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EFFECT OF DISTRIBUTED POWER CONVERSION ON THE ANNUAL PERFORMANCE OF BUILDING-INTEGRATED PV ARRAYS WITH COMPLEX ROOF GEOMETRIES

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ABSTRACT

Building-integrated photovoltaic (BIPV) systems have gained greater popularity in recent years; however, their effectiveness is often limited by nonuniform operating conditions. To increase potential for energy capture in PV systems, particularly those with series string configurations, an improved module integrated dc-dc converter (MIC) with maximum power point tracking has been proposed. This paper investigates the potential power gain provided by these MICs in situations where the architecture or surroundings of a building necessitate that a PV array include panels with differing orientations, which can significantly reduce system efficiency.

A flexible, comprehensive simulation model for BIPV systems is developed, which allows for variations in insolation and temperature at the PV cell level, while accurately modeling MICs and their effect on array performance. This model is used to simulate various directional array combinations in series string and parallel configurations for a representative set of climates around the US.

Results of these simulations show power gains attributed to both the photovoltaic generator/converter portion of the system and to increased inverter efficiency arising from a constant, controlled string voltage. When differing panel orientations within an array are considered, there is potential for annual power output gains of over 10% for a system with MICs when compared to conventional approaches. Further opportunities for increased energy capture in a BIPV system with MICs are identified and discussed.

Keywords: *photovoltaics, module integrated converters, energy simulation*

INTRODUCTION

Solar photovoltaic (PV) arrays are most commonly configured as a group of parallel strings of series-connected modules, tied to the utility grid through a central inverter with maximum power point tracking (MPPT). Uniformity of cell operating conditions, including uniformity of the solar resource, is essential to maximize the power output of a PV series string. However, the complex designs and landscapes of urban and suburban environments often create situations where PV systems on buildings have nonuniform radiation, resulting in decreased system power output. High efficiency, autonomous, module-integrated dc-dc converters with localized maximum power point tracking are proposed to allow a PV system to perform at its maximum potential, even under nonuniform cell irradiance and temperature operating conditions. Successful implementation of these systems will facilitate effective use of PV arrays on a more diverse set of roofs and buildings, thereby significantly enhancing the potential for distributed solar power generation.

This study examines the effect of these converters on annual system power output for different building-integrated PV systems, with a focus on system configuration and panel orientation in different climates. A detailed, flexible simulation model for PV systems with module-integrated converters has been developed. The model, which accounts for variations in irradiance and temperatures at the PV cell level, has been calibrated to experimental data taken using a series of PV modules with associated dc-dc converters. Several typical residential PV systems have been evaluated, based on parameters including array size and configuration (number of series and parallel panels) and panel directional orientation, accounting for complex roof geometries. Comparisons are

made between the annual energy production of each system, with and without the dc-dc converters, based on simulations using hourly weather data.

Simulation results indicate significant annual energy savings attributed to the use of module-integrated dc-dc converters in a variety of typical potential building-integrated PV system configurations, particularly in cases with large irradiance mismatches between panels controlled on the same PV system series string. Results indicate that energy production can be increased by more than 10% over conventional system configurations when considering irradiance mismatches due to directional orientation. Analysis of these results suggests that the percentage gain could be even higher if one examined the effects of shading or other nonuniformities in operating conditions.

SOLAR ENERGY FOR COMPLEX GEOMETRIES

Uniformity of cell operating conditions, including uniformity of the solar resource, is essential to maximize the power output of a PV series string. While a planar PV array in an isolated landscape would see uniform insolation, the complex designs and landscapes of PV systems in urban and suburban environments often create situations where PV systems on buildings have nonuniform radiation, resulting in decreased system power output. In this paper, we specifically address nonuniformities due to non-planar design in which individual cells have different orientations relative to the position of the sun in the sky. The opportunities for such complex geometries grow as manufacturers and architects continue to explore BIPV applications of thin-film products, including applications for roof surfaces, shading devices, vertical glass and façade elements, and curved architectural surfaces. In addition, PV systems frequently experience shading from nearby objects, such as buildings, vegetation, or chimneys, or even self-shading due to roof architecture.

As a further complication, the nonuniformity in radiation produces nonuniformity in cell temperatures that also affects power production. While these nonuniformities are often small, their impact can be significant with the growing application of BIPV on cluttered roofs in more dense environments.

The solar radiation striking a PV cell can be described in terms of three components: the direct or beam radiation from the sun (beam component), the diffuse radiation from the sky (sky diffuse component), and the radiation reflected from terrestrial objects (reflected component). The modeling and analysis of these components is well developed [1]. Under sunny conditions, the beam component of radiation on a surface facing the sun may account for more than 90% of the insolation. Under cloudy conditions, all incident radiation is diffuse or reflected. The beam fraction of the total radiation is largely determined by surface geometry relative to the position of the sun, described by the solar incidence angle, and by cloud conditions. On an annual basis, even in a city with a sunny climate like Boulder, Colorado, beam radiation on a residential roof-mounted PV system accounts for less than 80% of the total

energy, and it is less than half of the energy for almost 40% of the sunlit hours.

BIPV WITH NONUNIFORM OPERATING CONDITIONS

A typical residential or small commercial BIPV system configuration, consisting of one or more parallel strings of photovoltaic modules connected to the electrical grid through an inverter, is shown in Fig. 1. Standard inverters for these systems have an input voltage range of 100-600Vdc and output 120-240Vac to the electrical grid. Individual photovoltaic modules have an output voltage much lower than the input voltage of the inverter. They are placed in series strings to build up higher voltages, which are desirable to reduce wire sizes and maximize inverter efficiency. In general, the number of modules in series is determined such that the maximum voltage will never exceed the upper bound of the inverter. Similarly, parallel strings of photovoltaic modules may be installed to increase the current of the system, increasing the power output while keeping the voltage at a desired level. The output voltage of the PV series string can be highly variable when the system operates under non-uniform conditions of radiation. Therefore a dc-dc converter capable of maximum power point tracking is needed at the string level in order to regulate the input voltage to the inverter.

