it is recommended to install SolarMagic units on all the panels in the string in order to maximize mismatch mitigation. The power optimizers output the optimum voltage based on the output power and the common string current derived from the DC link voltage. Based on the power optimizer's ability to maintain the panel's max power over various conditions the output Power-Voltage characteristic curve of the SM1230 series maintains a relatively flat curve profile over it's operating voltage range, whereas the SM3320 will exhibit a relatively flat profile curve except for the region near the panel's MPP voltage where it will exhibit an increase in power due to the efficiency increase created by the SM3320 Panel Mode. The C/I with it's own MPPT, operating much slower, will see this flat curve characteristic and try choose a DC link voltage over thisrange. Different C/I will respond in different ways to this type of P-V curve. The SM3320, with it's panel mode of operation, offers the C/I a easier target to settle down at a given voltage.

To address this, let's configure some panels in a string to not have SolarMagic power optimizers (hereafter called "Reference panel"). Then the string current value is fixed to the output current of such Reference panel and the MPP of the entire string is fixed at the unique DC link voltage value, which MPPT of C/I can find as its MPP voltage ($V_{MPP}$). Additionally, each SolarMagic unit in the same string optimizes its own output voltage thanks to the Reference panel which fixes the string current. As a result, regardless of applying SolarMagic to some panels, it's capable to obtain utmost power output as irradiated. In terms of current-voltage (I-V) curve characteristics, when the panels with different characteristics are connected in the same string, with the SolarMagic assisted panel, the MPP of SolarMagic can move along the curve of "Pout = constant" in order to adjust the output current to the I(string). As shown in Figure 4, if one of the three panels is the Reference panel, and the others are the assisted panels, the MPP of the reference panel and I(string) is fixed. Then the MPPs of each SolarMagic assisted panel will move to the new MPP, adjusting the its output current to the common string current.

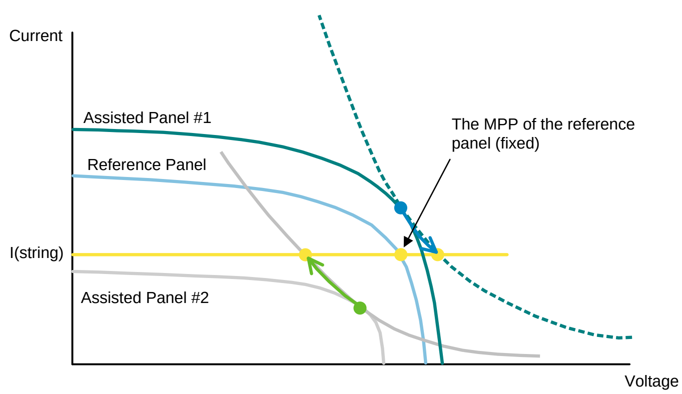



**Figure 4. Example I-V Curve of a Single String with Partial SolarMagic Units (1 reference + 2 assisted)**

## 4 General Design Rules for Single String with Partial SolarMagic System

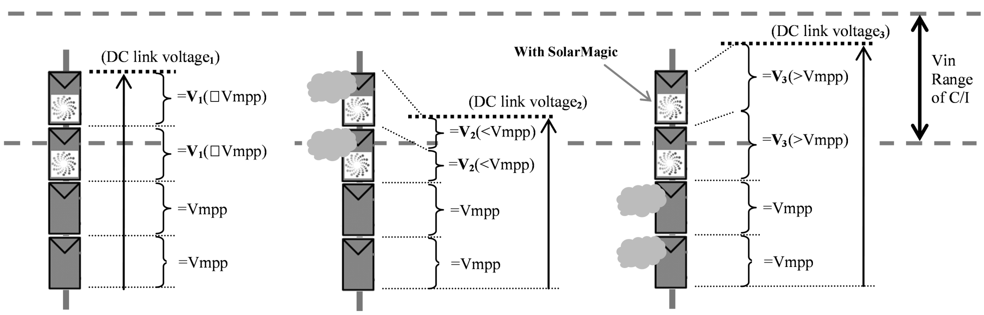
The general design assumptions are listed as follows:

1. Central MPPT is needed in the system. Fixing the DC link voltage by setting C/I is not allowed.
2. Parallel connection with other strings is not allowed.
3. Reference panel(s), which has no SolarMagic, will be needed and it's basically the most insolated panel(s) in the string.
4. The number of the Reference panel(s) and the assisted panel(s) should be determined so that the string voltage stays within the Vin range of the C/I.
5. The blocking diode is needed for the assisted string by SolarMagic.

