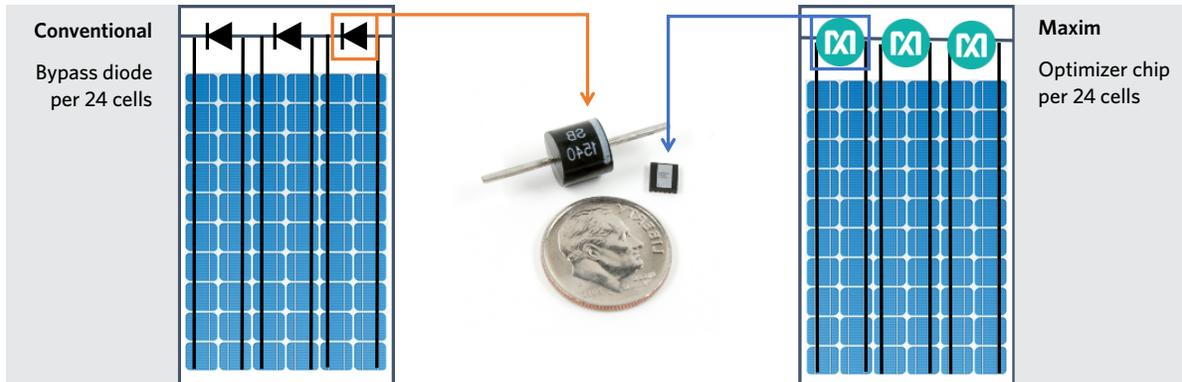


Submodule Optimizers Enable Flexible PV System Design

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Abstract



Maxim's Submodule Optimizers are highly integrated DC-DC converters that replace traditional bypass diodes by performing maximum power point tracking (MPPT) deep inside every photovoltaic (PV) module. This highly granular solution guarantees an unparalleled level of system performance compared to both standard PV systems and panel optimizer devices. This paper examines the benefits Maxim Submodule Optimizers provide in rooftop applications; particularly in enhancing PV design flexibility and offering designers the freedom to deploy systems in the most challenging of rooftop sites.

Background

Standard photovoltaic systems rely on a series architecture to generate adequate voltage for DC to AC power conversion. Typically, 20-24 cells are series connected into cell-strings, 3 cell-strings are series connected into PV modules, and 6-20 PV modules are series connected into PV strings. With this architecture, the typical 0.5V from one photovoltaic cell is stacked up by the hundreds to create usable power with a voltage in the range of 200-800V (Figure 2).

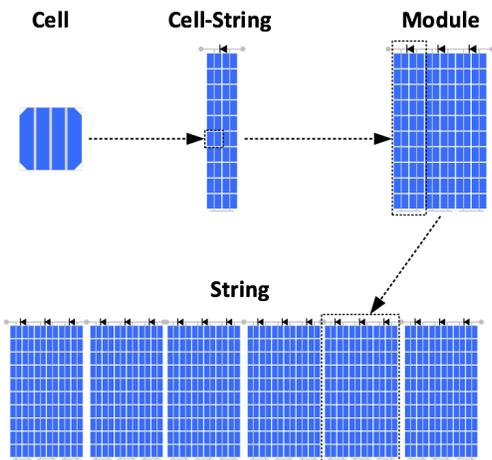


Figure 2. Standard Photovoltaic System with Series Architecture

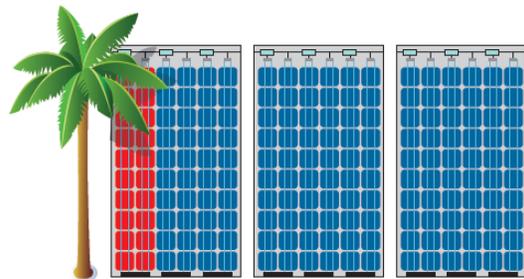
The series architecture promotes ease of installation, high system efficiency, and low overall cost; all important factors contributing to cost-effective solar energy. However, the series connection of cells and modules introduces one serious flaw: current through all series elements must be the same, so the entire PV string is forced to operate down to the level of the weakest cell-strings. In essence, one underperforming cell can limit production of the hundreds of other cells. In order to work around this fundamental limitation, bypass diodes are added in parallel with every cell-string so that severely weakened cells are electrically removed from the circuit instead of degrading the power output of the entire string

Bypass diodes are crude, yet effective, in preventing system wide production loss in the face of large mismatch, but there is room for significant improvement. Even modestly underperforming cells must be bypassed or they will throttle the entire string. This on-off decision point can lead to significant energy loss. In fact, while operating under partially mismatched condition, it is physically impossible for a standard PV system to produce maximum power.

