OPTIMAL CELL CONNECTIONS FOR IMPROVED SHADING, RELIABILITY, AND SPECTRAL PERFORMANCE OF MICROSYSTEM ENABLED PHOTOVOLTAIC (MEPV) MODULES

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ABSTRACT

Microsystems enabled photovoltaics (MEPV) is a recently developed concept that promises benefits in efficiency, functionality, and cost compared to traditional PV approaches. MEPV modules consist of heterogeneously integrated arrays of ultra-thin (~2 to 20 μm), small (~100 μm to a few millimeters laterally) cells with either one-sun or micro-optics concentration configurations, flexible electrical configurations of individual cells, and potential integration with electronic circuits. Cells may be heterogeneously stacked and separated by dielectric layers to realize multi-junction designs without the constraints of lattice matching or series connections between different cell types. With cell lateral dimensions of a few millimeters or less, a module has tens to hundreds of thousands of cells, in contrast to today's PV modules with less than 100. Hence, MEPV modules can operate at high voltages without module DC to DC converters, reducing resistive losses, improving shading performance, and improving robustness to individual cell failures.

Because these 'multi-junction' cells are integrated heterogeneously versus monolithically, different cell types need not be directly connected in series, improving the efficiency under conditions where different cell outputs are not ideally matched, for example with high incident angles in late afternoon. Instead, different numbers of same cell types are first connected in series, producing an intermediate common voltage, and then these 'micro-strings' of different cell types are connected in parallel. Further series and parallel connections enable module voltages of a few hundred volts in small areas (~ 18 x 20 cm) and allow nearly ideal linear degradation with shading across an installation of multiple modules.

We present details of these cell interconnection designs and performance under spectral and shading variations of the incident solar radiation for MEPV modules designed with heterogeneously stacked cells and single cell designs, and simulations of the relative efficiency of MEPV modules versus the probability of open and shorted cells.

INTRODUCTION

Microsystem enabled photovoltaic (MEPV) modules, comprised of many thin (few μm), small (few hundred μm to few mm, laterally) cells, build on micro-fabrication concepts developed in other technology areas (e. g., MEMS, ICs) to potentially yield modules with higher efficiency, lower cost, and enhanced functionality compared to today's photovoltaic modules [1,2]. One sun and concentrating systems with integrated micro-optical lenses have been proposed. Thin cells have been recently fabricated using epitaxial-lift off in Si and GaAs with efficiencies exceeding 10% [1,2]. Heterogeneously integrating (i.e., vertically stacking) different cell types with dielectric layers between them can yield high performance 'multi-junction cells' with superior performance by freeing the designer of both the lattice matching and series connection constraints of monolithic multi-junction cells. MEPV systems also can offer better thermal management, and new and simpler methods for optical solar tracking, and concepts that allow large scale, low-cost assembly of the cells into modules [2].

Here, we extend the cell connection concepts presented in [3] for conventional PV arrays to electrically connecting the cells within a MEPV module that can achieve improved performance under spectral and shading variations of the incident solar radiation, and show simulated shading performance of PV installations consisting of multiple modules of these types. We will also present simulations of the relative efficiency of an example MEPV module as a function of probabilities of individual cell open and short circuit failures.

CELL CONNECTIONS

It is well known that each cell type under solar radiation will approximately operate at a given known voltage and the cell's current will vary with solar intensity, With MEPV's flexible connections, we can connect different numbers of each cell type in series to arrive at a nearly matched intermediate higher voltage and connect those independent cell micro-strings in parallel effectively adding the currents. Further series and parallel connections enable module voltages greater than a few hundred volts in a small area (~ 18 x 20 cm) and allow nearly linear degradation with shading across an installation of multiple modules. An example MEPV module might be comprised of the cells listed in Table 1.

Cell Type	Eg	Vop	Ser Cells	Ideal V	Par Str	Cells / Grp	Ser Grp	Par Grp
Ge	0.7	0.3	36	10.8	2	72	20	24
Si	1.1	0.57	18	10.26	4	72	20	24
GaAs	1.4	0.9	12	10.8	6	72	20	24
InGaP	1.9	1.3	8	10.4	12	72	20	24

Table 1: Cell types, band gap, and operating voltages for the cells used in the analysis and simulations, and a summary of the cell numbers and connections. The module that was analyzed had 192 x 180 = 34560 cells of each type and operated at 205.2V.

