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Chris Deline and Bill Marion
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Jennifer Granata and Sigifredo Gonzalez
Sandia National Laboratories

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Executive Summary

Distributed power electronics such as micro-inverters and DC-DC converters can help reduce mismatch and shading losses in photovoltaic (PV) systems. Under partially shaded conditions, the use of distributed power electronics can recover between 10%–30% of annual performance loss or more, depending on the system configuration and type of device used. Additional value-added features may also increase the benefit of using per-panel distributed power electronics; these include increased safety, reduced system design constraints, and added monitoring and diagnostics. The economics of these devices will also become more favorable as production volume increases and integration within the solar panel's junction box reduces part count and installation time. Some potential liabilities of per-panel devices include increased PV system cost, additional points of failure, and an insertion loss that may or may not offset performance gains under particular mismatch conditions.

Introduction

A number of new products have come to the market in the field of distributed photovoltaic (PV) power electronics. This category of devices includes DC-DC converters and AC micro-inverters that are designed to either replace or work in concert with traditional central PV inverters. Recent improvements in the efficiency, reliability, and cost of these products have made them viable in many applications, from small residential installations to large commercial PV arrays. The breadth of options and claims among these various products shows that some differentiation exists between these devices. On the other hand, all of these devices share many similar benefits due to their distributed nature. This report intends to highlight the differences and similarities of these technologies and to provide some analysis of their benefits to power production and system economics.

In general, the use of power electronics at a per-module or per-PV string basis can reduce the impact of module mismatch and partial shading. A traditional central inverter will have only a few (typically one and rarely two or more) input channels that independently track the maximum power point (MPP) of the PV system. With large utility-scale inverters reaching up to half a megawatt (MW) in size, over 5,000 individual PV panels could potentially operate at one common peak power point. A reduction in the output power of one or more of these PV panels can lead to mismatch in the maximum power point between the various PV modules and strings. Possible causes of MPP mismatch include partial shading, soiling from dust, debris, and bird droppings, and module physical degradation. The impact of partial shading and mismatch can be reduced by increasing the number of independent MPP tracking channels in the PV system. The improvement from distributed MPP tracking depends on the amount of mismatch throughout the system, the size and configuration of the system, and the characteristics of its PV modules, among other factors.

A DC-DC converter is one type of distributed power electronics that can provide such an improvement in system performance. These devices are also sometimes called power optimizers or power boosters. Rather than replacing a traditional central inverter, DC-DC converters work in conjunction with a central inverter, which is still required to convert DC power to AC grid power. However, the distributed electronics on each module or string help to de-couple the maximum power operating point of the individual modules or strings from the overall maximum power point of the system. A DC-DC converter will track the maximum power point of solar module(s) connected to it and either increase (**boost**) or decrease (**buck**) the output voltage to

match the optimum voltage requested by the central inverter. Many currently available solar DC-DC converters use a separate enclosure for the power electronics at each panel, typically attached to the PV module frame or rack. Newer proposed versions of this technology involve partnering with PV module manufacturers to integrate the DC-DC electronics directly into the PV panel junction box. This convergence produces a so-called “smart junction box” or “smart panel” that provides some cost and labor savings over separate panel and power electronics.

Another type of distributed PV electronics is the AC micro-inverter. While this technology made an appearance a decade ago as an integrated AC module, cost and reliability issues prevented the technology’s widespread adoption. The current generation of micro-inverter products appears to be achieving greater market penetration through improved efficiency, reduced cost, increased reliability, and diagnostic capabilities. AC micro-inverters are installed on each PV module, replacing the use of a central inverter. Each PV panel’s DC power is converted directly to AC 120 V or 240 V and grid-tied. The output of each PV panel is therefore effectively in parallel, which eliminates power losses due to module mismatch. Thus the performance improvements that arise from independently peak-power tracking PV modules can be achieved with micro-inverters as well as with DC-DC converters. An additional benefit to micro-inverters compared with DC-DC devices is the reduction in DC balance of system components, including the central inverter. Also, voltages tend to be lower with micro-inverter systems, which could be a safety benefit for rooftop systems. Figure 1 shows some example topologies for per-panel micro-electronics, including DC-DC converters and micro-inverters.

