Photovoltaic String Inverters and Shade-Tolerant Maximum Power Point Tracking: Toward Optimal Harvest Efficiency and Maximum ROI

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Summary

Executive summary

An ability to harvest the maximum amount of energy from a photovoltaic (PV) array is one of a small number of critical features a PV inverter can offer to help optimize return on a PV system investment (ROI).

Historically, dynamic maximum power point tracking (MPPT) of the singular power peaks common to homogenously irradiated PV arrays and modules has provided adequate PV harvest performance for the marketplace. However, growing trends toward urban and rooftop PV installations are increasing the occurrence of partial array shading. In urban environments, array shade originating from chimneys, roof vents, power lines, trees, neighbouring buildings, and other obstructions is often unavoidable.

Various PV module-based micro-inverter technologies offering solutions to shaded PV arrays are beginning to appear in the market. These technologies claim increased PV array harvest efficiency based on the generalization that module-based MPPT allows a superior PV energy harvest as compared to string-based MPPT. Some products even claim a universal 5-25% increase in PV energy yield.

Unfortunately, informed technical discussions regarding the performance of shaded PV arrays are difficult due to the complicated nature of how PV modules operate and the infinite variety of shade conditions possible.

This white paper attempts to shed technical light on the fundamental principles of how shade affects PV modules and PV arrays. It specifically illustrates how Schneider Electric's new Conext™ grid-tied inverters with Fast Sweep™ shade-tolerant string-based MPPT can assist in harvesting maximum energy from shaded arrays. It is also shown that in many cases string-based MPPT from central inverters can result in better harvest efficiency than module-based micro-inverter MPPT.

Introduction

The core function of today's photovoltaic (PV) inverter is to harvest direct current (DC) electric energy from a solar PV array, convert it to useful alternating current (AC), and inject the harvested solar electricity into an AC power grid. PV inverters are a small but critical part of a larger investment in a PV energy generation system consisting of PV modules, module racking, inverter(s), interconnect hardware, and other equipment.

The lifetime goal of any grid-connected PV energy generation system is simple: to maximize the return on investment (ROI) by generating the largest amount of electric energy (kWh) for the least amount of financial outlay.

PV inverters can support the maximization of PV system ROI by optimizing four key characteristics:

1. Reliability/Bankability/Compliance: Regulatory compliant, safe and consistently reliable operation helps increase ROI

2. Price: Lower PV system capital cost helps increase ROI

3. High Conversion Efficiency: Not wasting power within the inverter helps increase ROI

4. High Harvest Efficiency: Ability to extract the maximum amount power available from the PV array helps increase ROI.

The first three characteristics are relatively easy to define and comprehend. However, an understanding of **harvest efficiency** requires a first-principles understanding of the PV system itself – specifically with respect to a PV array's I-V curve characteristics and the effect shading has on the I-V curve.

The goal of this white paper is to clearly demonstrate how Schneider Electric's new string-based MPPT products can help maximize PV system ROI by managing the PV array harvest in a shade-tolerant and harvest-efficient manner.

This paper also illustrates how module-based MPPT (e.g., micro-inverters) can result in less harvest efficiency than Schneider Electric's string-based shade-tolerant maximum power point tracking (MPPT) technology in many common situations of shade.

Toward Optimal Harvest Efficiency and Maximum ROI

The Problem: Shade is Happening!

Partially shaded arrays can introduce significant challenges when optimizing harvest efficiency

Urban PV arrays often experience partial shading that reduces the electric power available. Exactly how much power is lost depends on the resulting array's I-V characteristics and how efficient the PV inverter architecture and control is at harvesting this energy. A problem to consider is that the resultant I-V curves of shaded PV modules and arrays introduce new challenges for inverters to optimize harvest efficiency. (For I-V curve basics please see Appendix 1.)

Problem Details: Shaded Array I-V Curve Characteristics

Perhaps the best way to illustrate the challenges of PV array shade is to discuss a specific example. The following example examines the resulting I-V curve of shaded, partially shaded and non-shaded PV modules in series.

The shaded array example of figure 1 shows three uniformly shaded modules, three partially shaded modules and six non-shaded modules. It's sometimes thought that a small amount of partial array shade restricts the whole array disproportionally, and that just a few shaded modules or cells can cause a "Christmas light effect" (when one light goes out they all go out). This limits the current and power output of the entire array. It's also thought that performing MPPT at the module level rather than the series string level mitigates this effect. However, this isn't necessarily true (see further discussion on the following page).

The most informative way to understand how much power is available from a shaded array is to examine its I-V curve. The series string I-V curve of the figure 1 example is presented in figure 2. Figure 2 illustrates full current from the 24 non-shaded module sections (three sections per module), approximately 50% current from the one module section with no more than partial shading on any cell and, finally, the approximately 17% current from the 11 module sections that have at least one series cell restricted at 17% shade. (See Appendix 1 for I-V curve basics.)