Maxim's Submodule Optimizers replace the bypass diode and perform maximum point power tracking (MPPT) at the cell-string level. By replacing each diode with an MPPT tracking device, the on-off response to performance mismatch is eliminated. Every cell-string contributes maximum power without interfering with the power production capability of the others. This enhanced degree of flexibility leads to increased energy production; eliminating collateral performance loss due to module mismatch, degradation, soiling, localized shading, and row shading loss mechanisms (Figure 3).



Unoptimized: Sinks to the level of the weakest module



Maxim-Enabled Optimization: Harvest all available energy to the cell level

Figure 3. Standard PV Systems Perform Down to the Weakest Cell

CeThe Maxim Submodule Optimizer based system operates without the overhead of a communications network or additional management devices. Each individual optimizer seamlessly and transparently determines the appropriate operating condition needed to deliver maximum power from the cell-string input, while a standard inverter determines the string level operating point.

Fundamentals of Operation

Maxim's Submodule Optimizer is a DC-DC converter utilizing a "buck" or "step-down" topology. Buck converters can deliver power from a particular voltage and current to their output with an arbitrarily lower voltage and higher current.

This DC conversion capability affords an additional degree of freedom in the current and voltage operating points of the system. Instead of delivering maximum power at one specific current and voltage condition, cell-strings outfitted with Maxim optimizers can deliver maximum power over a range of currents and voltages. This is demonstrated by Figure 4, where it is clear standard modules only deliver maximum power at specific voltages and currents that are a function of the exposed irradiance and temperature. On the other hand, modules with Maxim's Submodule Optimizer can deliver maximum power over a wide range of voltages and currents.

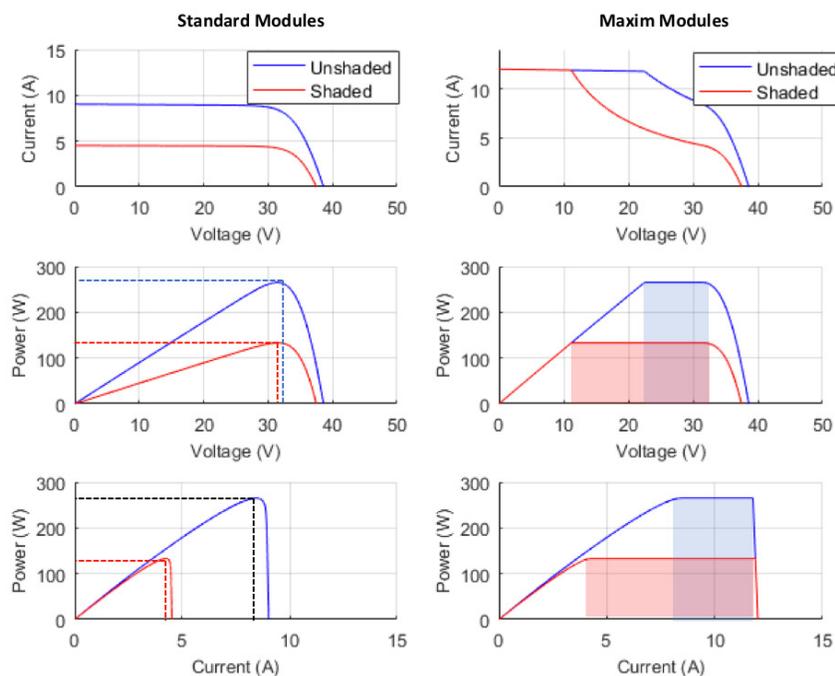


Figure 4. Standard (Left) and Maxim (Right) I-V-P Curves Indicating Regions of Maximum Power Delivery

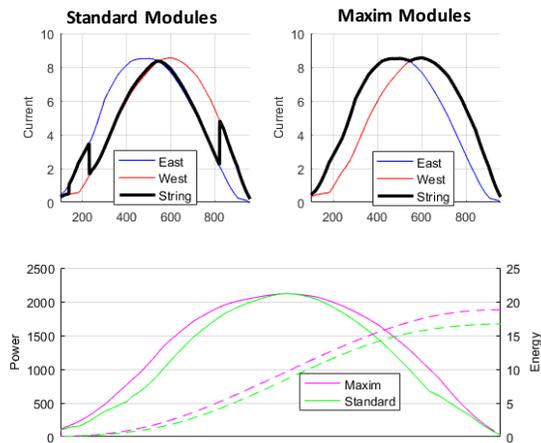
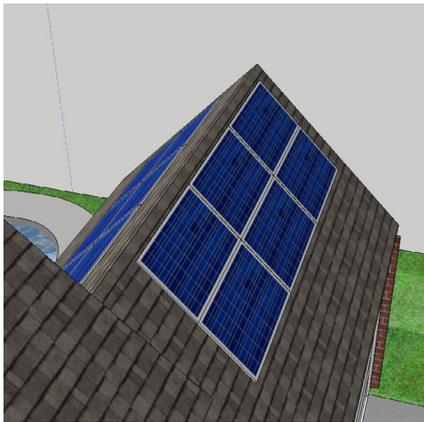