The first step is to pick the intermediate operating voltage for a group of cells, so as to minimize the operating

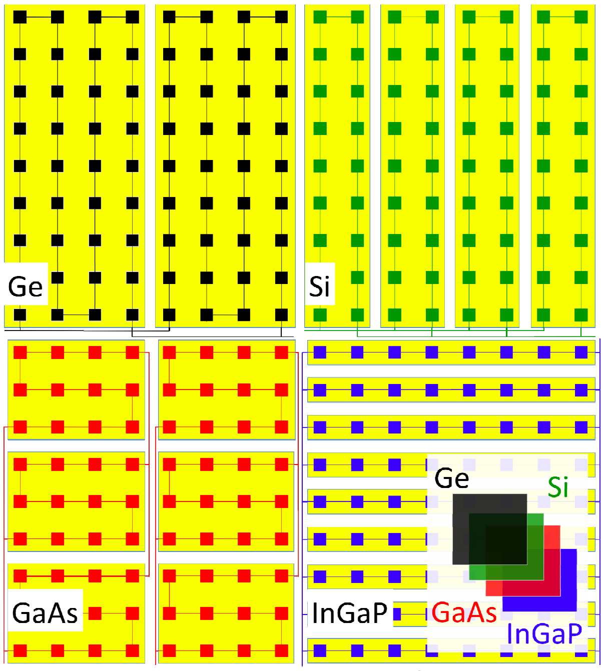

Figure 1: Example connections of 72 stacked, 4 junction cells. The lower right shows a single stacked cell order. In the rest of the figure, series connected diodes are shown in a yellow box; all yellow boxes are connected in parallel. The different cell types are stacked, not side-by-side.
Ge: 2 parallel groups of 36 series cells @ 0.30V;
Si: 4 parallel groups of 18 series cells @ 0.57V;
GaAs: 6 parallel groups of 12 series cells @ 0.9V;
InGaP: 9 parallel groups of 8 series cells @ 1.3V;

voltage mismatch. We define a group containing 72 instances of each cell type. There are 2 groups of 0.3V Ge cells (36 in series in each group), 4 groups of 0.57V Si cells (18 in each group), 6 groups of 0.9 V GaAs cells (12 in each group), and 9 groups of InGaP cells (8 in each group). Physically, these 72 diodes can be arranged in a 8 x 9 array, and with 5 mm spacing between cells; the size of the group will be 4 cm x 4.5 cm. In this case, because the voltages don't match exactly, the operating voltage of the group will be equal to the lowest voltage of the series connections or 10.26V. This does cause a significant 2.7% decrease in relative efficiency (with a flat spectrum) compared to a design with each cell operating optimally. A more complex layout with 819 cells per group (vs. 72) can reduce this penalty to only 0.6%.

In a traditional monolithically grown multi-junction cell, if one diode type has its current reduced by 10% compared to the design case, for example as spectrum changes throughout the day, the entire multi-junction cell power output will be reduced by approximately 10% as the current in the series connections will be limited by the cell with the least current. In the MEPV approach, because only one type of cell is initially connected in series, the other cells remain unaffected. For example, a 10% reduction of the current from one cell type yields a reduction in array current from 1.0% to 4.3% depending on which diode has the reduced solar input. This result confirms that an MEPV design can be less susceptible to output power reductions from spectral shifts that affect the response of the diodes in an unequal manner. Later, we present results using full I-V curves for the individual cells where we can also include differences in the optimal voltage outputs. Today, most silicon modules series connect ~ 72 cells, each with an open circuit voltage of ~0.6V to get an open circuit module voltage of ~ 40V. The cells are large (~3"), so there are only a few (~ 3) groups of series connected cells in the module. This makes the module susceptible to shading over a portion of the module.