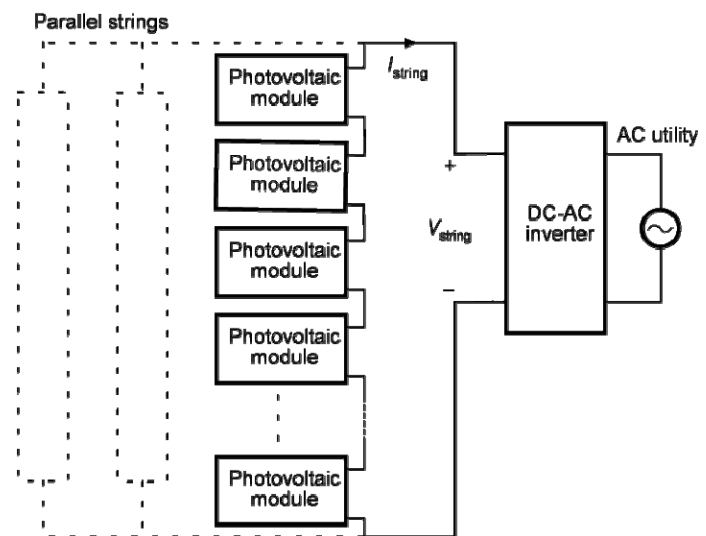


FIGURE 1. CONVENTIONAL SERIES STRING OF PHOTOVOLTAIC MODULES, CONNECTED TO A CENTRAL INVERTER FOR INTERFACE TO THE UTILITY

Photovoltaic Cell Characteristics

At the core of any BIPV system is the photovoltaic cell, the electrical properties of which are commonly represented by the five parameter diode model detailed in the System Model section of this paper. The relationship between current and voltage (I-V curve) for a standard PV cell operating under two different irradiances is found in Fig. 2a. As radiation is reduced, the shape of the I-V curve remains the same, but the cell's current production decreases. When these cells are wired

in series, forming a PV module, the same current must pass through each cell in the series, while the cell voltages are additive. Similar behavior occurs when multiple modules are wired in series.

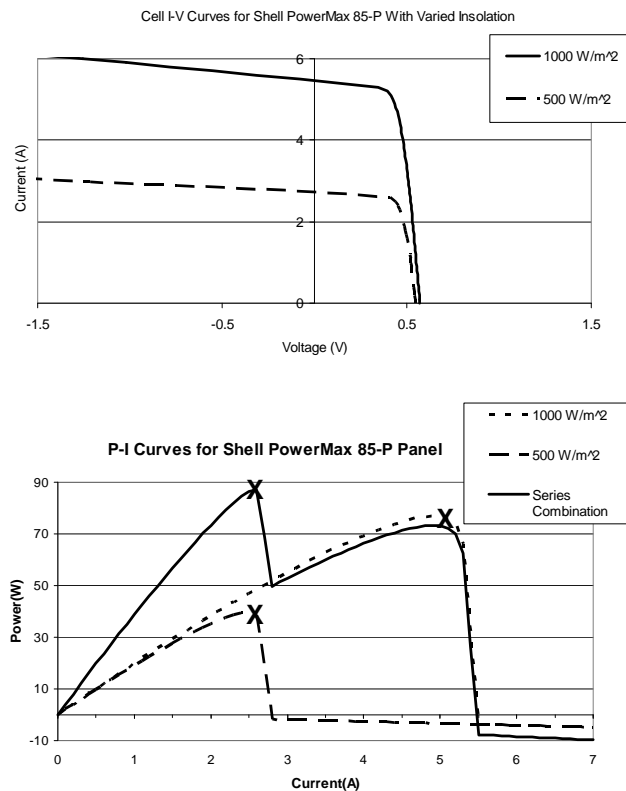


FIGURE 2. (A) (TOP). THE I-V CURVES FOR A PHOTOVOLTAIC CELL WITH DIFFERENT RADIATION LEVELS. (B) (BOTTOM). P-I CURVES FOR SINGLE PANELS WITH DIFFERENT RADIATION LEVELS, AND THE POWER OUTPUT FOR A SERIES STRING CONSISTING OF THE TWO PANELS COMBINED. THE THREE XS MARK THE MAXIMUM POWER POINTS OF THE THREE CASES.

In a series string of both unshaded and shaded PV panels, the unshaded panels will have a higher optimal power producing current. If the shaded panels in a string are forced to operate at the higher optimal current of the string's unshaded panels, which may exceed their short-circuit current, it is likely that their cells will become reverse biased (negative voltage) and actually dissipate power rather than produce it. To limit power losses associated with this dissipation, and also to keep the array from being damaged from heat generation, most PV panels have bypass diodes in their junction boxes. These are typically placed two per panel and allow current to bypass either group that is shaded or oriented such that it would otherwise produce a negative voltage larger than the bypass diode's forward voltage drop of ~ 0.7 V.