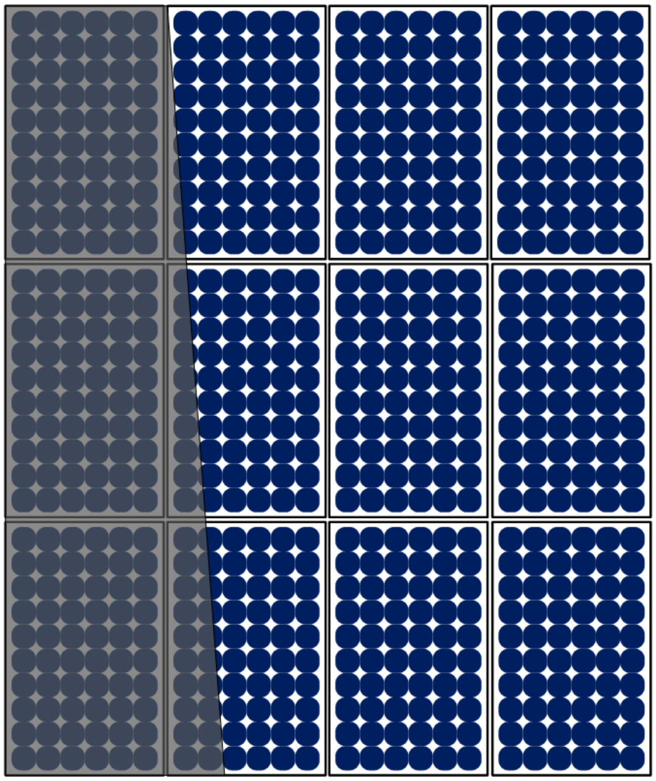


Figure 1
Shaded Array Example

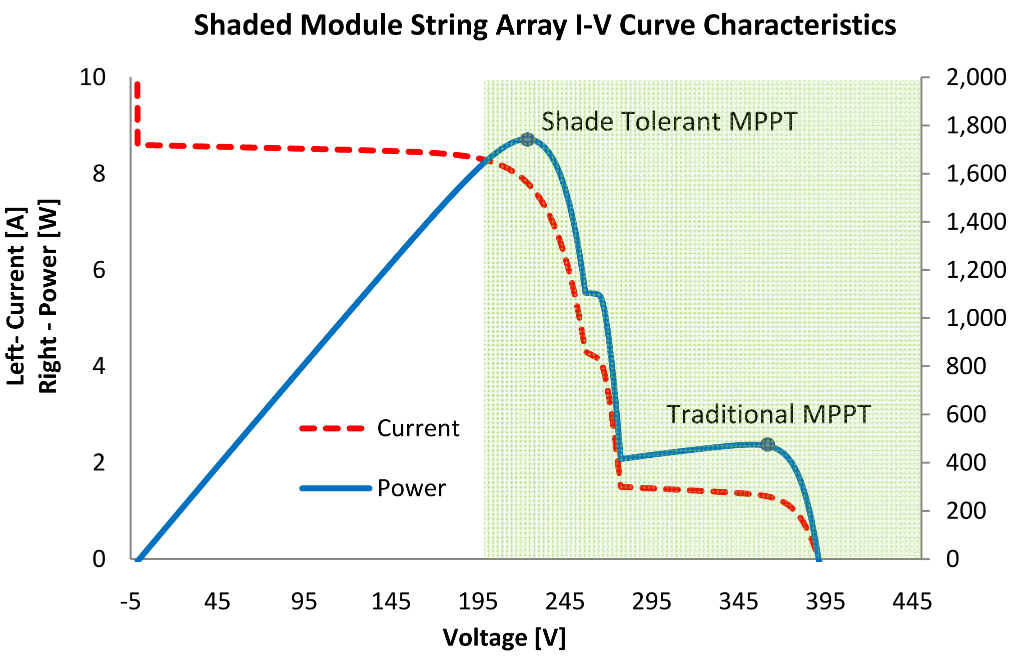


Figure 2
Shaded Array String I-V curve

Figure 2 shows the power available in the shaded array example. The maximum array power is available for harvest at approximately 1700W at 220V. However, there is another localized power maximum at approximately 475W at 360V. A problem with this kind of shaded array I-V curve is that many traditional string inverters on the market may track the 475W localized maximum power "bump" on the right-hand side and not the global maximum of 1700W available at a lower voltage.

Operating at 360V also illustrates the Christmas light effect. If the inverter is forced to operate at 360V then this effect occurs where shading a small amount of the array will limit the current for the whole array. However, if the inverter operates at a lower voltage the effect can be avoided as the shaded module sections are bypassed and the remaining array is allowed to operate at full current. Because of this, inverter operation at 220V is significantly more tolerant of the shaded array condition than at 360V.

Traditionally, non-shade-tolerant string-based maximum power point tracking has been acceptable since most PV arrays are homogenously irradiated most of the time. In fact, depending on how the shade evolves, the MPPT algorithm of the inverter may not get stuck on the right-hand bump. However, as technology progresses and more systems are being installed in urban situations, and increased emphasis is placed on system ROI, MPPT performance and harvest efficiency are becoming more important to customers; specifically for PV arrays that experience intermittent partial shading.

Inverter operation at 220V is significantly more tolerant of the shaded array condition than at 360V

Problem Solutions: Shade-Tolerant MPPT

Shade-Tolerant String Inverter MPPT

The shade-tolerant solution for string inverters lies within the string inverter's MPPT tracking algorithm. The MPPT algorithm must take into account the entire MPPT voltage window in order to act on the presence of a global maximum. However, each time the MPPT control algorithm moves away from a local maximum power point to look for global maxima it is at some expense of the static MPPT harvest efficiency. Furthermore, if the entire MPPT voltage window isn't searched often enough, relatively rapid changes in shade may be missed.