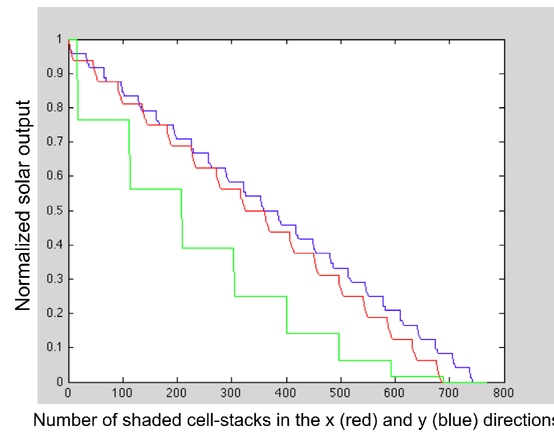

Figure 2: Plot of the normalized solar output of 4 modules, each at 205V as described in the text, in both the x (red) and y (blue) directions as shading progresses in one dimension across the modules. The approximate performance of a conventional installation with ideal bypass diodes for each half module is shown in green.

For example, if the bottom sixth of the module is in the shade, the entire output of the module is greatly degraded. In our case, we have many more cells, and we can make the module and PV installations consisting of multiple modules less susceptible to shading.

There are many possibilities for connecting the groups of diodes in Fig. 1 to get a larger voltage output. For example, 20 of the 72 cell groups could be series-connected to reach 205.2V. This 205V 'super-group' requires an area of 18 cm x 20 cm with 5 mm micro-optics. A module with an area of ~ 0.9 square meter might have ~24 of these super-groups connected in parallel. Therefore, shading within a module only adversely affects the super-groups that are shaded, unlike current modules where partial shading can adversely affect a large fraction of the whole module and an installation of several modules as well.

It is advantageous to use high voltages within the module to reduce the losses in the metallic lines that connect the cells together. On the other hand, if the voltages are too high, it will require greater separation between bus lines and the modules themselves to avoid the possibility of arcing.

MODULE TOLERANCE TO PARTIAL SHADING

In addition to lower losses with higher voltage modules, there is an increased tolerance to partial shading across a module and across an installation of modules. Figure 2 shows the simulated relative output of an installation consisting of four 205V modules in each direction as shade progresses across the installation. The individual cells are modeled as current sources with a given operating voltage, the shading is modeled as a sharp transition between light and dark, and series connected cells have a current equal to the minimum current of all the cells connected in series. As shading progresses across the installation, the output decreases in a stepped fashion that approximates an optimum linear decrease. This is simply because MEPV design yields a high voltage in a small area. Similar shading performance is realized in both stacked cell and single cell type designs.

MODULE PERFORMANCE WITH SHORTED AND OPEN CELLS

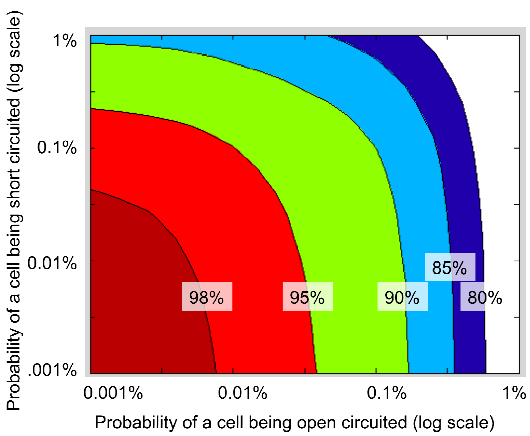

Figure 3: Simulated contour plot of the relative efficiency of the MEPV module as a percentage of a fully working module versus probability of a cell being open (x axis) or shorted (y-axis) for the modules described in the text, plotted on a log scale. The contour curves correspond to 80%, 85%, 90%, 95%, and 98%. Each of 256 data points (5 per decade) was calculated by averaging many (800) independent trials.

With so many cells, we are also interested in the performance as a function of the failure rate of the cells. We believe that the cell reliability will be high, based on low currents per cell and manufacturing contacting methods similar to those used in the electronics industry for flip-chip integrated circuit packaging. Figure 3 shows the expected output of the module versus the probability of a cell open and short circuit. Each cell is modeled as a current source operating at a given voltage. For an open circuit, the cell generates no current and a series connection of cells will generate no current for a single open cell. For a short circuit, the voltage on a series connected string is reduced by the voltage in one cell, and for parallel strings, if any series string has a shorted cell, the voltage on the parallel connection of them is reduced by the voltage of that cell. This module is more susceptible to open cells compared to shorted ones, but that depends on the exact cell-wiring configuration. We have similarly calculated relative efficiencies versus cell operating voltage and current variations.