Figure 5. Standard and Maxim Performance with East-West Series System

This ability to deliver maximum power over a range of output currents and voltages enables the Maxim Submodule Optimizer to overcome almost all conditions that otherwise result in power loss with standard PV systems.

Operation with Series Mismatch

The optimized cell-string can deliver maximum power at any output current ranging from the maximum power current (IMP) of the input PV cells up to the electronically limited maximum current of 12A. In essence, cells are never bypassed and the optimized PV string can operate up to the current of the strongest cells instead of down to the current of the weakest cells.

The example of Figure 5 shows a typical challenged rooftop application with 6 modules facing east in series with 6 modules facing west. A conventional PV system will only generate full maximum power at solar noon; impaired in the morning and afternoon by the lower irradiance received by the lesser exposed half of the PV modules. The same PV system using Maxim optimized modules is able to provide full maximum power throughout the entire day, with the weaker modules boosting their current to match that of the stronger modules. In this simulation spanning a sunny summer day in Sacramento California, the Maxim string produces 12.6% more energy than the standard system counterpart.

The same principle of operation applies for other forms of series mismatch, for example in the face of shading, soiling or long term aging; all well documented situations that can lead to significant mismatch within the string.

Operation with Parallel Mismatch

Just as a series connection of modules forces all to operate at the same current, a parallel connection of strings forces all to operate at the same voltage. If there is voltage mismatch between strings, not all can operate at their maximum power point and power is lost. Parallel strings are usually designed to minimize voltage mismatch by restricting module counts to be equal. However, even in this case parallel mismatch is found; for example, when one string is exposed to shade or soiling and one or more bypass diodes turn on. Any form of series mismatch within a string can lead to parallel mismatch amongst In many cases, the ability to combine strings of intentionally different module counts is advantageous, such as when working around placement challenges in larger regular arrays. The optimized cell-string can deliver maximum power at or below the maximum power voltage (VMP) of the input PV cells. This is achieved by lowering the output voltage and raising the output current, thus deliver maximum power into a lower output voltage.

In this manner, longer PV strings can operate down to the voltage of the shorter strings while still delivering maximum power. The example of Figure-6 shows a typical challenged rooftop application with 8 and 10 module strings placed in parallel. A conventional PV system can never provide full maximum power as the best operating point is a compromise between the maximum power voltages of the longer and shorter strings; both strings suffer due to the restrictions of the parallel combination. The equivalent PV system using Maxim optimized modules is able to provide full maximum power throughout the entire day, as the longer string drops its voltage and delivers maximum power at the electrical conditions preferred by the shorter string. In this simulation spanning a sunny summer day in Sacramento California, the Maxim string produces 7.3% more energy than the standard system counterpart.

Design Considerations

PV systems with Submodule Optimizers can be designed using the same methodologies as traditional systems with string or central inverters, simply affording the designer a higher degree of flexibility to incorporate multiple string lengths, multiple orientations, and expanding modules into partially shaded areas. Advanced PV Modeling tools, such as Aurora can greatly simplify the task of PV system design and accurately model the performance benefits of Maxim's Submodule Optimizer.

Solar Resource

Any project begins with a site evaluation to determine the solar resource available. A sample solar survey report from Aurora is shown in Figure 7, which can assist in the identification of valid module locations. In order to prevent excessive energy loss, standard PV system designs should not place modules across different mounting planes or across regions of high insolation variability. These restrictions can limit the use of available rooftop real estate or