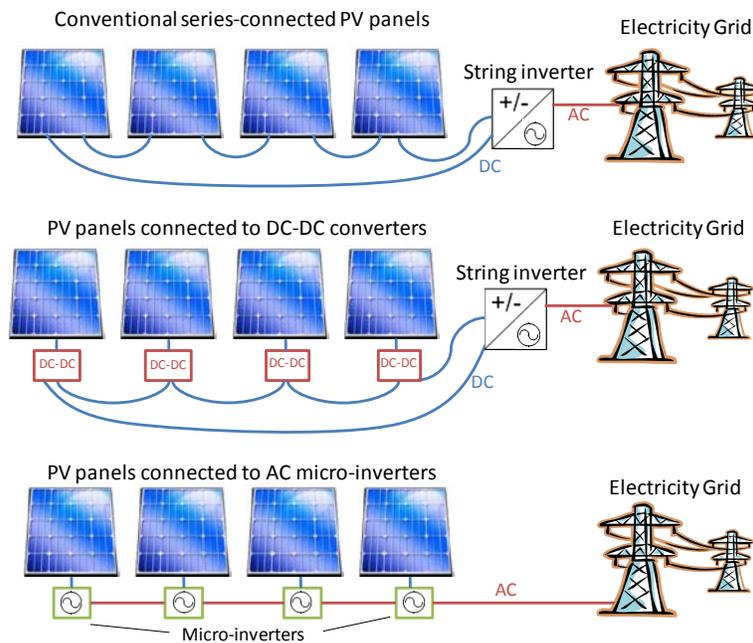


Figure 1. Schematic of conventional single-string PV system (top), DC-DC converter-equipped PV system (middle), and AC micro-inverter-equipped PV system (bottom).

There is also interest in reducing mismatch losses in larger installations, but perhaps not at the per-panel level. One strategy is to include DC-DC converters at the string level, which can reduce voltage mismatch between parallel strings. A boost converter can also provide a higher constant voltage to the central inverter, thereby reducing resistive losses and optimizing the DC operating point of the inverter. This type of string-level DC-DC equipment can be located inside or in place of a traditional combiner box, leading to the term “smart combiner box.” An example of this layout is shown in Figure 2.

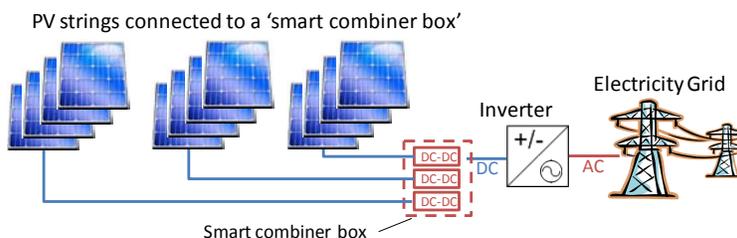


Figure 2. Schematic of a larger solar installation with multiple strings, each feeding into a “smart combiner box.” Maximum power point tracking is provided at the string level.

One aspect of distributed PV electronics that has yet to be addressed is the effect of their long-term reliability on the complete PV system. In general, the probability of system failure increases with each component in the system. Understanding the component-level reliability, failure modes, and effect of failure on system availability will be important in assessing the overall value of distributed PV electronics.

Background — Partial Shading and Mismatch Losses

The impact of shade and mismatch on PV systems has previously been studied, both with and without the use of DC-DC converters or micro-inverters [1-6]. Due to the variety of possible string configurations and module characteristics in PV systems, it is difficult to generalize how mismatch will affect a given system. However, in most PV systems with conventional silicon panels, the presence of shade or mismatch will have a greater than proportional impact on the system’s power output. This is due to the serial nature of PV modules in strings, which creates a “Christmas tree effect” in which current reduction in one series-connected module causes mismatch losses in the rest of the string. Because of this potential for greater power losses in mismatched systems (and for hot-spot safety concerns, which are not addressed here), solar module manufacturers typically include one or more **bypass diodes** in their modules, usually located in the module’s junction box. The function of the bypass diode is to allow current to flow past impaired sections of a module that are unable to produce as much current as the rest of the system. To accomplish this, the module section is shorted out by the diode, producing no power of its own. This bypass condition is preferable to allowing the shaded or impaired module to reduce the current of the entire string, thereby lowering production. Since the bypass diode shorts out the partially shaded section, causing its operating voltage to fall to zero, the overall operating voltage of the PV string will be reduced accordingly; see Figures 3 and 4.