VARIATIONS IN CELL CURRENT

The module performance as a function of variations in cell current and voltage was calculated by using a Gaussian distribution of both the operating currents and voltages across all cells in the module example. As before, series connected cells (or groups of cells) have their voltages equal to the sum of the voltages, and their currents equal to the minimum of the individual ideal operating currents in the cells or groups of cells. Parallel connected ‘micro strings’ of cells have their voltage equal to the minimum ideal operating voltage of the micro strings and their currents equal to the sum of the currents in the micro strings.

The results of the simulation are shown in Figure 4. It is interesting that a 10% variation in current (both up and down) causes an 18% variation in module performance. This can be explained as follows.

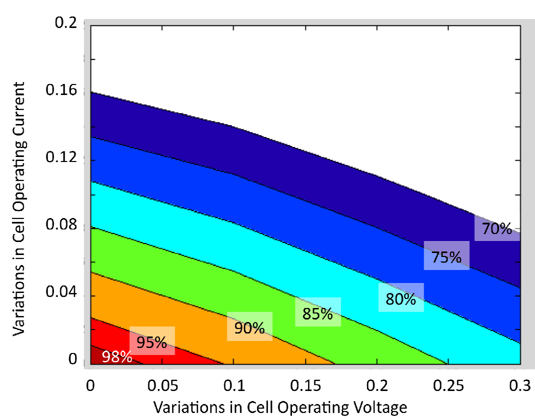

Figure 4: Simulated contour plot of relative efficiency of the module as a function of the standard deviation of the ideal individual operating voltages, (x-axis), and currents, (y-axis). The contours from 0,0 outward are 98%, 95%, 90%, 85%, 80%, 75%, and 70%.

Consider a number of diodes in series. Because the MINIMUM current sets the string current, it will always be less than the nominal current. For our case, the micro string lengths are 36, 18, 12, and 8. So, the nominal current in the 72-element group with a 10% standard deviation can be simply calculated to be 83.78%. Hence with a standard deviation of 10%, the relative loss in efficiency for the group is 16.22%.

As we connect 20 groups in series to form a super-group, we might expect there would be variation in characteristics in the groups, and because they are connected in series, there would be a further reduction in current. Indeed, that is what is observed in the figure 4, the actual number is 81.47% (although there were only 10 trials in that calculation) but the loss of efficiency as a result of those series connections are not as significant as the individual diodes – most likely because the 4 groups of 72 diodes already is a fairly large sample size. The last parallel connections will not show any further degradation in expected currents.

VARIATIONS IN CELL CONNECTIONS

It is evident that there are many possible cell connections to optimize. This section shows a quick comparison of all possible cell combinations for a 30 x 30 single cell type (Si) array with terminal voltages between 11V and 68V, with an individual cell operating voltage of ~ 0.57V.

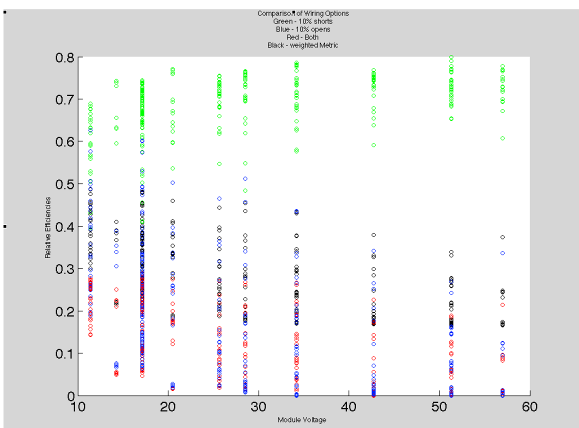

Figure 5: Simulated relative efficiencies (y-axis) for Si only MEPV modules consisting of 900 cells for 272 different cases for terminal voltages between 10V and 60V (x-axis):

1. **10% shorts and 0.1% opens (green)**
2. **10% opens and 0.1% shorts (blue)**
3. **10% opens and 10% shorts (red)**
4. **A metric described in the text (black)**

The first step is to determine the series and parallel connections for optimal tolerance to bad calls. It isn't clear whether opens or shorts would be more likely. With respect to cell variations, it is more likely that the cells would have variations in currents.