- In the single string with partial SolarMagic implementation, the output voltage of each SolarMagic is fixed uniquely in time based on the output power from the panel and the string current detected at the output stage. As a result, the unique optimum string voltage is determined.
- If the Reference panel is the most insolated panel in the string (higher Imp), SolarMagic will buck its output voltage to increase it's output current to match the Imp of the Reference panel. The total number of panels in the string also doesn't decrease. As a result, no matter what type of power optimizer is used, the optimization for the output power can be achieved. SolarMagic also has the

capability to boost up it's output voltage as in the case when the SolarMagic assisted panels are more irradiated than the Reference panels in order to adjust the output current to the lower string current caused by the Reference panels (Figure 5). In such case, if the irradiance gap is big, the boost up range will become wider and the maximum number of panels in the string will get smaller. For example, there could be a situation when the SM1230-xAx power optimizer version, whose Vout(max) is relatively lower, cannot boost up enough to the voltage level needed to optimize the power output.

- When SolarMagic power optimizers, in MPPT mode, boosts or bucks, the voltage change of Vmpp of the panel is proportional to the irradiance difference between the assisted panels and the Reference panels. Therefore the worst case is equivalent to the condition that the irradiance difference between the assisted panels and the Reference panels are maximum. This is acceptable as long as the string voltage doesn't exceed the Vin range of the C/I even in the worst case.
- Please refer to the "Installation and Safety Manual SolarMagic™ Blocking Diode" for instructions to properly install and connect the Blocking Diode .




Note: Each cloud symbol means equally-weaker irradiance and no cloud means equally-well

**Figure 5. Consideration for the String Voltage ( 4-panel string with 2 assisted strings)**

## 5 Global Design Variables

The following variables are used in the design equations later in this document:

$T_{Amin}$ = minimum ambient temperature

$T_{Amax}$ = maximum ambient temperature

$V_{in(min)}$ = minimum input voltage of C/I

$V_{in(max)}$ = maximum input voltage of C/I

## 6 Homogenous Panels, Shaded Partially

In a homogeneous configuration, all panels have the same tilt and orientation. The main impairment of this configuration focuses on shade. The irradiance is the same for all panels in a single string with this configuration. However, certain areas of the string can be shaded. In this case, avoiding the condition that the impaired panel will limit the current for all panels in the string, a conventional system utilizes bypass diodes in each panel. However, the bypass diodes aren't the solution to maximize power. They are implemented to protect the panels from spot heating when a PV cell is severely impaired. When bypass diodes are forward biased, the power of the bypassed cells or panels is no longer contributing to the system generated power and is considered lost energy.

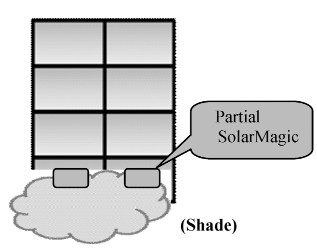



**Figure 6. Example of a 8 Panel String Partially Shaded**

On the other hand, as shown in Figure 6, applying SolarMagic power optimizer units to the impaired panels allows the string current to be maintained through the dynamic buck and boost functionality of the SolarMagic power optimizers. The output current from the impaired panels, through the use of the power optimizer, will be the same as the current of the well-irradiated panels, which will maximize the output power of the string.

### 6.1 DESIGN CONSIDERATIONS

Better irradiated panels should be the Reference panels which have no SolarMagic power optimizers. Only panels which are shaded or impaired should have SolarMagic power optimizers. The power optimizers won't boost as long as the irradiance is lower than the Reference panel. This makes it possible to capture all potential power given by the irradiation, from all panels in the string. The number of the Reference and assisted panels is determined in order not to exceed the Vin range of the C/I. It's difficult to estimate the irradiance of the shade without a pyranometer or simulation software, and the worst case condition can be different from installation to installation. We can design strings based on the rules described below, without measuring irradiance.