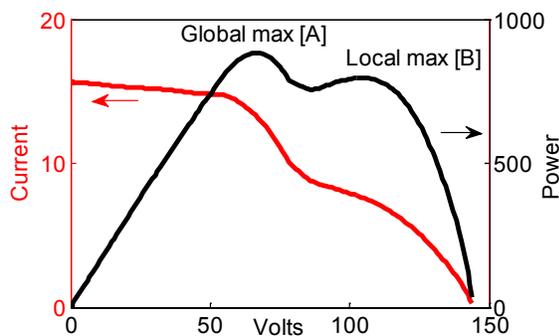
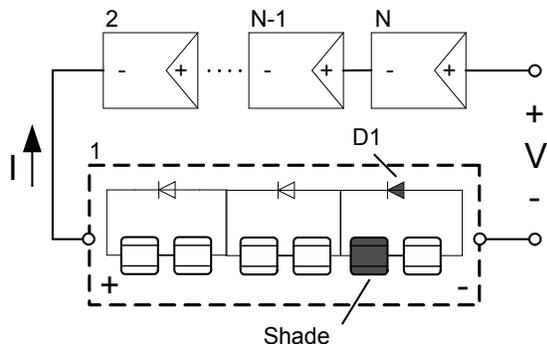


Figure 3 (left). PV modules are shown in series, each module containing 3 bypass diodes. A bypass diode will typically protect 15-20 cells from shade and reverse bias. In this example, shade causes diode D1 to short out its substring of cells, reducing Module 1's voltage by one third.

Figure 4 (right). System I-V curve (red) and power [W] vs. voltage [V] curve (black) for a partially shaded two-string PV system. The impact of shade is shown by a reduction in operating current and MPP of the system at higher voltages. Note that under certain operating conditions, both local maxima and global maxima can arise in the power vs. voltage curve.

If the PV system in question is only composed of a single string, there is no additional impact due to the shaded string's reduced voltage. However, if multiple parallel strings are present in the system, an additional source of mismatch loss occurs: voltage mismatch between parallel strings. In this situation, it's the voltage—not the current—that needs to be equal between parallel strings of PV modules. Given this constraint, the voltage of a partially shaded string must remain high, even if bypass diodes are shorting out sections of the shaded string. This results in the MPP tracking inverter to force unshaded modules in the affected string to operate at a higher than optimum voltage to make up for the voltage drop from bypass diodes elsewhere in the string. This mismatch loss causes power losses in both shaded and unshaded modules. The impact of this voltage mismatch can range from an additional 60% power loss for unbalanced shade on two-string systems [5] to an additional 400% power loss for shade covering 15%–20% of a utility-sized PV string [7]. It is clear that partial shading and other mismatch sources can result in performance losses much greater than the apparent scale of the shade itself. However, these worst-case values are not typically seen in real installations. An analysis of a shaded residential installation with somewhat more extensive shade than average showed a performance reduction of 22% due to shading from neighboring trees and other elements. Of this lost power, a majority (70%) was due to reduced irradiance and direct losses from shading. Only 30% of the power loss was due to mismatch of current and voltage [5]. Therefore, the installation of DC-DC converters or micro-inverters would improve this particular system's annual production by roughly 7% through the elimination of mismatch losses.

The use of distributed MPP tracking equipment can also improve system performance if the PV panels have mismatch in their nameplate operating conditions, particularly maximum-power current (I_{mp}). Although nameplate values are the same for identical module model numbers, there can be some variation from panel to panel, as manufacturers typically bin the modules in 5 W to 10 W bins. There can therefore be a 5% difference or greater between the power output of modules with identical model numbers. This can contribute to mismatch losses between modules

in the same string if the mismatch is between the I_{mp} of series-connected modules. Judging from datasheets of silicon PV panels in the 200 W to 240 W range, the variation in I_{mp} within a single bin is typically 2%–3%. However, this does not directly indicate that the power loss within a series string is also 2%–3%, as seen in Figure 5. Because of the flatness of the I-V curve of a PV panel in the neighborhood of the maximum power point, a 2.5% change in operating current near the MPP only leads to a 0.5%–0.7% reduction in power for an average (0.72–0.74 fill factor) module. It is this 0.5%–0.7% series current mismatch loss that could be recovered through the installation of per-module MPP tracking equipment. Of course, not every panel in a string can have below-average I_{mp} , so the real mismatch loss is likely to be lower than the previously stated limit, and efficiency losses in DC-DC devices may further reduce this benefit.