We only considered connections in 2 levels; that is, series, parallel, series, parallel, the same as in our other example. One can easily enumerate all the cases for such a small array. The array size of 30 x 30 is equal to 2 x 3 x 5 x 2 x 3 x 5. Thus, any connections in x and y have to use these factors as cells must be arranged as whole numbers. So we enumerated all possible reasonable cases, with voltage targets between 11.4V and 68.4V (20 to 120 diodes in series for 0.57V per diode).

We chose to compare the relative efficiencies for all the designs for four cases:

1. 10% shorts and 0.1% opens (green)
2. 10% opens and 0.1% shorts (blue)
3. 10% opens and 10% shorts (red)
4. A metric of 4 x the sum of the last two plus one times the first one and 1 times 0.1% opens and shorts (black)

A scatter plot of the results is shown below in figure 5. Interestingly, there is a weak dependence on the voltage – it might be expected to be stronger since there are a lot of series connections for higher voltage devices. There are 272 cases in the figure, and it really does show a huge dependence on the interconnection choices, even for the same module voltage.

It is interesting to note, that the one of the better choices (28.5V module voltage) only uses two diodes in series before connecting nine of these micro-strings in parallel. All of the best choices have the attribute of initially connecting only a small number of diodes initially in series, and connecting more groups in series later.

VARIATIONS IN SPECTRAL PERFORMANCE

To calculate the tolerance of the module to variations in incident light spectrum, we need to use a more complex model of the cells that includes their absorption characteristics. We modeled the individual cells using both ideal balance and a more detailed version of the model as described in [4-5]. The 4-layer device described in the example above, isn't the best device to compare a series connected example with our individually connected method, because it is difficult to provide a balanced response for that case. Instead, we chose an example from the literature of an InGaP, GaAs, InGaAs triple junction cell [6]. For this example, we chose to use the technique described in [4] to calculate the I-V characteristics of the individual cells and then adjusted the thickness and surface recombination values to agree with the efficiencies quoted in reference [6] and also adjusted the thicknesses to match the currents in the three diodes to within 0.1% for an AM1.5 spectrum. We then can calculate the individual I-V characteristics and maximum power tracking point, the series connected I-V characteristics and MPPT, and the MEPV module I-V characteristics and MPPT.

In figure 6, we show the group connections for the individually connected cells. We assumed a concentration

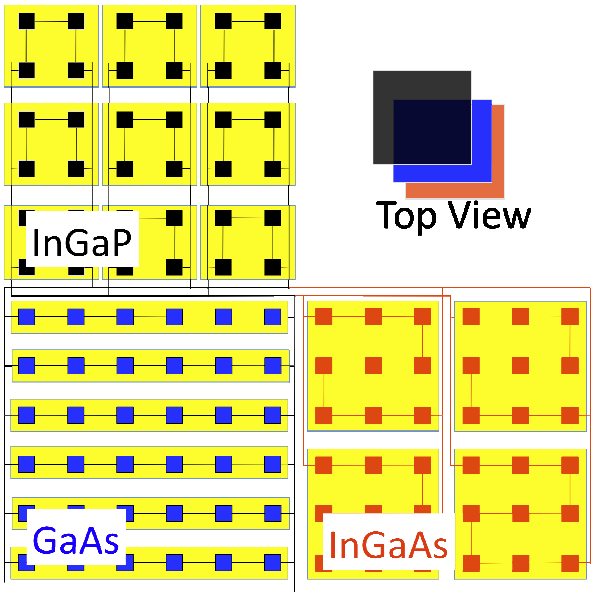

Figure 6: Electrical Connections of cells within a 36-cell group of vertically stacked diodes for the example used for analysis of spectral variations.
InGaAs: 4 parallel groups of 9 series cells @ 0.70V;
GaAs: 6 parallel groups of 6 series cells @ 1.07V;
InGaP: 9 parallel groups of 4 series cells @ 1.59V;
Module Voltage is ~ 192V = 30 series groups x 6.4V

of 50, which is a reasonable value for the MEPV module optics [7]. The ideal operating voltages determined from the calculated IV characteristics for the individual cells were 1.59V, 1.07V, and 0.70V. A reasonable choice for an intermediate voltage is ~ 6.4V, realized with series connections of 4 InGaP cells, 6 GaAs cells, and 9 InGaAs cells. 30 of these modules are connected in series for a module voltage of 192V, and then 4 of those super-groups are connected in parallel for the analysis.