Investigation of PV cell behavior in the reverse biased region and its influence on the bypass diode firing and the power output of partially shaded arrays has been performed by

Alonso et al. [2]. Results of their study demonstrate that the wide variation in cell behavior under reverse bias, which is directly related to a cell's shunt resistance, can have significant impact on system power output when individual cells are shaded. However, for the purposes of the present study, radiation differences arise from different geometries rather than shading from obstructions, so all of the PV cells associated with a particular bypass diode are assumed to have the same insolation. This diminishes the effect of each individual cell's behavior on bypass diode firing, though this effect must be considered in any future studies with insolation variations at the cell level.

Figure 2b shows the power output of an example two-panel system at a nominal cell operating temperature of 45°C with bypass diodes and mismatched insolation. The maximum power points for each panel, and then for the combined system, are marked with Xs. Notice that the series combination curve shows two local power maxima. The lower of the two system power maxima at about 5 A corresponds to the case where the operating current is optimal for the unshaded panel, and the panel with lower insolation is bypassed. The higher system maximum at about 2.5 A has power contributed from both panels, but the system maximum (87 W) is less than the sum of the maximum points from each panel individually ($38\text{ W} + 78\text{ W} = 116\text{ W}$), as the system must operate at a lower current to ensure that the shaded panel is not bypassed and will contribute power.

Mismatch Scenarios

It is convenient to consider solar radiation nonuniformities on a PV system under three main geometric circumstances. In the first case, a portion of a string is shaded or soiled, blocking beam radiation from striking the shaded cells. While a large fraction may be blocked, the reflected and diffuse components can be a significant portion of the total radiation for much of the year. A second case of radiation nonuniformities may occur even for unshaded strings with uniform orientation because of the reflected radiation from nearby objects. Large dark objects can block the view of the sky, affecting the distribution of diffuse radiation. Similarly, light-colored or reflective surfaces can concentrate radiation on portions of the string. Finally, the third case arises from different cell orientations in a series PV string. A common example is the installation of PV on a cross-gabled residential roof, with a portion of the string facing south and a portion facing west. The difference in orientation alone can produce significant variation in beam radiation. This paper focuses on systems with differing orientations, as this is perhaps the most basic situation that may benefit from the use of modular integrated dc-dc power conversion.

Series vs. Parallel Configurations

The choice between series and parallel array configurations depends on the characteristics of an individual BIPV system, as both configurations have benefits and shortcomings in different scenarios. A single series string array is usually simpler and cheaper to install, and it operates at a higher voltage/lower

current than an array of parallel strings, reducing the required wiring size. However, a series array is most suitable in cases with uniform irradiation. On buildings with geometries requiring the array to have multiple orientations, it is beneficial to install parallel strings, which have a more optimal power output under nonuniform conditions. Small power losses associated with parallel strings -- blocking diode voltage drops and greater wire losses from higher currents -- are outweighed by the increased system efficiency.

However, parallel strings are not always possible or practical in BIPV applications, particularly for residential buildings. For example, many modern architectures include roofs with numerous differently-oriented small faces, none with enough area to support a full string of PV panels. The homeowner still may desire BIPV functionality, which could only be achieved by having differently-oriented panels wired together on the same series string. Additionally, if BIPV is desired on a curved surface, any string configuration would certainly include many orientation variances. Finally, the use of parallel strings may be precluded even for simple roof geometries if, for instance, a section of the roof is shaded during peak solar hours, limiting the area available for effective PV in a certain direction. All of these situations show significant need and opportunity for improved PV series string performance under mismatched operating conditions.

MODULE INTEGRATED DC-DC CONVERTERS

Several authors [2-6] have suggested the use of module integrated dc-dc converters (MICs) in PV systems to minimize power losses caused by shading and other nonuniformities in series strings. Though the results of this paper are generally applicable to any dc-dc converter designed for PV applications, the present study focuses on the unique buck-boost converter [3], integrated into a PV system as shown in Fig. 3. This approach effectively decouples each solar panel from the rest of the string, making the module insensitive to changes in the string and allowing each module to operate at its maximum power point even under nonuniform operating conditions.

These converters differ from previous approaches by featuring three operating modes, buck, boost, and pass-through. A description of the modes of operation follows:

A. Buck mode

The MIC operates as a buck converter whenever the current of its associated module is less than that of the string as a whole, due to module shading or other string mismatches that would cause this module to operate at a lower power level. It effectively decreases the module's output voltage while increasing the output current, allowing the module to operate at its maximum power point with a current equal to the rest of the string.

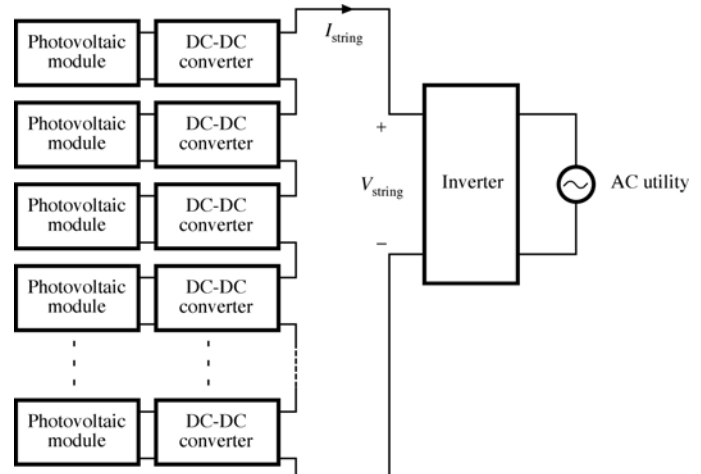


FIGURE 3. BLOCK DIAGRAM OF SYSTEM COMPRISED OF SERIES STRING OF MODULES INCLUDING MODULE INTEGRATED CONVERTERS

B. Boost Mode

The dc-dc converter enters boost mode when the current of its associated module is greater than that of the string as a whole, due to other modules in the string operating at a lower power levels. It effectively increases the module's output voltage while decreasing the output current, allowing the module to operate at its maximum power point with a current equal to the rest of the string.