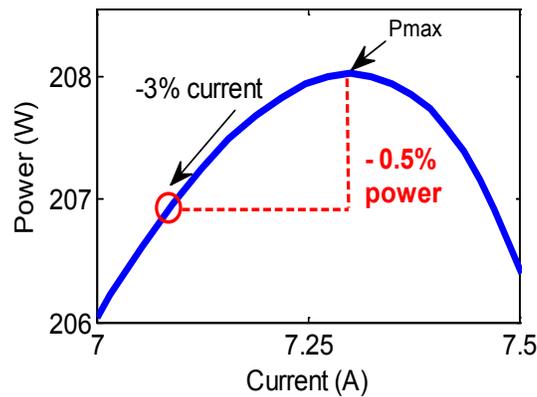


Figure 5. Power vs. current curve for a typical Si PV panel (Sharp ND-208) with fill factor = 0.71. Note that current mismatch of 3% leads to only 0.5% power reduction.

DC-DC Converter Deployment and Topologies

Several different DC-DC converter device topologies are available for use with individual solar panels, each with different strengths and operating uses. The simplest DC-DC converter uses a single converter stage to either **buck** (reduce) or **boost** (increase) the output voltage of a PV panel. In either case, the PV panel output voltage is MPP tracked by the control algorithm in the device. A slightly more advanced DC-DC converter is the **buck-boost** converter, which uses both buck and boost stages to allow the converter to either increase or decrease the output voltage of a PV panel. A list of some available DC-DC converter devices and their topologies is given in Table I.

Table I. Select commercially available distributed DC-DC devices

Company	Model	Input V	Power	Topology	Output V
Azuray	AP250	14-80 V	250 W	Buck	0-80 V
e-IQ energy	vBoost 250	20-50 V	250 W	Boost	250-350 V
Solar Edge	PB250-AOB	5-65 V	250 W	Buck/Boost	5-60 V
Solar Edge	PB350-TFI	10-95 V	350 W	Buck/Boost	5-60 V
Solar Magic	SM1230-3B1	30-80 V	230 W	Buck/Boost	0-86 V
Solar Magic	SM3320	15-40 V	350 W	Buck/Boost	0-43 V
ST Micro-electronics	SPV 1020	0-36 V	100 W [†]	Boost [†]	0-36 V
Tigo energy	MM-ES50	16-48 V	300 W	Buck [‡]	0-48 V
Tigo energy	MM-EP35	28-42 V	280 W	Boost	375 V
Xandex Solar	SunMizer	15-48 V	250 W	Buck	0-48 V

[†] Preliminary spec, based on 3 devices per PV module.

[‡] Uses 'impedance matching' circuit, which is a buck converter with synchronous rectification [8]

The advantages of a buck-boost converter include an increased operating range and the ability to correct for a greater amount of system mismatch. Since the device includes two conversion stages rather than one, the increased flexibility may come at the cost of a slight efficiency reduction as well as possible size and cost increases relative to single-stage devices.

In a buck-only DC-DC converter, the output voltage from a shaded panel is decreased, and the output current is increased to match the operating current of the unshaded modules in series with it. Because the current is boosted, there is no mismatch in current between the series-connected modules. There is no longer any need for the shaded module's bypass diodes to begin conducting. Therefore, the panel equipped with the buck DC-DC converter can produce power at a reduced level without needing the bypass diodes to conduct. This type of converter works best in PV systems with limited mismatch, e.g., where shade or mismatch occurs only on a few PV panels. In this case, the buck DC-DC converter is installed only on those PV panels experiencing shade. An increase in annual production results from the partially shaded modules producing some limited amount of power (due to the diffuse component of irradiance that is still present even under shaded conditions) rather than no power at all. The amount of power that can be recovered depends on how diffuse the shade is, but it may account for half or more of the recoverable mismatch loss under certain conditions [5].

