FRONIUS IG – Reaction to Non-Optimal Conditions

Good system design is a critical component in obtaining the maximum amount of energy (kWh) out of a PV system. However, non-optimal site conditions will often dictate that a system will lose a percentage of its typical output. These conditions fall into three general categories: shading, similar strings in parallel at different orientations, and dissimilar strings in parallel.

This paper explains the FRONIUS IG's reaction to each of the above conditions. Although module and site conditions vary, these results should be similarly exhibited in most cases with similar design issues. For most typical, non-optimal situations encountered in the field, the FRONIUS IG is able to still output within 99% of the total available energy.

Shading

Shading is an unavoidable presence on the array in many systems. It is always advisable to eliminate shading to the best of the installer's ability and avoid excessively shaded surfaces. Shading typically affects output current in a non-linear way – when a portion of a string is shaded, it often costs the PV string a great fraction of the total current and hence the total power of that string.

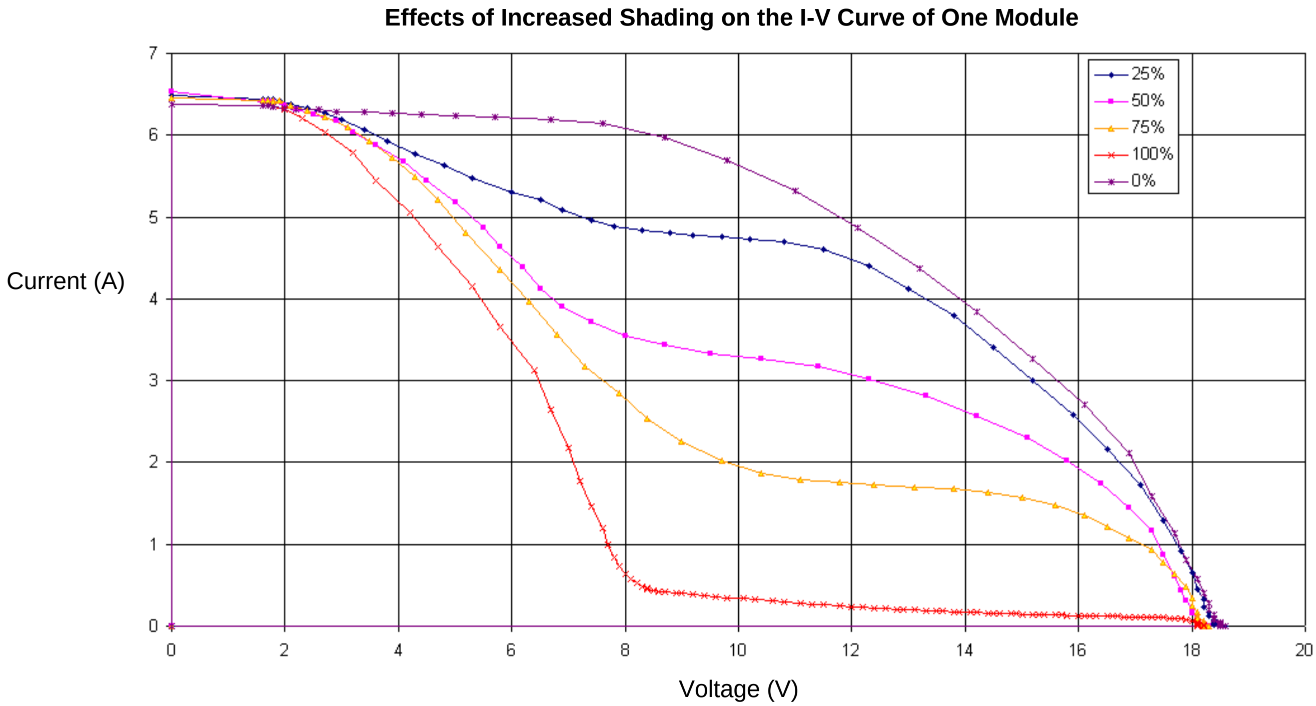
However, certain installations call for the sacrifice of output due to permanent structures or other objects just so they can be installed. In these cases, the question becomes "how big of a shading problem is there." The energy output from a PV system is worth a significant dollar value per kWh, and hence the losses due to shading must be minimized to the greatest extent possible. There are three different factors that will dictate the amount of energy lost: the extent/placement of the shading, the inverter reaction to these conditions, and the type of module.