### 6.2 DESIGN PLAN

1. The number of Reference panels, R, is determined based on the following condition:
   - **R x $V_{mpp}$@$T_{Amax}$ > $V_{in(min)}$**
2. PV panel voltage is inversely proportional to temperature so the designer should consider the highest ambient temperature at the location where the system is installed.
3. The practical lower Vout limit of SolarMagic in MPPT mode is about 3V. So if the equality is not met then you can add 3V for each additional assisted panel until the equality is satisfied.
4. Given the following conditions for the C/I and 3 panels:

   $$\text{C/I } V_{in(min)} = 100V \quad (1)$$

   $$\text{Panel } V_{oc}@85°C = 32V \quad (2)$$

   $$32V \times 3 \text{ panels} = 96V < 100V \text{ [NG]} \quad (3)$$
5. Where NG = No Good; doesn't meet design criteria.
6. This result indicates that we need to add 2 assisted panels with SolarMagic as shown in the equation below,

   $$32V \times 3 \text{ panels} + 3V \times 2 \text{ panels} = 102V > 100V \text{ [OK]} \quad (4)$$
7. The number of assisted panels, S, is determined based on the following conditions:
   - **Z = # of all the panels in stringZ x $V_{oc}$@$T_{Amin}$< $V_{in(max)}$S = Z - R**In this configuration, the irradiance of the shaded panels is less than the Reference panels and SolarMagic won't boost. Therefore the maximum string voltage can be assumed to be the sum of Voc which will be seen while each SolarMagic starts MPPT operation and panel-mode is engaged. Everything will operate as intended as long as the string voltage is under the Vin(max) of the C/I.

## 7 Non-Homogenous Panels, (3 Different Orientations)

Also note that all of the design descriptions described in this Application Note assume installations in the northern hemisphere. For the southern hemisphere, substitute all "south" references with "north".

Even if there is no shade on any panel in the string, the difference in orientation or tilt creates a irradiance difference current mismatch between the panels within the string and causes consequential power loss. Buildings with relatively small shaped roofs, (pyramid-shape, each surface facing multi-orientations) can create situations where, although it's preferable for all the panels to face south, there may be no room for enough panels facing south as preferred and/or no other choice than to place panels facing east or west. However, connecting panels in a string with different orientations may not be an option for the installer using the typical equipment and the design may have to be disallowed.

Making a single string partially assisted with SolarMagic power optimizers can address and mitigate such problems achieving both power optimization and flexibility for installation. Such as the example shown in Figure 7(a), which has panels installed on multiple surfaces facing different orientations (south, east, and west), indicates where power optimizers have been deployed to allow for maximum energy harvest.