A boost-only DC-DC converter operates by taking the input PV voltage (typically at the maximum power voltage of the particular panel) and increasing it. This type of system is typically designed with every PV panel in the system equipped with a boost converter. In some systems, the converter boosts the voltage to a high constant value (~300 Vdc –550 Vdc), and all of the panels are placed in parallel. System mismatch is eliminated here because each panel contributes current proportional to the amount of irradiance it receives. This system will work even with panels facing different directions, or at different tilt angles, because all of the converters are placed in parallel. The high constant-output voltage from the boost converter is chosen to maximize the efficiency of a fixed-input voltage inverter connected to the output of the

converters. Another similar style of boost system places 10 to 20 of the PV modules and converters in series to achieve the high constant voltage of the inverter's DC input. In this system, the amount of voltage boost is reduced for each converter, possibly improving its efficiency or durability. Both of these boost converter systems can allow for mismatched module tilt and orientation—and even mismatched module size, brand, or technology (to a point). If multiple parallel strings are present, they can also be of different lengths within the input range of the fixed-input inverter.

A system using buck-boost converters enjoys most of the benefits of both buck and boost converters. For instance, if shade is limited to only a few modules in the system, a buck-boost converter can be selectively installed on only the affected modules, and it will operate in buck mode to reduce the current mismatch between shaded and unshaded modules. Also, if the PV system includes modules of different size, power rating, or orientation, a buck-boost converter can be placed on every module in the series string, allowing for differences in the various module power outputs. If parallel strings are of different lengths, buck-boost converters on the shorter string will increase the operating voltage of the string to match the other longer strings. Buck-boost converters can also be used with specialized fixed-input-voltage inverters that operate at a constant high input voltage. Because the converters can also buck the output voltage, they are also compatible with conventional input voltage inverters, which operate at a lower, variable voltage.

In addition to per-module DC-DC converters, which account for the majority of products currently available, other converter deployments are possible. On larger utility-scale arrays, per-string MPP tracking places the power electronics at the end of each series string. On a smaller scale, MPP tracking can be accomplished with three or more independent channels per module—requiring access to the interconnection tabs within the PV panel. The benefit of finer (or coarser) MPP tracking resolution depends on the scale of mismatch within the system, balanced by the increased cost and complexity of additional MPP tracking channels.

General Benefits of Distributed PV Power Electronics

As stated above, there can be performance benefits to using per-panel distributed DC-DC and micro-inverter products based on the reduction in panel current and voltage mismatch. These advantages are primarily realized in residential and commercial installations, where localized shading and possible orientation mismatch are more common. Additional benefits include greater flexibility in system design and reduced time to engineer PV panel placement in complicated rooftop designs. This can lead to lower levelized cost of energy (LCOE) and possible reduction in balance of systems (BOS) wiring cost in the case of boost converters that operate at higher voltage and lower current, or micro-inverters that do not require string combiner boxes.

Additional value-added features are present in many distributed PV power electronics, providing further benefit to the system owner and installer. System performance monitoring on a per-module basis is offered with some products, providing both PV energy production and converter health information. This is useful to the PV system installer as a remote diagnostic and warranty repair indicator, thereby helping to maximize system uptime. The owner also has more feedback from the PV system to understand what conditions influence PV performance, possibly leading to better system maintenance, cleaning, and snow removal.

In the case of micro-inverters, one specific value-added benefit is the elimination of the single-point failure of a central inverter. It is possible that individual independent power conversion devices might require more individual replacements, but since a single micro-inverter failure does not cause the entire system to fail, power reduction during a single failure is limited to the power of a single module. This advantage is balanced by the generally more difficult replacement of a micro-inverter on a rooftop underneath PV panels when compared with a typical wall-mount central inverter in a more easily accessible location. The overall lifetime of current micro-inverter products is also difficult to compare with central inverters, as these micro-inverters have not been available long enough to obtain field lifetime results.

The safety aspects of certain distributed products may also influence their adoption. In conventional residential rooftop applications, a particular safety concern is the presence of high DC voltages (up to 600 V) even when the AC and DC disconnect are thrown. This can cause issues such as arc-fault damage to modules in the case of an internal module failure, and rescue personnel could be exposed to high voltage in the event of a rooftop fire. In the case of AC micro-inverters, these issues are mitigated because the system is de-energized when the AC disconnect is thrown. The available DC voltage is limited to that of a single module, which is considered benign. This arc-fault safety concern may also be mitigated by the use of per-module DC-DC converters, although further system tests would be required to verify this safety benefit.