C. Pass-Through Mode

This mode occurs when the operating conditions of the string are nominal and therefore the converter's associated module is operating at a current equal to the optimal string current. During this mode the PV panel is naturally operating at its maximum power point and no tracking or switching is necessary. The input is directly connected to the output, so very high efficiencies can be achieved.

In addition to allowing PV modules to operate at their individual maximum power points, the system with MICs enables production of a fixed total string voltage, thereby allowing the downstream inverter to be designed to operate with a regulated dc input voltage. With a good design, the inverter input voltage can be chosen to be slightly greater than the peak ac line voltage, and hence the efficiency and cost of the inverter can be substantially improved relative to present approaches. The proposed module autonomous control architecture allows this to be attained simply with an inverter that varies its dc input current to control the overall input voltage. This benefit is attained without need for a central controller or high-speed communications between modules.

SYSTEM MODEL

A model to simulate the performance of BIPV systems with and without MICs under nonuniform operating conditions

was created in the MATLAB environment. This MATLAB simulation allows for user input irradiance and temperature data on a cell-by-cell basis.

Photovoltaic Generators

The system's PV panels were modeled after Shell Solar's PowerMax Ultra 85-P panels, which are rated for 85 Watts peak power and have an open-circuit voltage and short-circuit current of 22.2V and 5.45A, respectively.

Individual cells and panels in the system are modeled using the standard five parameter diode model pictured in Fig. 4 [7]. Its current/voltage relationship is given by Eq. 1.

$$I = I_L - I_O \cdot \left[\exp \left(\frac{V + I \cdot R_s}{a} \right) - 1 \right] - \left[\frac{V + I \cdot R_s}{R_{sh}} \right] \quad (1)$$

Determination of the current I and voltage V requires knowledge of the light current, I_L , diode reverse saturation current, I_O , series resistance R_s , and shunt resistance R_{sh} and modified ideality factor a .

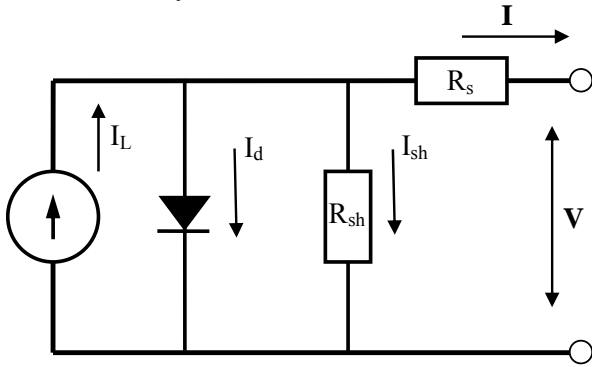


FIGURE 4. EQUIVALENT CIRCUIT FOR A PV GENERATOR

These parameters, described in detail by Lorenzo et al. [7], are all determined from the manufacturer's panel data at reference conditions, then adjusted using the cell's actual insolation and operating temperature at other conditions. The panels also each have two bypass diodes, each with an assumed forward voltage drop of 0.7V. In all simulated cases, each panel is assumed to be completely unsoiled and unshaded, with negligible performance deviations caused by the manufacturing process; in this way it is assured that all performance variations are attributed only to differing panel orientations within the arrays.

MICs

The dc-dc converters are modeled under steady state conditions [3]. The input control signals are duty cycle and frequency for each stage. Sources of converter power loss included in this model (later referred to as "insertion loss") are the MOSFETs' on-resistance and inductor copper loss.

Additionally, there is a small amount of power required for several of the MIC's on-board controllers, which in the most recent prototype is a constant 0.75W in buck or boost mode and 0.5W in pass-through mode for each converter. The converter model output is adjusted so that its efficiency approximates the average experimentally determined power stage efficiencies, which are above 95% during most of the normal range of operation and approximately 98% in pass through mode as shown in Fig. 5 [3].

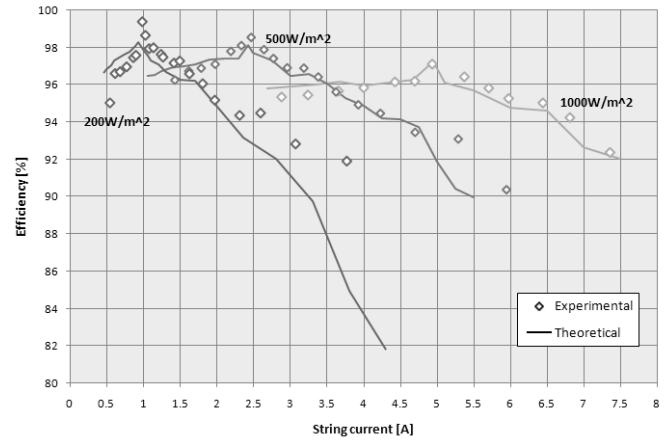


FIGURE 5. PREDICTED AND MEASURED EFFICIENCIES FOR 85 WATT PROTOTYPE MIC UNDER DIFFERENT LEVELS OF SOLAR IRRADIATION

Inverter

As previously mentioned in this paper, conventional inverters include a dc-dc converter to regulate their input voltage. The efficiency of the centralized converter (and thus the inverter) is dependent upon the voltage made available by the PV panels, which can be highly variable in a conventional system that is operating under non-uniform conditions. The efficiency of the inverter stage of a PV system can vary greatly between a system with MICs controlling the inverter's input voltage and a system without this feature.