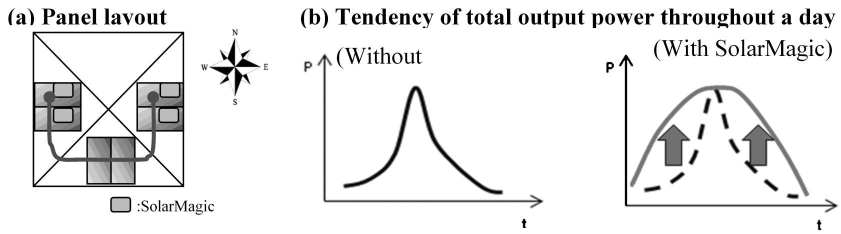



**Figure 7. Test Results**

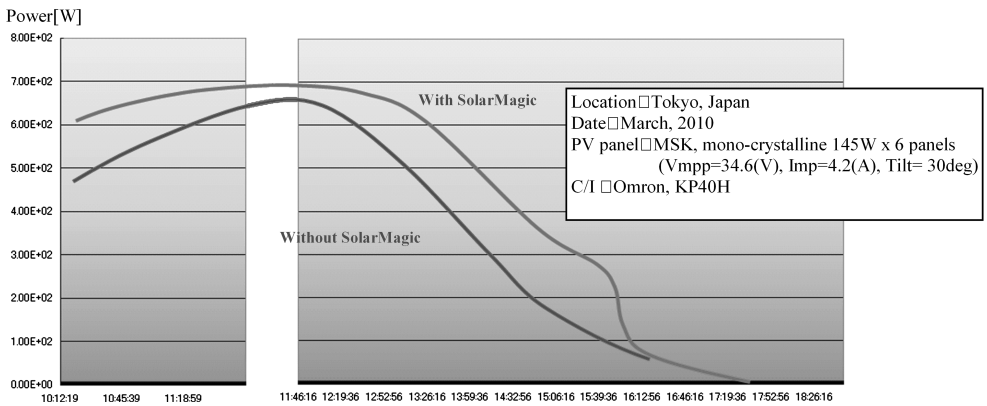



**Figure 8. Example of Single String With Panels facing 3 Different Orientations**

## 7.1 OPERATION WITHOUT SolarMagic POWER OPTIMIZERS

1. In the morning as the sun rises from the east, the panels in the string are limited by the least irradiated panels which happen to be facing west.
2. In the evening, the reverse of item 1 will occur where the panels performance is limited by the east facing panels.
3. The power of each panel is always limited by the least irradiated panel. Only at solar noon will the mismatches among the panels be at their minimum and total power output is relatively high, Figure 7(b).

## 7.2 OPERATION WITH SolarMagic POWER OPTIMIZERS

1. All the panels will be able to individually deliver as much power as dictated by the received irradiation and not limit the performance of other connected panels in the string.
2. The total output power is equal to the sum of the max power output from each panel, Figure 7(b).

Figure 8 shows an example of actual test results comparing the output power of a string with partial SolarMagic power optimizer assistance and without SolarMagic power optimizers.

## 7.3 DESIGN CONSIDERATIONS

String design for panels with different orientations, to some degree, is more complicated than a design considering only shade because the irradiance difference between the assisted panels and the Reference panels may cause the output voltage of the power optimizers to continuously change. As shown in Figure 7(a), based on the general design rule, the south panels should be the Reference panels and power optimizer units are applied to the east and west panels. In the early morning when the east panels are more irradiated than the south panels, power optimizer units on the east boosts its Vout and the power optimizer units on the west operates in buck mode decreasing its Vout. In the evening, the relation of the east and the west compared to the south reverses, and the power optimizer units on the west panels boosts, and the power optimizer units on the east operates in buck mode. It's necessary to design the string, realizing the varying panel voltages, so that the string voltage is always within the Vin range of the C/I.

### 7.4 DESIGN PLAN 1: COMPONENT SPECS

This design plan is a method to design a single string with only the electrical specifications of the panels, C/I and SolarMagic power optimizers.

1. The most irradiated panels in the string should be the Reference panels which have no SolarMagic. The panels facing south are usually the most irradiated as long as they are not shaded or not affected by some other factor.
   - The number of Reference panel, R is determined based on the following condition:

$$\mathbf{R \times V_{mpp}\ @T_{Amax} > V_{in(min)}} \tag{5}$$

2. The number of assisted panels, S, is determined based on the following conditions:
   - A = max common # of panels facing east and west
   - B = Difference of # of panels between east and west

$$\mathbf{(R+A) \times V_{oc}@T_{Amin} + B \times V_{out(max)} < V_{in(max)}} \tag{6}$$

$$\mathbf{S = 2A + B} \tag{7}$$

   - It's preferable to equalize the number of panels on both the east and west orientations whenever possible as this will minimize the shift of the string voltage throughout the day and make the ratio of buck and boost modes balanced for each power optimizer unit. If the expression "B x $V_{out(max)}$" in Equation 6 equals zero, the number of panels in the string can get large.
   - If there is a difference in the number of panels facing east and west (B>0), it's possible for S x B units to boost. This design plan does not consider irradiance or the ratio between each orientation. It's assumed the power optimizers will boost to its maximum output voltage. So it's possible that the number of panels in the string will decrease when the higher voltage version, such as SM1230-xBx (86$V_{outmax}$), is used.
   - If the power optimizer units boosts up to its $V_{outmax}$, it won't disturb the operation of the C/I. When the output voltage reaches $V_{outmax}$, it is held there even if the optimum MPP requires a higher $V_{out}$.
3. It is not recommended to include north facing panels in a single string. North panels are always less irradiated than panels on any other orientation and will force the power optimizers to always boost unreasonably. Also, the number of panels in the string may decrease and therefore decrease the maximum power from the string.

### 7.5 DESIGN PLAN 2: METHOD CONSIDERING IRRADIANCE

If the irradiance on each panel is known, you can design a single string more optimally.