A study was conducted at Fronius International's headquarters in Summer 2004 to establish the relationship of the first two points. The third point will not be quantified in this analysis due to the wide variety of modules and extended period required to test such a matrix. However, several relevant findings were discovered that are applicable to most arrays.

When a string becomes partially shaded, it's I-V curve becomes distorted. The current is lower for this string, and the total maximum power available also drops. The maximum attainable power from a shaded string depends on the exact I-V curve, but it is typically the case that the greatest amount of power available from a string is still achieved at or near the original, un-shaded maximum power point voltage. Therefore, shading may change the magnitude of the maximum power point and the shape of the I-

V curve, but the greatest number of Watts that can be taken from a string will usually be close to the maximum power point voltage of the unshaded string.

Figure 1: I-V curves of a module under a variety of shading conditions.



The distortion of the shaded I-V curve may cause "false" power points that can make it difficult to determine the true maximum power point for certain inverters. However, this is not the case with the FRONIUS IG. The FRONIUS IG inverter's was designed to track the "strongest", or least affected, string. The IG will find the optimum operating point of the unshaded (or least shaded) string and operate there.

Because the total power available from a shaded string is substantially lower than an unshaded one, the ramifications of operating near but not directly on the shaded string's MPP are also diminished. So, provided the inverter can operate at the MPP of the strings that are fully productive, the net effects to the total system output between operating *on* the shaded string's MPP versus operating *near* the shaded string's MPP will be minimal.

Figure 2: P-V curves of two strings, one with shading.