A study of the conversion efficiency of inverters with different input voltages [8] found that while inverter behavior varies significantly depending on topology and manufacturer, there does exist a trend that isolated (with transformer) inverters tend to perform better at low input dc voltages, whereas non-isolated (transformerless) inverters see their maximum efficiency at higher input dc voltages. In all cases, the inverter efficiency varies more with input voltage at lower power, which is a concern for arrays with multiple, possibly non-optimal orientations.

For the purposes of this paper, a non-isolated inverter was chosen for simulation. Non-isolated inverters, by operating at a higher input voltage (and thus lower current), have decreased wire losses and tend to have higher efficiencies than their isolated counterparts. Furthermore, as MICs are able to control the string voltage feeding the inverter, they are ideally situated to allow a PV system to take advantage of these benefits.

Figure 6 illustrates the conversion efficiency for the Sunny Boy 3000TL, a European inverter. Its efficiency is highest at an input voltage of ~ 400 Vdc, which correlates well with the voltage produced by a 2 kW single series string array of the previously-described Shell PV panels, as well as with a 4 kW array consisting of two parallel strings. Though the efficiencies shown are for a specific 3 kW inverter, the Sunny Boy line also includes 2 kW and 4 kW models which have the same input voltage ranges and rated efficiencies, suggesting that they exhibit the same behavior.

The inverter included in the simulation of a PV system with MICs demonstrates the efficiencies shown in Fig. 6, with identical performance trends simply scaled to account for the higher and lower rated power of the modeled arrays. For each simulated hour, the output power of the photovoltaic array is multiplied by the appropriate inverter efficiency to find the total system power produced.

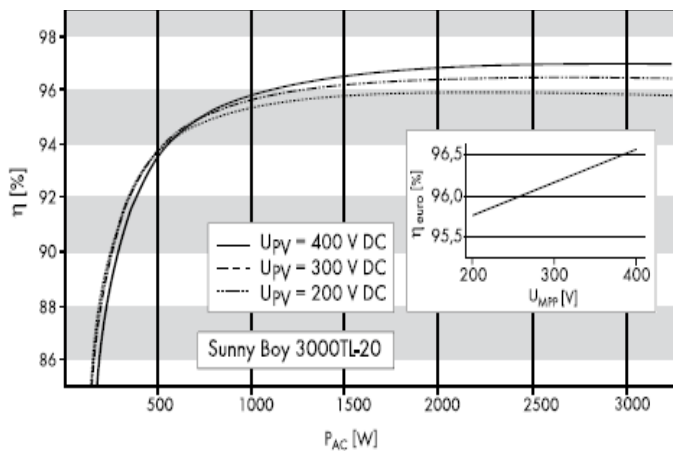


FIGURE 6. INVERTER EFFICIENCY VS. OUTPUT POWER AT DIFFERENT INPUT VOLTAGES. DATA FROM NONISOLATED SUNNY BOY 3000TL¹

System

At the system level, the simulation model allows the user to select array size and configuration (single series string vs. set of parallel series strings), the string voltage (with MICs) and the module size (number of PV cells per dc-dc converter). The simulated systems vary in size and configuration, described in the Annual Simulation Details section of this paper. All simulated systems have one converter per panel (36 cells), and a controlled string voltage of 50 V per panel when MICs are included. In a parallel string configuration, each individual parallel string is modeled to have a combiner blocking diode with a forward voltage drop of 1 V, to prevent reverse string currents when they are operating under nonuniform conditions.

Experimental Verification

Model results have been validated with experimental data [3]. When directly compared with the prototype system experimental results for a small single-string PV system with

differently-oriented panels, the simulation model's predicted results are 5-15% higher in the test system both with and without MICs. This is attributed to measurement bias errors and additional testing is planned. However, because the simulated result predictions are uniformly higher regardless of system configuration, the comparative converter performance is consistent with the experimentally obtained data, demonstrating that the model's behavior correlates well with the experimental prototype converter.

ANNUAL SIMULATION DETAILS

Annual simulations are performed for standard residential-sized BIPV systems, examining the impact of MICs on power output for both series and parallel configurations. Results presented in this paper account for the MICs' effects on panel power generation and inverter efficiency.

System Geometries and Configurations

Four common roof configurations are considered, pictured in Fig. 7, each with a BIPV system that has portions of its array facing in two different directions and a standard 5:12 residential roof pitch. The east-west and south-west direction pairs simulated were chosen to represent typical 180° or 90° roof joints; results of these simulations may also be applied if the building is rotated directionally. System size varies, with one design consisting of a 2 kW single series string and the other consisting of two strings wired in parallel, for a total array size of 4 kW.

Figures 7(a) and 7(b) show roof configurations with significant area for PV panels in multiple directions, providing potential to divide the array into parallel strings, each with its panels facing in only one direction, depending on roof size and rated inverter input dc voltage. In this paper, each of the arrays representing these situations is simulated with the panels divided evenly per direction. The arrays are simulated for two electrical configurations: two parallel strings and a single series string.

Figures 7(c) and 7(d) represent realistic cases where the available area for PV panels is greater in one direction than the other, reducing the potential for optimal use of parallel strings. Each of these arrays is also simulated in both series and parallel configurations. In the former, a single series string of 24 panels is simulated, with 18 facing in one direction and 6 facing in the other. In the latter, each array is modeled with two parallel strings, one with all of its panels facing in a certain direction, and the other with half of its panels matching the first string and half oriented in a different direction.