Particular Concerns for Systems Using Distributed PV Electronics

The inclusion of distributed PV electronics in a system may give rise to additional concerns or considerations for the system design or operation. For instance, the input voltage and current range of a given converter may require the use of a limited set of compatible PV panels. Also, the inverter that is used with a particular set of DC-DC converters might need to be specific, based on the output voltage of the converter and the MPP tracking algorithm of the string inverter. Certain combinations of inverter and DC-DC converter have been shown to lead to inverter input voltage instability because both the output voltage of the converters and the input voltage of an inverter are variable. This condition has been observed during testing at both the National Renewable Energy Laboratory and Sandia National Laboratories using different DC-DC converter/inverter combinations. This particular condition may be mitigated by ensuring that at least one parallel string of PV panels is not equipped with DC-DC converters. This provides a stable input voltage for the inverter to track, with the parallel DC-DC converter-equipped strings matching this operating voltage. It may also be possible to work with equipment manufacturers to optimize the MPP tracking algorithms and DC-DC converter set point to improve stability. Output stability issues are typically discussed in a device's operation manual. Another similar consideration is whether the manufacturer requires a blocking diode in series in which each PV string is equipped with DC-DC converters.

Regarding reliability, there is not yet enough field data nor independently measured accelerated testing to confidently assess the lifetime of these distributed power electronics. Currently, limited warranties are offered on some products for 15 to 25 years, with the longer warranties being offered on DC-DC converter products. This reflects the conventional wisdom that micro-inverters contain more life-limiting parts and also intertie to the grid, which exposes devices to power-surge induced failures. In general, the warranties and expected lifetime for distributed products are at least as good as those for traditional central inverters and are approaching the lifetimes of the PV modules with which they are seeking to become integrated. One aspect of

distributed PV electronics that has yet to be addressed is the effect of their long-term reliability on the complete PV system. In general, the probability of system failure increases with each component in the system. Understanding the component-level reliability, failure modes, and effect of failure on system availability will be important in terms of assessing the overall value of using distributed PV electronics. Despite these predictions of long service life, it is possible that the product could last longer than the manufacturer is able to replace or support it. Indeed, in the past year several product lines have been discontinued, with additional culling anticipated. In this climate, it is wise to evaluate the product's interoperability with other similar products as well as what might happen if support is no longer available for a particular product in the future. For example, buck-only DC-DC converters that are installed on only a few PV panels in a system could be freely replaced with other buck-only or buck-boost converters. However, boost converters using a specialized central inverter might require identical replacement parts, leaving the system owner exposed to possible obsolescence risk. Similarly, micro-inverter interoperability may not be possible due to incompatible electrical connectors and in certain cases the use of proprietary powerline modem communications. In this case, a separate AC branch circuit would be required for the replacement micro-inverter device(s).

Performance Analysis of Various DC-DC Topologies

Computer simulations were conducted of a variety of shade conditions and DC-DC converter deployments. It is difficult to account for every possible system configuration and mismatch condition, so a few example situations were considered. Three different "typical residential installations" were simulated, all based on an actual residential installation described in [5]. The residential installation is a 3-kW roof-mounted PV system with 14 mc-Si modules (Sharp ND-208s). The system is modeled either as a single-string installation or two parallel strings. The shading on the system is somewhat more extensive than average, with an annual irradiance reduction of 20% as measured by a detailed site survey. A reduced shading condition is considered as well, in which the annual irradiance loss due to shade is only 10%, concentrated entirely on one of the two strings.

In addition to the residential rooftop shading simulations, larger systems with inter-row shading were also considered. For these systems, it was assumed that rows are spaced such that 3% of the annual irradiance is lost due to inter-row shading. This value is consistent with industry practice to optimize the roof or land utilization of a PV installation. Sharp ND-208 PV modules were assumed for this simulation case as well. A ground coverage ratio of 0.54 and a module tilt of 18.5° are assumed. Modules are oriented in landscape, with two modules stacked vertically and eight modules horizontally per row, shown in Figure 6. A total of ten rows are simulated in the commercial (33 kW) case.