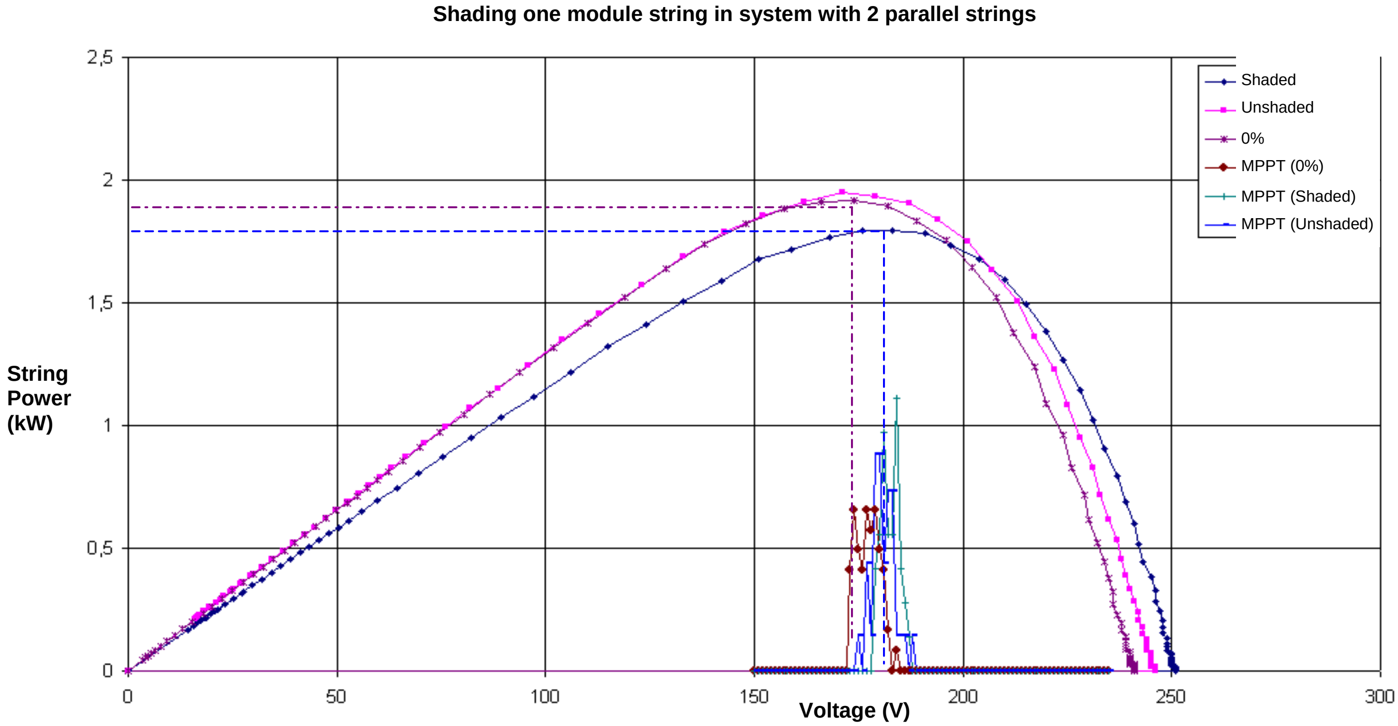


Table 1: String power and voltage of control, optimum shaded, & operating point of shaded strings.

	Power of String	Vmp of String
String 1 (optimal):	$P_{MPP} = 1900W_{DC}$	$V_{MP} = 173V_{DC}$
String 2 (optimum shaded):	$P_{MPP} = 1800W_{DC}$	$V_{MP} = 184V_{DC}$
String 2 (shaded operating):	$P_{MPP} = 1780W_{DC}$	$V_{MP} = 173V_{DC}$
$P_{Total} = P_{String\ 1} + P_{String\ 2}$ ➔	P_{Total}: $1900W_{DC} + 1800W_{DC} = 3700W_{DC}$	
$P_{Real} = P_{String\ 1} + P_{String\ 2}$ ➔	P_{Total}: $1900W_{DC} + 1780W_{DC} = 3680W_{DC}$	
Losses = P_{Real} / P_{Total} x 100 = 99.46%; 0.54% difference from optimal		

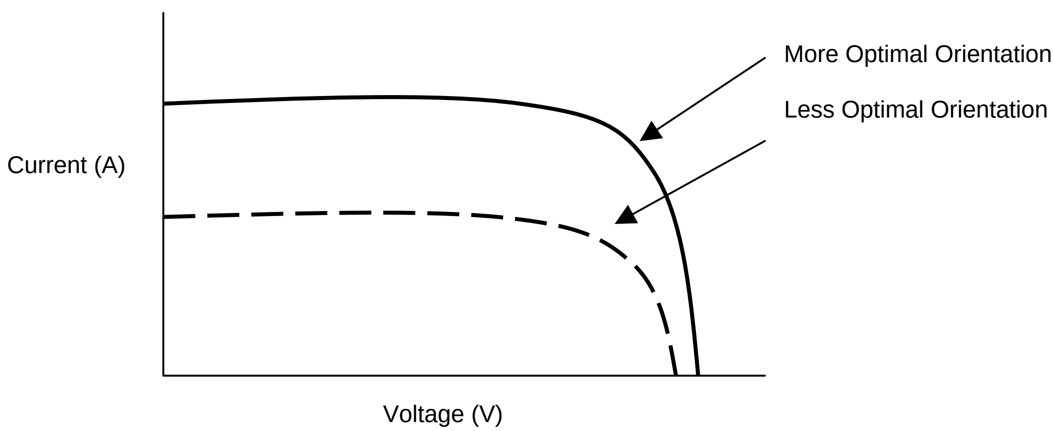
The study performed by Fronius has borne out these statements to be true. The total percentage of power lost by a string due to the shading itself far outweighs any impacts from the inverter operating the string off its MPP. Furthermore, the total percentage of this difference between the shaded string's MPP and the FRONIUS IG's operating point is under 1%. In cases where shading is likely, it is recommended that the system be designed such that shading only occurs on one string at a time while the other strings remain unshaded. This will optimize the energy output in such conditions.