¹ Sunny Boy inverter specifications available from the manufacturer, SMA Solar Technologies

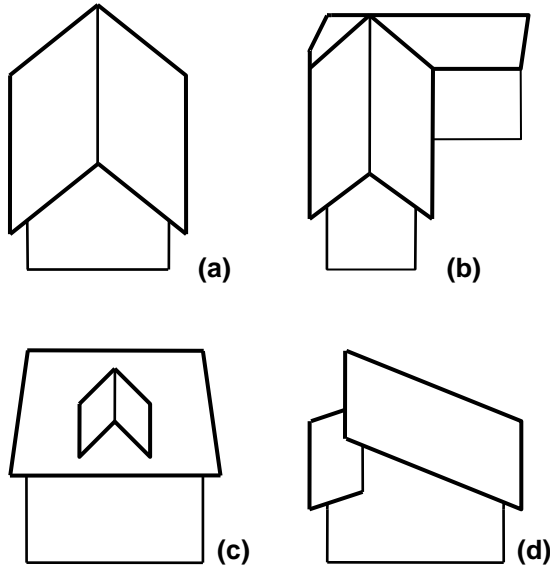


FIGURE 7. REPRESENTATIVE ROOF GEOMETRIES SUITABLE FOR BIPV.
(A) SINGLE GABLE, (B) CROSS GABLE, (C) DORMER, AND (D)
CLERESTORY

Climate Data

Simulations were performed using TMY2 and TMY3 weather data² for a representative set of US cities. These data include hourly total insolation and direct beam radiation on a horizontal surface, as well as ambient temperature. Total insolation on the tilted panel surface was calculated from these data using the HDKR model [9], which accounts for direct, diffuse, and ground-reflected radiation components, as well as the effects of circumsolar diffuse radiation and horizon-brightening.

Cell Operating Temperatures

Cell operating temperatures were calculated using the panels' nominal operating cell temperature (NOCT). Equation 2 is used to calculate the cell operating temperature at any irradiance or ambient temperature [1, 10].

$$T_{\text{cell}} = \frac{G}{G_{\text{NOCT}}} \cdot (\text{NOCT} - T_{\text{ambient, NOCT}}) \cdot \left[1 - \frac{\eta_c}{\tau \cdot \alpha} \right] + T_{\text{ambient}} \quad (2)$$

In this equation, $G_{\text{NOCT}} = 800 \text{ W/m}^2$, $T_{\text{ambient, NOCT}} = 20^\circ\text{C}$, $\eta_c = 13.5\%$, and $\tau\alpha$ is assumed to be 0.9. The variables G (irradiance) and T_{ambient} are procured from the hourly weather data. However, this equation assumes that the panel is mounted in a standard roof-mount configuration, rather than integrated into the roof in a BIPV application. BIPV panels tend to operate at a higher temperature because there are no convective and radiative heat losses from the back of the panel; instead they exhibit conductive heat loss which is very dependent on

the installation method and roof construction. To account for this, the difference between the cell and ambient temperatures calculated in Eq. 2 is multiplied by 1.75, assuming that the back of the panel has limited conductive heat transfer. Resulting cell temperatures correlate well with experimental BIPV cell temperature data [10].

ANNUAL SIMULATION RESULTS AND ANALYSIS

Simulation Results

An initial set of annual simulations of power output for typical residential-sized BIPV arrays comprised of Shell Solar's PowerMax Ultra 85-P panels is performed for Boulder, Colorado. The purpose of these simulations is to compare the power output of a system with MICs to a conventional system, examining performance in the power generation portion of the system as well as in the inverter. A summary of the findings is found in Table 1. It should be noted that all of the simulation results describe a system with MICs applied with a conventional nonisolated inverter, which includes an internal dc-dc converter that would be redundant in a system with MICs, and that accounts for most of the inefficiency of a conventional inverter [11].

Simulation results show that the series string arrays achieve the highest gains in annual output power when using MICs. As discussed previously (see Fig. 2), PV modules with different irradiances operate optimally at very different current levels. In a string configuration with insolation mismatches, MICs enter buck or boost mode to modulate panel voltage, allowing the modules to operate at their independent maximum power points while maintaining the necessary single string current. The series string configuration in Boulder shows modest power output gains with the use of MICs, with a maximum annual gain of nearly 5% for a south-west oriented array and over 9% for an east-west oriented system. Greater gains for the east-west system arise from a greater frequency of large insolation mismatches between halves of the array. Large mismatches provide more opportunity for power recovery with modular control because without MICs, portions of the mismatched string are forced to operate farther from their maximum power point than they would were the insolation levels more closely matched.

Arrays that include parallel strings show decreased gains, or even slight losses in power output when the MICs are included in the array. The basic reason for this is that there is not as much potential for power recovery under mismatched conditions in parallel arrays. Individual parallel strings in a system each must operate at the same voltage, with independent currents, and Fig. 2 demonstrates that the optimal operating voltages of photovoltaic generators do not vary much with irradiance, indicating that each parallel string will often be able to operate very close to its maximum power point even if it has a different irradiance from neighboring strings. Thus the benefit of the MICs in parallel situations is not always enough to overcome their inherent insertion loss.