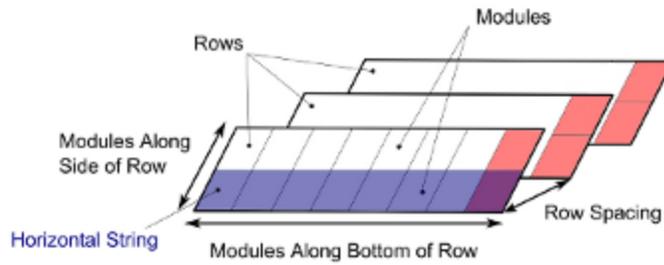


Figure 6. Commercial row-row shading example with 18.5° tilt and 0.54 ground coverage ratio. The modules are stacked two high and eight wide for a total string length of 16. Ten strings are placed in parallel (figure courtesy of DOE/NREL’s Solar Advisor Model).

To predict the performance gains from the use of distributed electronics, substring-level I-V curves were calculated and summed based on the predicted irradiance and shade on a given module substring. The performance of the DC-DC converter was modeled by a constant power curve, as discussed in [9]. DC-DC converter efficiency was set equal to 0.99 for all devices. This was done partly because detailed efficiency data for the different devices were unavailable, and also because the DC-DC efficiency loss will partly be offset by mismatch from soiling, aging, and manufacturer distribution of PV panels, which are all mismatch terms neglected in this simulation. Annual performance data is produced using the PVWatts engine [10], modified to allow for reduced irradiance due to partial shade. TMY3 meteorological data is used for Boulder, Colorado. The simulation results are provided below in Table II.

Table II. Annual performance of four PV systems, different DC-DC configurations*

	No DC-DC device	Buck DC-DC on all panels	Buck/Boost DC-DC on all panels	Per-string DC-DC
Rooftop system, 1 string. 20% shaded. Unshaded annual production : 4051 kWh				
Annual energy:	3376 kWh	3440 kWh	3440 kWh	3349 kWh
Power lost to shade:	-17 %	-15 %	-15 %	-17 %
Shade loss recovered:	N/A	10 %	10 %	-4 %
Rooftop system, 2 strings. 20% shaded. Unshaded annual production : 4051 kWh				
Annual energy:	3310 kWh	3427 kWh	3437 kWh	3364 kWh
Power lost to shade:	-18.3 %	-15.4 %	-15.1 %	-17 %
Shade loss recovered:	N/A	16 %	17 %	7 %
Rooftop system, 2 strings. Shade on one string only. Unshaded production : 4051 kWh				
Annual energy:	3646 kWh	3693 kWh	3712 kWh	3682 kWh
Power lost to shade:	-10.0 %	-8.8 %	-8.4 %	-9.1 %
Shade loss recovered:	N/A	12 %	16 %	9 %
Commercial system, 10 strings. 3% shaded. Unshaded annual production : 46.3 MWh				
Annual energy:	44.9 MWh	44.5 MWh	44.5 MWh	44.2 MWh
Power lost to shade:	-3.1 %	-3 %	-3 %	-3.6 %
Shade loss recovered:	N/A	1 %	2 %	-17 %
	No DC-DC device	Buck DC-DC on all panels	Buck/Boost DC-DC on all panels	Per-string DC-DC

* DC-DC device efficiency = 0.99. Soiling, aging and distribution mismatch are neglected.

For these particular installations, the presence of shade led to performance losses of 3%–18%. The addition of DC-DC converters with MPP tracking led to a recovery of 10%–20% of the annual loss due to partial shade, with more gain coming from systems with more parallel strings and greater amount of shade.

The above simulation results and additional results from literature are summarized in Table III below:

Table III. Sources of mismatch loss cited in the literature

Type of mismatch	System loss (est)	Potential DC-DC gain*	Ref
Residential roof shade, 1 string	5-15%	+15-20% of loss	[5]
Residential rooftop tree shading – multiple strings	5-20%	+20-30% of loss	[5]
Residential rooftop, pole shading – multiple strings	4-8%	+40-70% of loss	[6]
Commercial system with inter-row shading	1-5%	+0% of loss **	[Table II]
Residential orientation mismatch within a string	1-20%	~100% of loss	[11]
Imp distribution mismatch	0.2 - 1%	~100% of loss	[Fig. 4]
Soiling – CA and Southwest US	1.5 – 6.2%	+15-40% of loss	[12]

* For typical cSi PV panels and per-panel DC-DC devices, not accounting for device efficiency and insertion loss

** In this simulation, the small amount of inter-row shading was not enough to benefit from DC-DC devices when device efficiency is accounted for.