Schneider Electric's proprietary shade-tolerant Fast Sweep™ string inverter MPPT technology allows for tracking of dynamically changing global power peaks with no significant decrease in traditional static and dynamic tracking and harvest efficiency. Part of the shade-tolerant solution is an ability to frequently scan the array I-V curve in a very short amount of time. Schneider Electric's Fast Sweep™ MPPT technology maintains industry-leading static and dynamic harvest efficiency over a wide range of shaded and non shaded I-V and I-P curve scenarios, thus helping optimize PV system ROI.

Shade-Tolerant Micro-Inverter MPPT

Another shade-tolerant solution approach is to perform MPPT at the module level with micro-inverters. The general argument in favour of the shade-tolerant micro-inverter MPPT is that performing MPPT at the module level will yield superior harvest efficiency as compared to performing MPPT at the string-level – especially for shaded PV arrays suffering from the Christmas light effect. This argument is based on the idea that shade and debris create unique maximum power operating voltages and/or currents for each module, and that module-based MPPT allows each module to be operated at its unique maximum power point. The assumption is that module-based MPPT inherently improves harvest efficiency and therefore PV energy yield, and that enough extra energy will be harvested to justify the premium cost for module-based MPPT technology, which then increases the overall system ROI.

The argument for superior module-based MPPT harvest efficiency appears sound, for the most part, if the modules are shaded evenly. A major caveat, however, is that this is rarely the case.

When discussing shaded PV, partial module shade can't be ignored. It's virtually impossible to find a PV array that experiences only even shade on each module. The sun is constantly moving in the sky and shadows are dynamic. Even modules soiled with dirt and debris aren't often soiled in a homogenous way. For these reasons it is necessary to further examine the I-V curve characteristics of a partially shaded module. The effects of partial module shade on the module's I-V curve can be understood by considering individual module sub-sections (see Appendix 1 for details).

Notes on Partial Module Shade

Figure 3 illustrates the resulting I-V curve of a top-selling 60 cell silicon-based PV module with corner shading of 15%. Again, distinct global and local power maxima can be observed due to the bypassed module section (It appears that the micro inverter also needs to be shade-tolerant of global and local

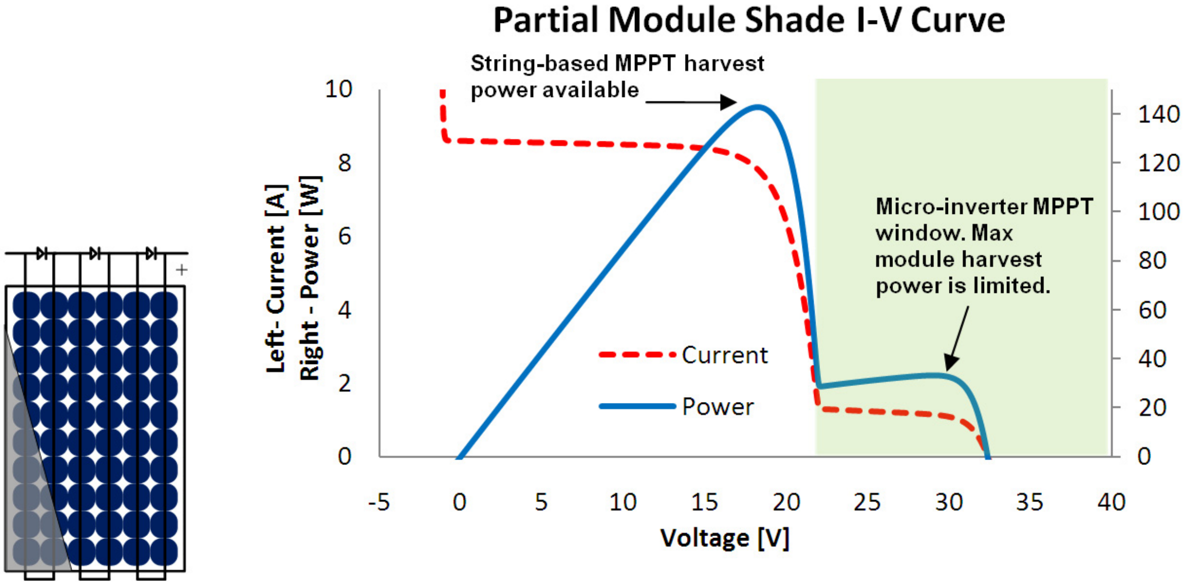


Figure 3
Shading on one sub-module string where shaded irradiance is approximately 150W/m^2 and non shaded irradiance is approximately 1000W/m^2

maximum power bumps). However, upon closer examination, the micro- inverter's ability to harvest I-V curve energy is also inherently limited by its MPPT voltage window.

Micro-inverter designers have to make compromises on MPPT voltage windows to carefully balance efficiency and cost. Lower and wider voltage MPPT windows tend toward higher cost and/or less efficient designs. Manufacturers presumably have been forced to make design trade-offs sacrificing lower MPPT range for gains in the more noticeable efficiency, cost and maximum Voc metrics.