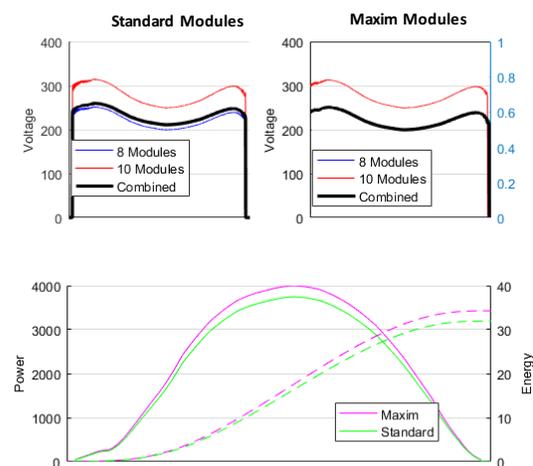
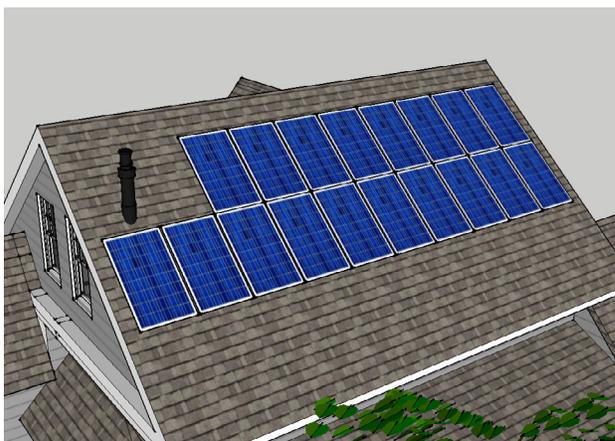


Figure 6. Standard and Maxim Optimized Performance with 8 and 10 Module Strings in Parallel

force designs to sacrifice performance efficiency for overall higher energy production. With Maxim's Submodule Optimizer technology, placing modules is as simple as surveying the solar resource map and placing the desired number of modules in the areas indicated as having the highest solar resource available. With this technology, system design is no longer constrained by module orientation and irradiance variability.

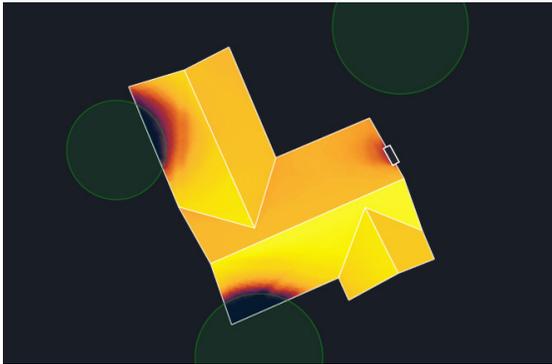


Figure 7. Example Solar Resource Map

String Length

Minimum and maximum string lengths with Maxim Submodule Optimizers are determined in the same manner as with conventional PV systems. The open-circuit and maximum power point voltages are found in the PV module manufacturer's datasheet. Standard string length calculations are used to determine minimum and maximum module counts per string. PV modules incorporating Maxim optimizers typically have 5% lower open-circuit voltages compared to their conventional counterparts (Table 1). This lower voltage can enable a higher module count in certain systems. Modeling tools such as Aurora can help a system designer more accurately determine the string operating voltage

characteristics and the overall suitability of a design with respect to module, string length, inverter, and geographic location.

Module Electrical Properties		
Example Data Sheet	Optimized Module	Standard Module
Max Power	265W	265W
V_{oc}	36.7V	38.6V
V_{mp}	29.8V	31.4V
Temperature Coefficient	0.30%/°C	0.30%/°C

Table 1. Data Sheet Electrical Properties Comparison

Multiple Mounting Planes

Installing modules on multiple mounting planes is easy with few considerations needed to be taken. Conventional systems of this type operate inefficiently due to significant irradiance and current mismatch between mounting planes versus time of day. However, with the Maxim Submodule Optimizer the series mismatch is easily accommodated and energy production reaches its full potential.

The primary consideration when designing series connected modules on multiple mounting planes is minimum string voltage. In the presence of series mismatch, the optimized modules will drop their voltage in proportion to the mismatch in order to meet the current level of the stronger modules while still delivering maximum power. The system designer should be aware of the minimum string length and the minimum voltage margin required by the inverter MPPT operating voltage window.

The greatest mismatch occurs between east and west mounting planes. A general rule-of-thumb for installations with two mounting planes is to increase the minimum string length by 1 module if one of the mounting planes is south-facing, or by 2 modules if neither mounting plane is south-facing. As an example, if the design calculations call for a minimum of 8 modules; increase the string length to 9 for a south-west or south-east facing system, and to 10 for an east-west facing system (Table 2).