Qualitative Economic Analysis of Expected Applications

The relative benefit of distributed PV electronics depends on the system configuration, the amount of current and voltage mismatch within the system, and the cost of the PV electronics. A greater performance improvement could support a greater equipment cost. In some cases, the system is limited by the available space, and performance improvement is sought above all other considerations. In other cases, there is available space to include additional PV panels, and the increased performance provided by distributed power electronics must be compared with the alternative of including additional solar panels to increase production.

In general, distributed power electronics manufacturers seek to reduce installation time and component expense by integrating directly with PV panels inside the junction box. This also streamlines distribution channels, but effectively commoditizes the “smart junction box” which may prevent the electronics manufacturer from differentiating. PV module manufacturers will likely push for more uniformity and interoperability, in addition to demanding lower margins for junction box electronics. This model of pre-integrated power electronics—which stands a chance to reduce component costs enough to become cost-competitive on a \$/W basis—works best with new rooftop installations that include the power electronics on every panel. The compatible technologies include micro-inverters, high-voltage boost converters, and buck-boost DC-DC converters. In the case of buck DC-DC converters which are intended for installation on only a few PV panels experiencing isolated shade, using a module-integrated “smart junction box” may not make the most sense, as the amount of shade and power loss may not be apparent until after the system is installed. Buck converters may work the best as a standalone retrofit device, similar to the first-generation DC-DC converters available now. However, one advantage of selective installation on only a few modules is that performance improvement can be achieved with a much lower part count (and cost) than installing the converter devices on each module in a string. This configuration also minimizes reliability risks based on part count. Another application that may warrant the use of either the pre-integrated or standalone retrofit DC-DC converters could be an expansion of an existing PV installation. If the existing central inverter were oversized, using DC-DC converters could allow mismatched modules to be included into the existing array, even if the existing array’s modules are no longer manufactured. Alternatively, a separate AC branch circuit could be supplied to micro-inverters to increase the capacity of an existing PV array.

In the case of larger PV installations 100 kW or greater, the prospect of per-module power electronics is limited. This is because the uniformity of such large installations is usually better than on a residential or commercial warehouse rooftop. Also, the additional part count, monitoring and installation time, and desire to reduce levelized cost of electricity is a disadvantage to per-module power electronics in large installations. In the case of isolated shading from nearby obstructions, individual modules could be fitted with retrofit buck or buck-boost DC-DC converters. If there is some nonuniformity on a per-string basis—for instance, if the installation is on rocky or otherwise un-level ground—there could be an advantage to using per-string MPP tracking. This technology can be integrated into the equivalent of the existing DC combiner boxes, so no additional installation or part count is required. In the case of boost DC-DC converters, higher DC voltages between the combiner box and the inverter can lead to reduced I^2R wire losses or lower wiring cost. Also, the central inverter can be designed to operate at a fixed high voltage, further reducing complexity and cost. In certain applications, this

technology may be cost effective, particularly if the benefit of per-string monitoring is included, with its concomitant improvement in system up-time and reduced O&M costs.

Summary

Distributed power electronics have the potential to reduce PV performance loss due to partial shade and mismatch. Depending on the mismatch condition and system size, a variety of products are available to help improve system performance. The benefits of per-module power electronics are greatest for multi-string residential installations with close-in shade obstructions or mismatch from orientation or panel size. Value-added features of some devices include performance monitoring and emergency power-off, which may assist in market penetration, along with reduced cost through integration within PV panels' junction boxes. While the performance aspects of these distributed electronics can be assessed, it is still unclear what effect the introduction of more components and complexity will have on system reliability. Larger PV installations may prefer to install string-level DC-DC equipment to achieve some of the mismatch reduction benefits of distributed power electronics without the part count and cost of per-panel electronics.

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