1. The most irradiated panels in the string should be the Reference panels which have no SolarMagic. The panels facing south are usually the most irradiated as long as they are not shaded or not affected by some factor.
   - The number of Reference panels, R is determined based on the condition following:

$$\mathbf{R \times V_{mpp}@T_{Amax} > V_{in(min)}} \tag{8}$$

2. Regarding the east and west panels, obtain the irradiance ratio to the Reference panels (SRatio(e), SRatio(w))
   - The worst case is the situation where SolarMagic boosts and the output voltage becomes the maximum for the condition of the installation. In other words, it's when the irradiation of the east or west panel is higher than one of the south panel and the difference is largest. To obtain hourly irradiance values based on date, direction and tilt of panel, it's useful to take advantage of official databases in each country or region.
   - For example, we can use the irradiance values from a database in Japan called METPV-3 by NEDO. The following conditions apply: location = Tokyo (Japan), Tilt = 30°, Time = 8:00a.m. or 4:00p.m. on a given day in May when the irradiance on the east or west facing panels is higher than the south facing panels and the difference is maximum, as shown in Figure 9. In terms of the irradiance ratio, SRatio(e) becomes maximum in the morning and SRatio(w) becomes maximum in the evening. Therefore,

$$\text{SRatio(e)} = 2.9 / 1.6 = 1.8125 \tag{9}$$

$$\text{SRatio(w)} = 2.6 / 1.6 = 1.625 \tag{10}$$

3. Obtain the Vout of the east and west panels during the worst case, boost voltage mode**$Vout_{(e,max)} = V_{mpp} \times$ SRatio(e)$Vout_{(w,max)} = V_{mpp} \times$ SRatio(w)**

4. The number of assisted panels, S is determined based on the following conditions:A = max common # of panels on east and westB = gap of the # of panels between east and west**$Vout_{(max)}$' = greatest of $Vout_{(e,max)}$ or $Vout_{(w,max)}$(R+A) x Voc + B x $Vout_{(max)}$' < $V_{in(max)}$S = 2A + B**

It's best to consider the ambient temperature based on the season and time of day for Vmpp and Voc.

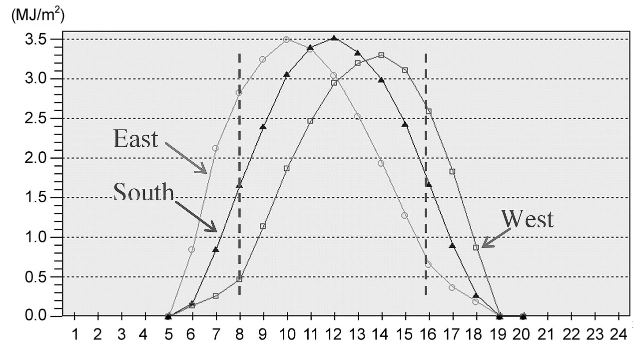



**Figure 9. Irradiance Data Example**

## 8 Other Application Examples

### *8.1 NON-HOMOGENOUS PANELS (2 ORIENTATIONS)*

Although it's not better than a 3-orientation-connection within a string, there's the possibility for a 2-orientation-connection within a string. This leads to a single string which consists of panels facing 2 different orientations, such as south and east or south and west. If the assisted panels need to boost, then all the SolarMagic units will boost and there will be no units operating in buck mode. That's why the string voltage varies throughout the day.

In the case of a single string which consists of panels facing 2 directions without south, i.e. east and west, the string voltage will have more variance. The panels facing the east and the west will always have irradiance gaps and it's larger than the gaps against the south.

#### 8.1.1 Design Considerations

The main point to consider during the design is that the assisted panels with SolarMagic might boost up very high and that there's the possibility that the optimum power output might not be delivered when the power optimizer outputs its Vout(max).

#### 8.1.2 Design Plan

1. The number of Reference panels, R, is determined based on the following condition: **R x $V_{mpp}$@$T_{Amax}$ > $V_{in(min)}$**
2. The number of assisted panels, S, is determined based on the following condition:**[R x $V_{oc}$@$T_{Amin}$ + S x Vout(max)] < $V_{in(max)}$**This is based on the assumption that SolarMagic can boost to its own maximum output voltage. So it's possible that the number of panels in the string happens to decrease when the higher voltage version of SolarMagic, such as the SM1230-xBx (Vout:86Vmax) is used.
3. It's better to make the east facing panels assisted by SolarMagic, as shown in Figure 10, for a gable roof which consists of east and west facing surfaces or a hipped roof which consists of southeast and southwest roofs, as long as the conditions in Step 1 and Step 2 above are met. This is because of the specification that SolarMagic Power Optimizer can maintain their own MPPT control as long as the string current detected in the output stage is more than 0.5A. For example, in the morning, the timing when each SolarMagic starts up MPPT operation (i.e. the string current exceeds 0.5A) won't vary no matter if the assisted panels are on the east side or the west side. However, the timing when each SolarMagic ends MPPT operation (i.e. the string current becomes lower than 0.5A) becomes later in the case of the east side assisted because the east side panels will keep higher current value thanks to SolarMagic and the string will be kept optimized for a longer period of time.