² TMY weather data obtained from NREL

TABLE 1. SIMULATED IMPACT OF MICs ON ANNUAL POWER OUTPUT FOR DIFFERENT CONFIGURATIONS OF 2 kW (SERIES STRING) AND 4 kW (PARALLEL STRINGS) BIPV ARRAYS IN BOULDER, COLORADO

Orientation	Array Configuration	Annual Output Power % Gain by Part		Total System % gain with MICs
		Power Generator	Inverter	
East - West	Series String: 50% W, 50% E	9.0%	0.3%	9.3%
	Series String: 75% W, 25% E	4.8%	0.4%	5.2%
	Series String: 25% W, 75% E	5.6%	0.5%	6.1%
	2 Parallel Strings: 50% W, 50% E	-4.8%	0.1%	-4.8%
	2 Parallel Strings: 75% W, 25% E	4.4%	0.1%	4.5%
	2 Parallel Strings: 25% W, 75% E	4.2%	0.1%	4.4%
South - West	Series String: 50% S, 50% W	4.7%	0.2%	4.9%
	Series String: 75% S, 25% W	1.8%	0.2%	2.0%
	Series String: 25% S, 75% W	3.0%	0.2%	3.2%
	2 Parallel Strings: 50% S, 50% W	-4.6%	0.1%	-4.5%
	2 Parallel Strings: 75% S, 25% W	-1.1%	0.1%	-1.0%
	2 Parallel Strings: 25% S, 75% W	-1.3%	0.1%	-1.2%

Such is the situation in the system with two parallel strings with panels evenly divided in two directions; there is very little power for the MICs to recover, as both strings operate very near their maximum power points even without MICs present. This case leads to an output power loss of 4.8% with MICs, and is a “worst case” scenario, as there are assumed to be no mismatches within the individual strings, which does not often occur in real rooftop applications.

The other systems with parallel strings have a configuration in which one string has a uniform insolation and the other is evenly divided between two insolutions. In these cases, there is little power recovery from the first half of the system, the uniform string, but the second half of the system, the string with two orientations, experiences gains from the MICs as previously described in this section for a series string with insolation mismatches. These arrays show less gain than their single series string counterparts as increased power capture with MICs really only comes from half of the array. As in the earlier series string case, the arrays with an east-west orientation exhibit the largest gains, again because of larger insolation mismatches.

Annual power gains associated with the increased inverter efficiency from the use of MICs are very small, accounting for less than one half of one percent. This is partly a function of the well-designed inverter, which performs consistently under a wide range of input voltages. Also, the benefits from the

inverter are less significant in the parallel case, because the parallel strings show less variation in input dc voltage production.

The optimal orientation and configuration scenario with MICs, a single string array with its panels evenly distributed facing in opposite directions (west-east), is then simulated for five other representative cities in the US. The cities are chosen to demonstrate geographical and climate variation and preference is given to areas in which PV use is practical. Results of these simulations are presented in Table 2. The results show that the greatest benefit from the use of MICs is available in climates with the most direct sunlight, such as Phoenix and Boulder, because direct sun encourages greater insolation mismatches between differently oriented PV panels in the series string. Large insolation mismatches allow the MICs to provide the most benefit to the photovoltaic generators and also to the inverter.

Further Analysis of Results

These simulations were conducted on an annual basis to fully understand realistic system performance with MICs in an actual building climate. Figure 8 compares the system output power ratios with and without MICs for one of the system configurations modeled in this paper, a 2 kW single string array with half of its panels pointing in each of two directions. While this system with MICs can achieve a simulated

TABLE 2. SIMULATED IMPACT OF MICs ON ANNUAL POWER OUTPUT OF A SINGLE SERIES STRING 2kW BIPV ARRAY IN VARIOUS US CITIES

Orientation	Location	Annual Output Power % Gain by Part		Total System % Gain with MICs
		Power Generators	Inverter	
East - West	Boulder, CO	9.0%	0.3%	9.3%
	Los Angeles, CA	8.3%	0.3%	8.6%
	Washington DC	7.6%	0.3%	7.9%
	Orlando, FL	7.1%	0.3%	7.3%
	Phoenix, AZ	10.0%	0.6%	10.6%
	Chicago, IL	8.1%	0.3%	8.3%

instantaneous power gain of over 40%, this magnitude of gain only occurs when there is a large insolation mismatch between the two panel directions. In fact, below a mismatch of approximately 20%, the insertion loss of the MICs actually causes a small reduction in system power output. The annual simulation of a system includes many hours with limited availability of the solar resource and small mismatch ratios between the different directions' insulations, both of which lead to decreased gains with MICs.

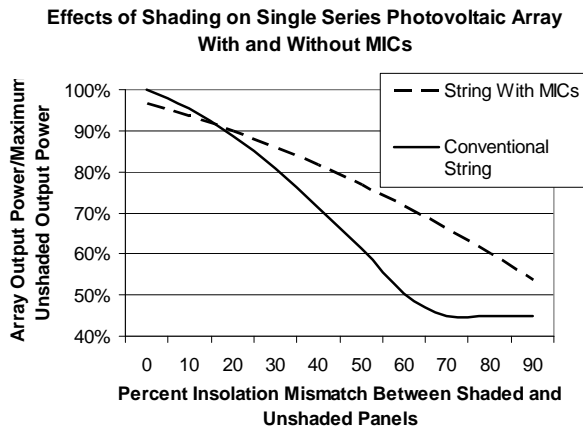


FIGURE 8. EFFECT OF SHADING ON A SERIES STRING PV ARRAY WITH AND WITHOUT MICs. DATA SHOWN IS FOR A 2 kW SYSTEM OPERATING WITH AN UNSHADED IRRADIANCE OF 1000 W/m² (CELL TEMPERATURE = 45°C). SHADING OCCURS ON HALF OF THE ARRAY PANELS.