Similar Strings at Dissimilar Orientations

Another problem sometimes encountered in the field is finding the appropriate amount of roof space facing one direction. In cases such as these, the array must be broken up into two or more sub-arrays. This presents a similar set of challenges for an inverter's MPP algorithm as the shading issue described above – if the I-V curves of two different strings going to the same inverter have different I-V curves, the inverter's algorithm again is tasked with discerning the appropriate point at which it should operate.

However, this case is different from the above in that the voltage and current will be impacted in somewhat different ways. Whereas the shaded string would exhibit a non-standard I-V curve shape, the strings in indirect sunlight will simply have proportionally-lower current values with only slightly lower voltage values.

Figure 3: Qualitative graph showing I-V curves of two similar strings facing in different directions.



Although the current (and hence, the power) is significantly lower from the string with the less-direct sunlight, the voltage is not as adversely affected. Even indirect sunlight will allow a PV module (or string) to achieve substantially high voltages.

As a result, tracking the strongest string allows the FRONIUS IG to optimize the total power out of this type of array as well. Since the MPP voltages of the string in direct sunlight and in less direct sunlight are largely similar, there is once again a very small difference in the net impact on power output.

Studies show that the percentage of total power lost as a result of operating on the MPP of the directly-lit string but off the MPP voltage of the weaker string is approximately 1% for crystalline silicon module. This effect would be even smaller for thin-film materials since the maximum power point is not as well-defined, meaning the difference in power at different operating points is even smaller than for crystalline silicon.

This data was based on the I-V curves of a system containing modules with the following parameters:

Table 2: Sample module's specifications.

Parameters at STC	Value
Maximum Power	85W
Voc	22.1V
Vmpp	18.0V
Isc	5.0A
Impp	4.72A

For a FRONIUS IG 3000, one optimum configuration for a system with this module is two parallel strings of 16 series modules. In this example, we take one string to be at a different angle. The net effect of this is a drop in direct irradiance relative to the optimally-oriented string. The larger the disparity in orientation and tilt angles from one another, the larger the possible relative difference in irradiance on the array is. In the case below, we have examined the string values and

Tables 3 & 4: Data on performance of system with one string at optimal orientation and one at non-optimal orientation.

Irradiance (W/m^2)	Power of Optimally Oriented String (W)	Power of Non-Optimally Oriented String Operating at its own Vmpp (W)	Power of Non-Optimally Oriented String Operating at Vmpp of Optimal String (W)
1000	1103	1103	1103
900	X	1010	1006
800	X	911	904
700	X	810	799
600	X	703	689
500	X	590	576
400	X	475	461
300	X	357	346
200	X	235	230

Irradiance (W/m^2)	Total of Optimum String & Non-Optimum Sting: Each at Their Own Vmpp	Total of Optimum String & Non-Optimum Sting: Both at Vmpp of Optimum String	Difference Due to Vmpp (W)	Difference Due to Vmpp (%)
1000*	2206	2206	0	0.0%
900	2113	2109	4	0.2%
800	2014	2007	7	0.4%
700	1913	1902	11	0.6%
600	1806	1792	13	0.7%
500	1693	1679	14	0.9%
400	1578	1564	14	0.9%
300	1460	1449	11	0.7%
200	1338	1333	5	0.4%

** This case is similar to 2 strings in the same optimal plane; as the second string is moved to subsequently less optimal orientations, the first string continues to output 1103W while the second string outputs less.*