For example, if we assume a micro inverter MPPT window low voltage limit of 22V, we can see how the micro-inverter will have difficulty operating the I-V curve example of figure 3 at maximum power. In this example, the lower limit of the MPPT window prevents the micro-inverter from being able to operate at the Vmp of this slightly shaded module. This significantly compromises harvest efficiency.

Conversely, a string inverter with shade-tolerant MPPT technology has a much better ability to operate at the true Vmp due to the extra range and flexibility of the string inverter's MPPT voltage window.

Figure 4 illustrates how the so-called "leaf problem" affects the I-V curve of the PV module. The leaf effectively blocks one module section completely and the resulting I-V curve is formed by the I-V characteristics of the remaining two module sections. Again, a MPPT voltage window of 22V will have trouble harvesting any of the approximately 150 available watts.

It's now possible to understand a significant challenge micro-inverters can have with common partial module shading conditions. Furthermore, even if micro-inverter MPPT windows were designed to go well below the sub-module section voltages – how would one know if they were engineered to be multi-maxima shade tolerant of partial module shading?

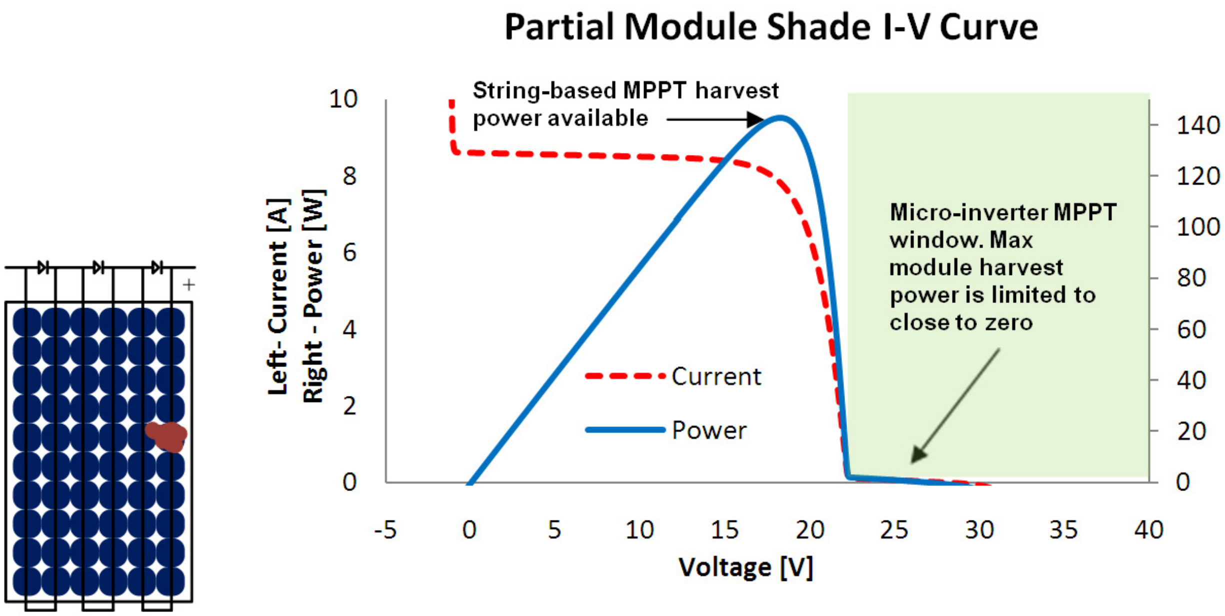


Figure 4
Single cell opaque shade from a leaf or other material where non-shaded irradiance is approximately 1000W/m^2

Micro-inverters specify limited MPPT windows that may be too narrow to operate many 60 cell or less (or hot 72 cell) PV modules at the maximum power voltage (Vmp) under common partial module shading conditions. Lower-cost shade-tolerant MPPT enabled string inverters are inherently superior at managing these common conditions and can provide a higher ROI for PV generator systems.

Solution Comparison

Shade-Tolerant Comparison: String Inverter vs. Micro-Inverter Energy Harvest

While it's possible to engineer examples of shaded arrays that optimize the benefits of micro-inverter technology, it's also possible to do the same with shade-tolerant string inverters. There will always be specific circumstances where each technology or approach will yield superior results. The reference example of figure 1 wasn't selected as the best case for string inverters, but rather to include full module shade where module-based MPPT technologies work very well compared to string inverters.

As a final exercise, we can examine the power each approach can harvest from the shaded array example of figure 1. The results for traditional string inverter, micro-inverter and shade-tolerant string inverter are found in figure 5.

When operating with traditional non-shade tolerant string-based MPPT the string is operated at about 360V and 1.3A. Each module is operated at 1.3A and the individual module powers can be determined by looking at the I-V curve of each module. We can see that the increasingly shaded modules make a lesser power contribution. Total power harvested at the right-hand-side power maximum is 475W.

The micro-inverter architecture harvested power is the maximum power available within the micro-inverter allowable MPPT window of the I-V curve for each PV module. Note the shaded modules all contribute some amount of power, but the partially shaded modules must operate above their 22V MPPT window which does not permit maximum module power harvest. The total micro-inverter energy harvest of 1599W is significantly higher than the 475W of the non-shade-tolerant string inverter.