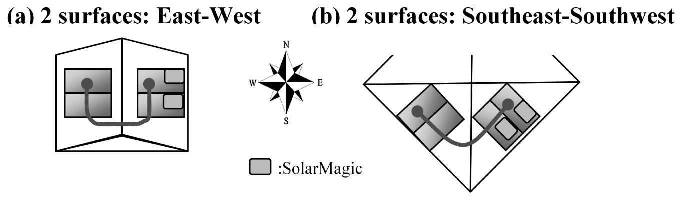



**Figure 10. Example of 2-Orientation-Surface String with Power Optimizer Units on the East Side Panels**

## *8.2 PARALLEL CONNECTION UTILIZING EXTERNAL BOOSTER*

As stated in the general design rule, it's may not be allowed for a single string to be connected with other strings in parallel due to lack of flexibility for DC link voltage. As a solution for this, with an external booster, an assisted single string can be connected with other strings which are based on basic array design rules. A booster is a DC/DC converting equipment that performs the function of boosting the shorter string voltage up to the level of the common DC link voltage used for the PV array that has string length differences between the strings, Figure 11.

### 8.2.1 Design Plan

The design plan of the single string depends on the configuration. For example, panels facing the same direction with partial shade or multiple orientations. Please see the section on relevant configuration, described above.

A booster also has its own MPPT control as well as C/I and the single string requires at least one reference panel in the string. On the other hand, the strings to be connected in parallel are not allowed to apply SolarMagic partially.

A booster also has its own Vin range and can only boost up and cannot operate in buck mode. These devices are usually also very inefficient and pricey. So check if the string voltage is within the Vin range of the C/I and less than the DC link voltage which equals the sum of Vmpp for the strings to be connected in parallel.

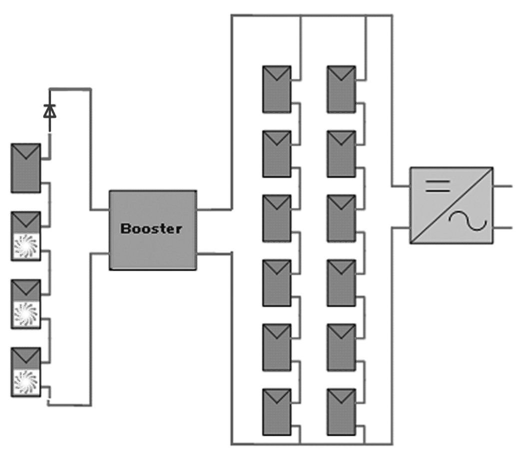



**Figure 11. Example of Parallel Connection with Booster**

## *8.3 APPLICATION FOR STRING INVERTERS*

String Inverters (Multi-String Inverters) have multiple MPPT controllers which are assigned to a single string input to avoid the mismatch losses between strings. Each string input is similar to the booster and it may not be possible to apply SolarMagic units on all the panels in the string, depending on if inverter cannot be placed into a constant voltage mode Figure 12. For this kind of inverter, SolarMagic can make it possible to optimize capturing the output power per panel and to install panels more flexibly.

### 8.3.1 Design Plan

The design plan of each single string depends on the configuration, for example panels facing the same direction with partial shade or multiple orientations. Please see the section on relevant configuration, described above.

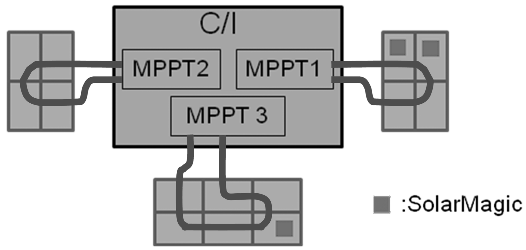



**Figure 12. Example of Application for String Inverter**

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