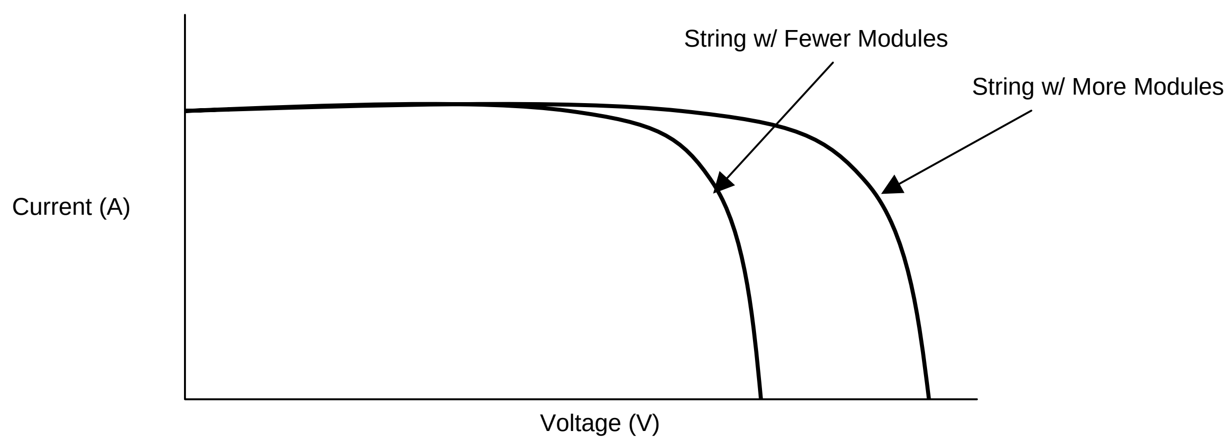
As can be seen from the above charts, the larger difference in output is the difference in orientations itself – not the difference in operating voltage. This low difference is the result of the string that is in indirect sunlight naturally outputting substantially less power, so the total power loss achieved by operating near but not exactly on the less-directly luminated sting's MPP is a relatively trivial value. The optimally-oriented string is still outputting 1103W, but as the sun becomes increasingly indirect (or the roof face is turned farther from optimum), the non-optimum string outputs less and less. But since the Vmpp is still extremely close between the two strings, there is very little difference (< 1%) between the best this system could do if the strings were each operating at their own optimum Vmpps and what it can do when operating at the optimum string's Vmpp only.

Dissimilar Stings in Parallel

As stated above, the FRONIUS IG's MPP Tracking algorithm is designed to follow the most optimum string's I-V curve. As a result, the FRONIUS IG is not as well suited to paralleling multiple strings of different module types or different numbers of modules between strings.

Adding additional modules of the same rating to a string increases the string's voltage while maintaining the same current level.

Figure 4: Qualitative graph showing I-V curves of two dissimilar strings.



Therefore, as the larger string's voltage goes up, the Vmpp of that string does as well. And as the Vmpp increases, it gets increasingly farther from the Vmpp of the smaller string. In cases with a one module disparity between strings, the system will work but the larger strings will operate off their Vmpp by the value of that extra module's Vmpp. The total power of two parallel strings is the point-by-point addition of the individual power of each string at each voltage. Therefore, the total maximum power point will be close to the MPP of the string with fewer modules. The total power output difference will be roughly equivalent to the value of the extra module, and therefore there is no net advantage by adding it. In cases where the strings are imbalanced by more than one module, the Vmpps between the two strings will drift farther and farther apart, having an increasingly negative impact on the value of those modules. Therefore, in cases with imbalanced arrays, it is often advisable to use multiple smaller FRONIUS IG units as opposed to a single larger unit.

Conclusions

The FRONIUS IG has been designed and modified over the last decade to optimize the total amount of both power and energy from your system. The MPP tracking algorithm was specifically designed to track the optimum strings in cases of shading and dissimilarly oriented strings. In these cases, the FRONIUS IG is an optimum choice. In situations that call for strings of different module types in parallel or different numbers of modules in each string, multiple smaller units are required such that the strings can be brought back into balance.

Though it is strongly encouraged for system designers and installers to avoid shading as much as possible, the net effects of using the FRONIUS IG inverter with a shaded array versus two separate units or a unit with separate MPP tracking functions is minimal – in sum, under 1%. Furthermore, when taking into account the inherent inefficiencies of operating multiple power conversion devices (whether they are integrated into a multi-MPP tracking unit or not), the FRONIUS IG's industry-leading thermal performance, and its consistently-high DC-AC conversion efficiency, the FRONIUS IG will continue to outperform other inverters in situations that involve shaded arrays or similar strings at different angles.