	Traditional String-based MPPT				Micro-Inverter / Module-based MPPT				Shade-Tolerant String-based MPPT			
Individual Module Operating Point Power (W)	28	45	45	45	30	120	219	219	-9	139	219	219
	28	39	45	45	30	39	219	219	-9	139	219	219
	28	39	45	45	30	39	219	219	-9	139	219	219
Total Harvested Power (W)	475				1599				1702			

Figure 5
Power Available From the Shaded Array Example

The shade-tolerant string inverter operates at the global maximum power voltage (Vmp) of approximately 220V and at full current of the un-shaded module sections. The means that each partially shaded module section is bypassed allowing each other module section to operate at full current. The flexibility of the string-based MPPT window allows a significant number of module sections, in any location, to be bypassed before the Vmp is lower than the string inverter's MPPT window limit. This means the three completely shaded modules have -9W output due to forward biased bypass diode heating and the remaining three modules, each with 1 of 3 substrings now bypassed, operate at approximately 2/3 of the non-shaded power. In this situation of shade, the total power output of the shade-tolerant string inverter is actually higher than the micro-inverter approach.

The main difference between the two approaches is that micro-inverters are good at harvesting the 30W from the fully shaded modules but not at harvesting the available energy from the partially shaded modules. Conversely, the string inverter is not good at harvesting any energy from the fully shaded module sections but is much better at harvesting energy from the un-shaded module sections of the partially shaded modules. Considering the amount of partial module shade appearing in the field, this is a point worth understanding.

Conclusion

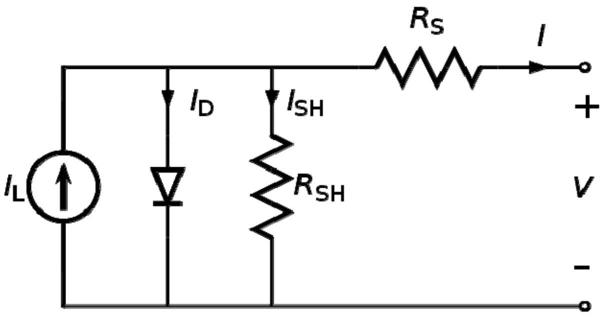
Shade-tolerant string inverters:

This white paper has discussed the harvest efficiency challenges of partial PV array shading. Schneider Electric's shade-tolerant string inverter approach is shown to solve some of the challenges faced when obtaining maximum harvest efficiency of shaded module arrays with local maximum power "bumps" on their I-V curves. This paper has shown in a conservatively shaded array example that more shaded array energy harvest is possible with a shade-tolerant string inverter as compared to a micro-inverter. This example demonstrates that micro inverters don't necessarily provide better harvest efficiency or energy yield in all situations of shade.

Schneider Electric's Conext™ grid-tied inverters with Fast Sweep™ MPPT technology provide a shade-tolerant solution from a provider you can trust.

Appendix 1: Fundamentals of Harvesting Electric Energy from Photovoltaic (PV) Modules — I-V and P-V Curves

A basic understanding of how PV module technology operates is necessary to have an informed conversation about PV array shading and harvest optimization. This section reviews the characteristic electrical behavior of a PV module. To illustrate the key concepts we first start with the PV cell, then combine PV cells to form sub-module sections and finally show the electrical behavior of a complete PV module. It should be noted that the following applies specifically to market-leading crystalline silicon PV technology. Other PV technologies may vary slightly in their behavior.



$$I = I_L - I_0 \left\{ \exp\left[\frac{q(V + IR_S)}{nkT} \right] - 1 \right\} - \frac{V + IR_S}{R_{SH}}.$$

Figure A1
PV Cell Model

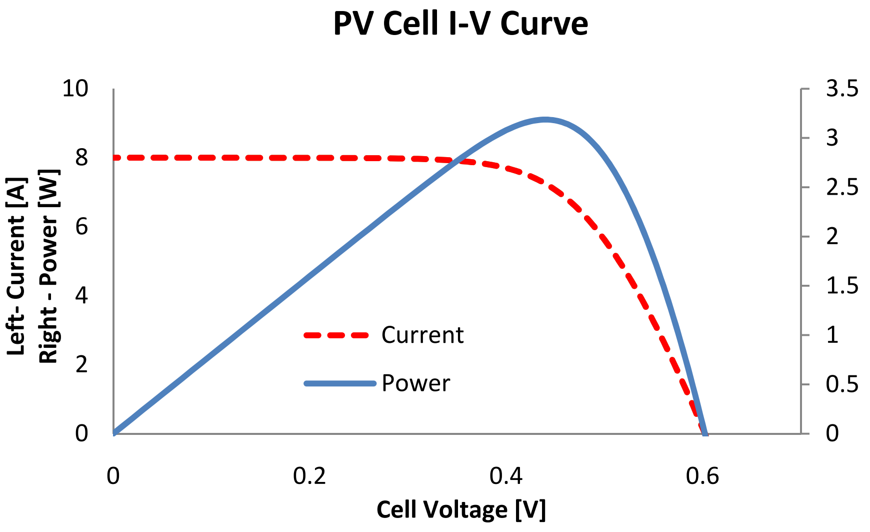


Figure A2
PV Cell I-V Curve

The PV Cell

The PV cell is the core building block of larger PV arrays ranging from a few watts to hundreds of megawatts. The electrical characteristics of a PV cell can be approximated by the simplified electrical model of figure 1. The equation presented defines the key relationship between PV cell voltage (V) and current (I). This I-V relationship is the also basis of all issues related to harvest efficiency. The relationship between cell voltage (V) and cell power (P) can also be illustrated by plotting the relationship of V and I*V = thus creating the I-P curve. The I-P curve clearly shows a singular maximum power peak of a PV occurring at what we can define as the maximum power operating voltage, Vmp.