String Length Considerations (STC Conditions)			
Configuration	Calculated Min String Length	Upsize By	Upsized String Length
East-West	8	2	10
East-South	8	1	9
West-South	8	1	9

Table 2. String length with Multiple Mounting Planes

More complex scenarios should be modeled with an appropriate modeling tool, such as Aurora, to determine minimum string length needed to avoid low-voltage operation losses.

Parallel Imbalance

Maxim Submodule Optimizers enable two strings of unequal length to be electrically combined. In this configuration, the longer string reduces its voltage to match that of the shorter string; with a proportional increase in current to maintain power output. Consequently, the minimum module count of the shorter string must meet the inverter MPP minimum operating voltage while the maximum module count of the longer string must comply with maximum open-circuit voltage limits. If the difference in module counts between the shorter and longer string exceeds 20%, the longer string may reach the electronically limited maximum current of 12A during high irradiance conditions resulting

in clipping losses. Advanced modeling tools, such as Aurora, should be used to determine the impact, if any, on overall annual energy production. For systems with more than two strings in parallel and imbalances greater than 20%, the shorter strings should include blocking diodes to prevent large reverse currents during open-circuit conditions.

System Expansion

Optimizing at the cell-string, Maxim technology provides best-in-class shade tolerance due to the finest granularity of maximum power point control. Independent data collected by the National Renewable Energy Lab (NREL) shows modules equipped with Maxim Submodule Optimizers outperform standard modules by over 40% in certain shading conditions (Figure 8).

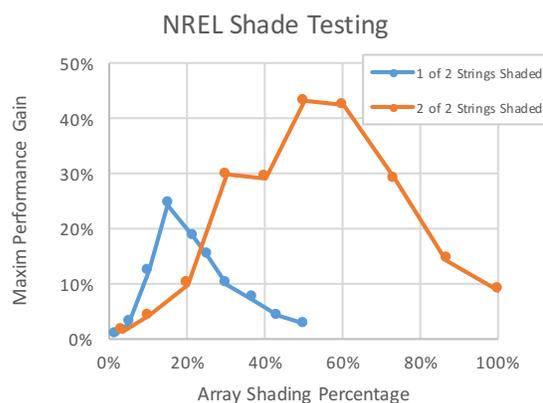
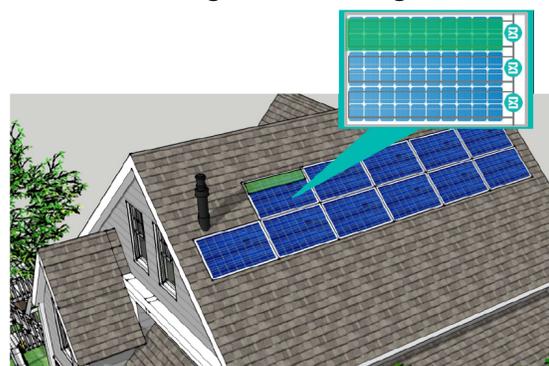


Figure 8. Shading Obstacles on Residential Rooftops (Top) and NREL Shade Mitigation Test Data (Bottom)

With Maxim Submodule Optimizers, there exists an opportunity to expand systems into partially shaded areas that would normally be avoided due to the disproportionate system power loss caused by one partially shaded module. In most cases, these partially shaded areas will produce cost-effective energy so long as cell-string optimizers are used to ensure maximum power delivery.

Every site and condition is different, so modeling tools, such as Aurora, are useful in predicting the power generation with cell string level accuracy and are an invaluable tool for designing PV systems in all but the most perfect rooftop scenarios. Studies conducted by Maxim have observed 5%–20% gains in yearly energy when installed next to an identically shaded system.

Summary

Maxim Submodule Optimizers are highly integrated DC-DC converters performing maximum power point tracking in place of traditional bypass diodes. The highly granular optimization offers best-in-class shade mitigation, helps improve module lifetime performance, and enables flexible system design.

Designers can take advantage of this technology to produce more energy and simplify the design of complex rooftops; all while continuing to use preferred inverter and BOS components. Installers will appreciate the fact that there is no change to their existing installation and commissioning process; meaning no additional labor steps or installation headaches associated with traditional MLPE products.

The modeling software developed by Aurora Solar enables simple yet accurate design of challenged rooftop systems. Aurora calculates shading and mismatch down to the cell-string level, confidently forecasting the unique benefits that Maxim Submodule Optimizers provide in real world rooftop systems.

Maxim's Submodule Optimizers afford the designer increased flexibility with everyday PV system design challenges, enabling better performance and a simpler approach to PV system design.

Learn more

For more information, visit:

www.maximintegrated.com/solar

www.aurorasolar.com

[1] Aurora Solar, Inc.