Figure 9 illustrates the annual insolation frequencies and percent insolation mismatch between panels during daylight hours for the Boulder west-east oriented simulation case. Interestingly, with the exception of low insolation levels with a low degree of orientation-associated mismatch (which represent cloudy hours), the insolation levels and mismatches are fairly evenly distributed. However, one third of hours with any available sunlight have an insolation mismatch of less than 20%, which equates to a slight power loss in a system with MICs. The hours with most significant gain potential from the insertion of MICs are those with a relatively high insolation (>500 W/m²) as well as a relatively high insolation mismatch between the different orientations (>40%). Figure 9 shows that these cases occur together during approximately one fifth of the daylight hours. Assuming a average gain of approximately 35% for a system with MIC insertion in these cases, the total annual output power gain of the system would be at least 7%. In fact it was measured to be over 9% for the Boulder west-east evenly divided single string simulation, demonstrating that the MICs do perform as expected in the system on an annual basis.

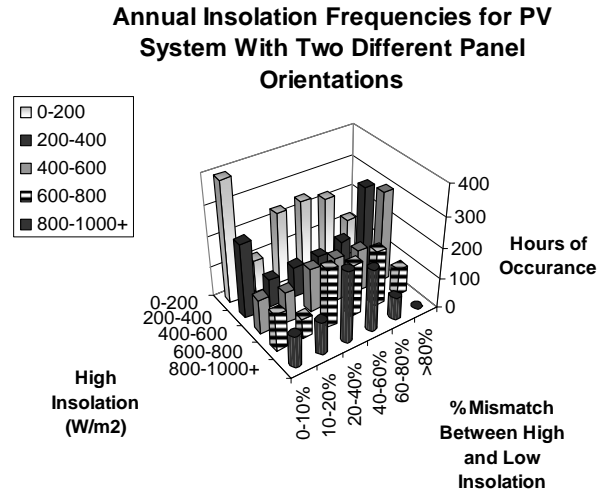


FIGURE 9. ANNUAL INSOLATION FREQUENCY DISTRIBUTION FOR A BIPV SYSTEM WITH EAST AND WEST FACING PANELS, LOCATED IN BOULDER, COLORADO AND MOUNTED ON A STANDARD 5:12 PITCH ROOF

Additional Opportunities

These simulations consider only operating mismatches that arise from differences in panel orientation. Panel orientation variances tend to produce smaller radiation disparities than other potential sources of operation nonuniformity, while simulation results clearly indicate that the greatest opportunities with MICs come with large radiation variances. Greater power gains from the MICs are possible if other sources of nonuniform operating conditions are taken into account. These would include shading, array soiling, and any performance nonuniformities arising from the cell manufacturing process.

Additional opportunities for increased power capture exist through optimization of system components. For instance, power used by the on-board controllers in the present instantiation of the converter prototype could be reduced through design optimization. Also, the operating range of the converter's pass-through mode could be optimized to increase the time that the converter is able to operate in this state, while still maintaining an acceptable string voltage input to the inverter. Both of these measures would decrease the converter's insertion loss, increasing its overall efficiency.

Additionally, previous studies indicate that no more than one percent of the inefficiency associated with power conversion comes from the inverter itself, with the large majority due to the associated input voltage converter [11]. These central units are designed to handle large voltages and large voltage and current variations. They are also generally less efficient and more expensive than the small MICs proposed in this paper, which due to their modularity are designed with smaller, cheaper, and more efficient components. Future PV systems with MICs will control the string voltage at the MIC level, which will improve the system efficiency by eliminating the need for a central converter. The inverter for such a system can also be optimized with a design that operates at a fixed dc input voltage that is slightly higher than the ac-line voltage.

CONCLUSIONS AND FURTHER RESEARCH

BIPV systems represent a way for architects and building owners to employ environmentally friendly technologies directly into buildings, offsetting some of the price PV systems with decreased construction costs. However, inherent limitations of the PV series string place limitations on the effectiveness of these systems when used in common building and roof geometries. While working to directly increase the efficiency of solar cells does yield some power gains, there is a greater impact in mitigating the effects of nonuniformities in operating conditions. Authors of this paper are among the researchers exploring the use of module integrated converters to capture lost energy due to nonuniform operating conditions [3].

The model developed here allows for variations in temperature and irradiance at the cell level, as well as for PV modules to be connected in series or parallel configurations to form arrays of any size or orientation. It accounts for potential power gains associated with both the photovoltaic generators and increased system inverter efficiency. In all simulated cases, performance variations between systems with and without MICs account only for differing panel orientations within the arrays, and effects such as shading, soiling, or manufacturing variations are ignored. While previous measurements have proven the MICs to have some gain potential, annual simulations most accurately show benefits in real environments with real weather data.

Results of these annual simulations, performed with differing array orientations, configurations and climates, show that the inclusion of MICs in a PV system has the greatest benefit when separate PV strings or panels have a high level of insolation mismatch, which may occur in cases with differences in roof orientation. The benefit of MICs further increases in climates with the greatest solar availability (beam radiation), where PV systems are most likely to be popular. The use of MICs in BIPV systems with complex geometries results in the potential for output power gains of over 10% annually. Most of these power gains may be attributed to increased energy output of the photovoltaic generators, achieved through effective modular power point tracking and control. Small gains are also observed to arise from increased efficiency of the central system inverter, as MICs allow it to operate at a constant, optimal voltage.

Distributed power conversion shows additional potential for gains in other portions of the PV system. For instance, with the constant string voltage set by MICs, the efficiency of the central inverter may be further increased by removing its associated dc-dc converter. Furthermore, MICs show great promise to mitigate power losses caused by operating mismatches that arise from sources other than differing roof geometry, including shading from surroundings and cell manufacturing performance mismatches. Further research will focus on quantifying these benefits.

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