Achieving 100% PV array harvest efficiency is solved, ideally, by insuring that each PV cell operates continuously at its maximum power-generating voltage.

Series Cell Module Section with Bypass Diode

Generating electrical power at approximately 0.5V is not very practical. In order to generate useful voltages, cells are connected together in series. However, series cells introduce a new problem of imposing significant voltage across a cell with less ability to generate current. If series cells form a circuit and one cell is shaded (the current source of figure 1 is reduced) then the series voltage of the remaining cells can appear across the shaded cell. Depending on the voltage this may cause destructive heating in the shunt resistance, Rsh, of the cell. To solve this problem, bypass diodes are installed across a limited number of series cells to control the maximum voltage and thermal damage to a shaded cell. We will see later that bypass diodes also play a critical role in allowing shade-tolerant operation of partially shaded PV modules and PV arrays.

Figure A3 illustrates the relationship between 20 series cells (a common number) and a bypass diode. The voltages of the cells add together and create the same I-V shape as figure 2 only at 20 times the voltage. The other defining characteristic of the module section is the effect of an approximately 0.4V Schottky bypass diode on the I-V curve relationship. The bypass diode prevents any significant reverse voltage from appearing across the module section and also limits the reverse voltage seen by any shaded cell within the section. We will see later that the bypass diode allows for maximum array currents to be shunted by a shaded module section(s) thus creating the multi-maxima I-P curves characteristic of partial PV module and PV array shading.

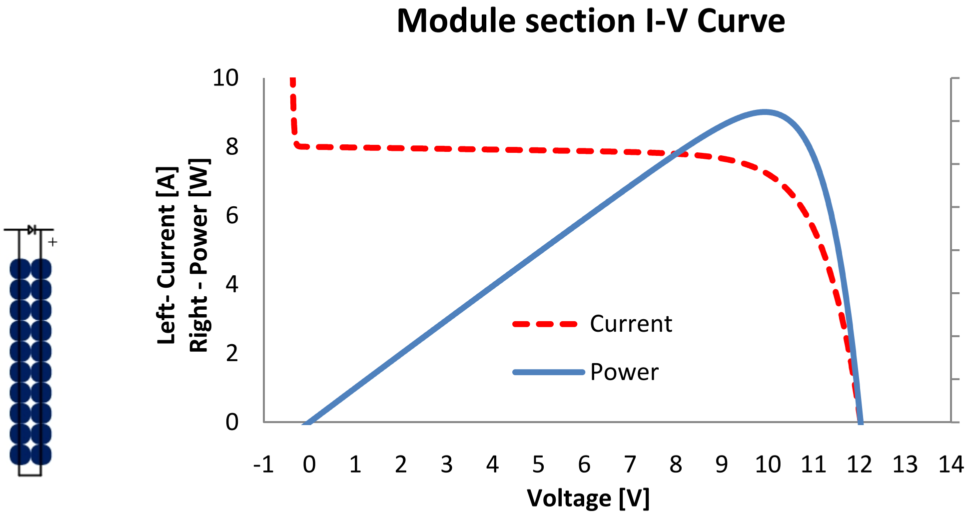


Figure A3
Module Section I-V curve with bypass diode

Complete PV Module

A complete PV module is comprised of a number of module sections connected in series. A common wiring configuration is for module sections to be long or “portrait” pairs of cells. This has to do with the electrical interconnections on each cell requiring a linear layout and where right angle corner-turning connections are located at the top and bottom of the module.

Again, in this example the I-V curve is now 60 times the voltage of the PV cell and requires 0.4V x 3 volts to forward bias the three series bypass diodes. The I-V curve has the same overall shape and qualities as the individual PV cell plus the added behavior of the thee bypass diodes.

This is also the curve data that manufacturers use to describe their modules. Any reputable PV module will include the following four data points at the standard test conditions (STC: G = 1000W/m^2, module temp, T = 25C):

1. Short Circuit Current (Isc)
2. Open circuit voltage (Voc)
3. Max Power Voltage (Vmp)
4. Max Power Current (Imp)

Manufacturers don’t tend to detail the placement of bypass diodes within their modules. However, it is very common to find the cell and diode architectures of figure A4. Sub-module information can be useful, if not necessary, to insure an optimal layout of PV array designs.

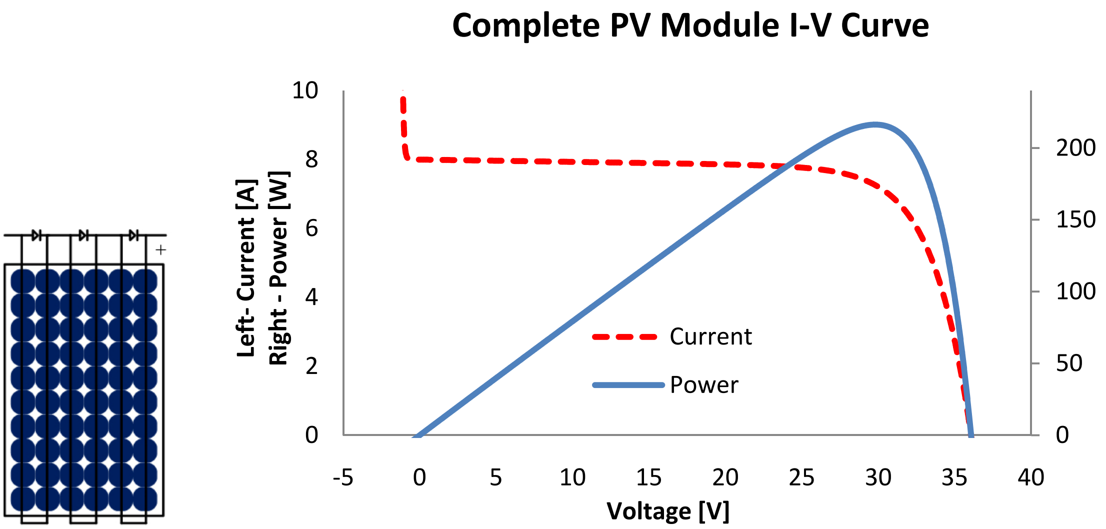


Figure A4
Complete PV Module Curve with Bypass Diodes

IV Curve Behavior

The characteristic I-V curve of any PV cell is influenced by two main external factors: solar irradiance and cell temperature.

The PV cell current source, IL, of the equation within figure A1 is directly proportional to the solar irradiance, G, to which the cell is exposed. The value of IL varies with the position/angle of the sun, clouds passing, dirt, shade and so on.

To illustrate the effect of varying IL has on the I-V curve, figure A5 has been developed using the PV cell equation of figure A1 to represent a homogenously solar irradiated 60 cell PV module. Figure A5 is based on module data for a top-selling Sharp 235W 60 cell panel. The top I-V curve shows the module characteristics at STC and the bottom I-V curve shows module characteristics when solar irradiance has been reduced to 15% of STC. It is clear that the maximum power voltage moves slightly to the left as the irradiance is reduced. This agrees with the varying irradiance I-V curve data Sharp includes on their data sheet.

In order to harvest maximum power from the PV module during normal changes in irradiance, one has to insure a method of strategically controlling the PV voltage accordingly in real time.

Temperature also has a significant influence on the I-V curve of a PV cell. The manufacturer's data sheet often contains information on the relationship between Isc-vs-temp and Voc-vs-temp. For crystalline silicon Isc varies by about -0.05% per deg C temperature rise and Voc is more sensitive varying by about -0.3% per deg C rise. The effects of varying temperature are shown in figure A6.

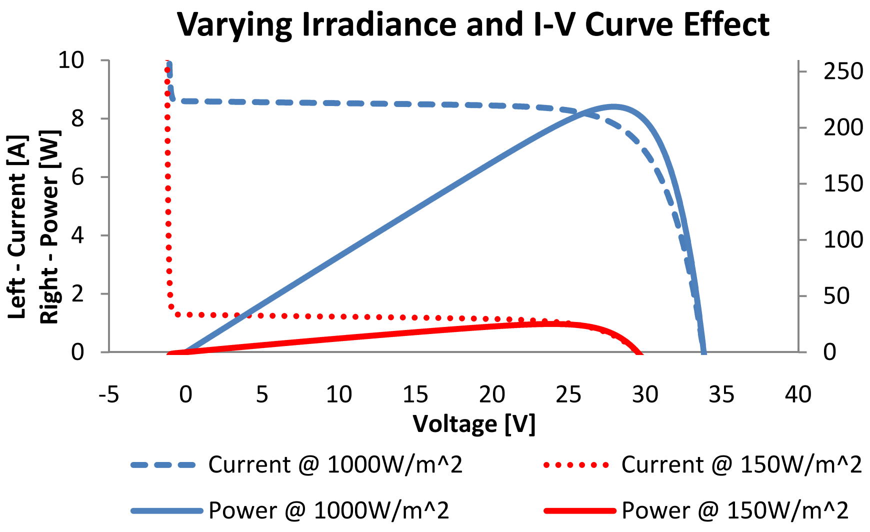


Figure A5

Irradiance and I-V Curve Characteristics

When designing PV arrays one has to ensure the worst-case cold Voc doesn't exceeded the max input voltage rating of the PV inverter. One also has to ensure the worst-case warm module temperature results in a Vmp that is within the MPPT operating voltage window of the inverter.

Cooler cells produce higher voltages, notably Voc, and can produce more power output than warmer cells. The I-V curve effectively compresses to the left for warmer cells and stretches to the right for cooler cells.

Figures A5 and A6 show how Vmp varies with irradiance and temperature. Interestingly, when the sun comes out and the irradiance increases, pushing the I-V curve right, the cell temperature increase seconds afterwards, pushing it back left.

PV Harvest Efficiency by Active Maximum Power Point Tracking

Achieving 100% harvest efficiency requires the PV inverter to continuously harvest energy from the PV cells at their Vmp. For a homogenously irradiated PV module or array of identical cells this requires the inverter to operate continuously at the PV voltage that produces the characteristic singular maximum power "bump".

Since Vmp is dynamic the inverter must incorporate a maximum power tracking system that has the ability to search for the maximum power point. Historically these control technologies have assumed that challenge is to find the characteristic max power bump in figures A2-A6 and operate at the peak power. The challenge would be simple if the I-V curve was static, but the I-V curve is dynamic. In order to notice movement in the Vmp, the control system must be constantly checking to see if and where the Vmp is moving. The only way it can do this is to move away from where it is currently operating to see what's happening elsewhere – thus it's theoretically impossible to achieve 100% harvest efficiency.

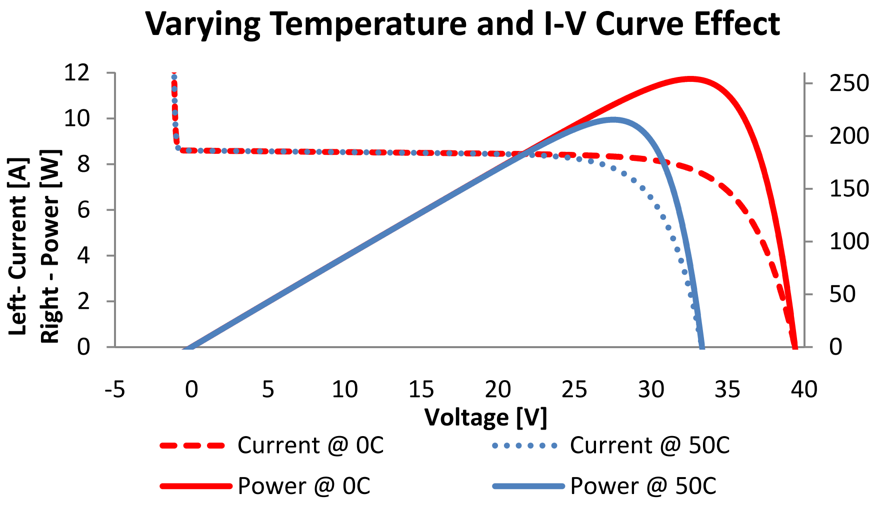


Figure A6
Temperature and I-V Characteristics

Any MPPT control system has two main challenges:

1. The MPPT control strategy needs good static efficiency for slowly varying arrays. This can be achieved by a slow MPPT tracking approach that finds the Vmp and stays there without moving too much away from Vmp.

2. The MPPT control strategy needs to have good dynamic efficiency for quickly varying arrays. This can be achieved by a fast MPPT approach that can quickly find the new Vmp. This requires more searching and will compromise static efficiency.

Any real array will therefore need an appropriate balance of dynamic and static efficiency.

The only way to evaluate static and dynamic MPPT efficiency is to operate the MPPT controller on accepted reference I-V curves where the theoretical Vmp is known. A static efficiency test performed with a static I-V curve provided by a PV simulator is straightforward. However, the dynamic evaluation depends entirely on the selected I-V dynamics modeled, thus requiring a defined reference set of data for comparative tests to be meaningful.

Unfortunately standardized MPPT efficiency tests are not yet established. Some evolving approaches simply vary the irradiance over time as shown in figure A7. Other approaches involve using reference profiles of I-V curve data based on measured data from real PV array measurements thus accounting for cloud, weather and temperature dynamics. An example of this is the ISORIP test profile from the Austrian Institute of Technology. There is currently no definitive standard for evaluating MPPT efficiency. That being said, MPPT efficiency should be in the 99%+ range regardless of the testing method.

There is currently no established method to evaluate the MPPT harvest efficiency for PV inverters operating on partially shaded or non-homogenously irradiated PV arrays.

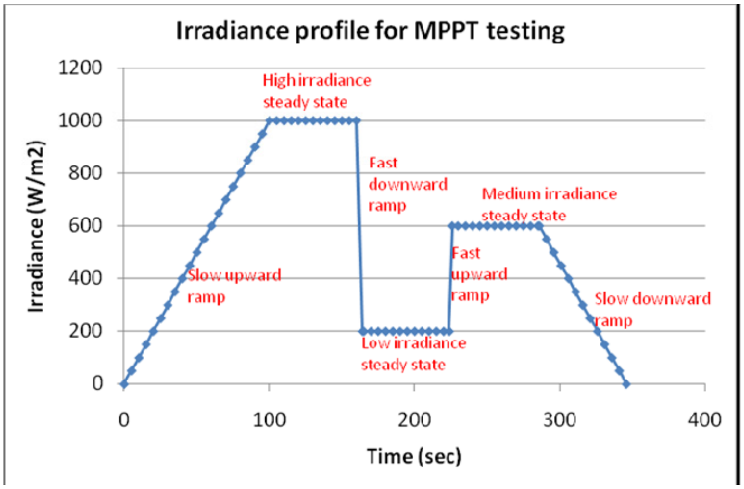


Figure A7
Sample Homogeneously Irradiated PV Array Irradiance Profile

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