Figure 7 shows the absorption characteristics of cells in the structure. The top curves that are slanted downward with increasing wavelength illustrate the portion of the spectrum that is absorbed by each cell. The dashed lines show the absorbed photocurrent generated by each cell as a function of the wavelength, assuming a flat spectral input. The absorption data for the InGaP and InGaAs cells were derived from shifted GaAs absorption data. The middle set of solid curves shows the contribution to the photocurrent of each cell with the incident spectrum, taking into account the transmission spectra of the cells on top of the bottom two cells.

From the absorption data and the saturation current, J0, we calculate the individual IV characteristics as shown in Figure 8 for an AM1.5 and AM3.0 spectra. We can of course observe the imbalance in current for the three cell types as the spectrum changes from its design point at AM1.5 to AM3.0. The magenta curves are the IV-characteristics for series connected cells. Notice of course, the decrease in the combined photocurrent as

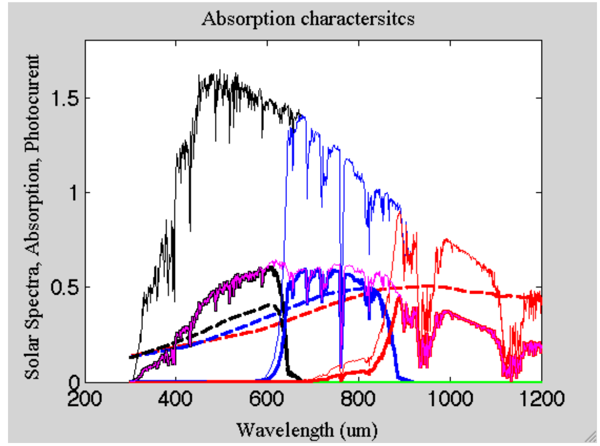

Figure 7: Incident AM1.5 light spectra and the portion absorbed by the InGaP (black), GaAs (blue), and InGaAs cells (top curves); their absorption (dashed curves) as a function of wavelength; and their contribution to the overall photocurrent (bottom solid curves). The magenta curve is the combined overall photocurrent

expected, and its combined value is of course equal to that of the least of the three individual photocurrents.

We then calculated the combined series-parallel-series-parallel IV characteristics for the MEPV module from the

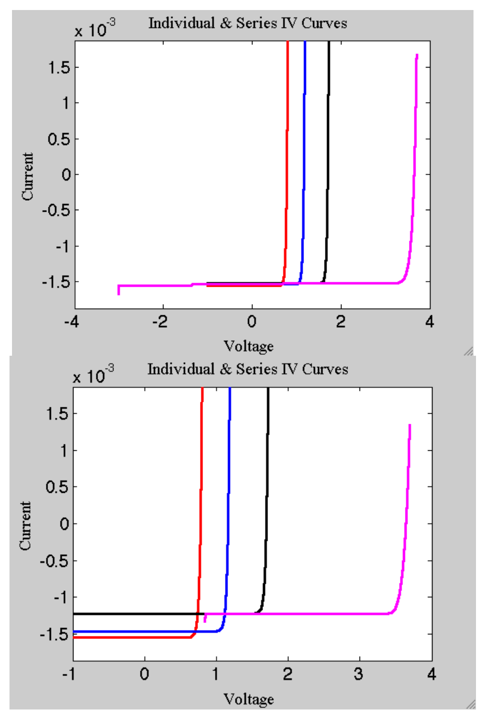

Figure 8: Individual IV characteristics for the three cells (InGaP in black, GaAs in blue, and InGaAs in red) for AM1.5 (top) and AM3.0 (bottom) spectra and combined series connected triple cell characteristics.

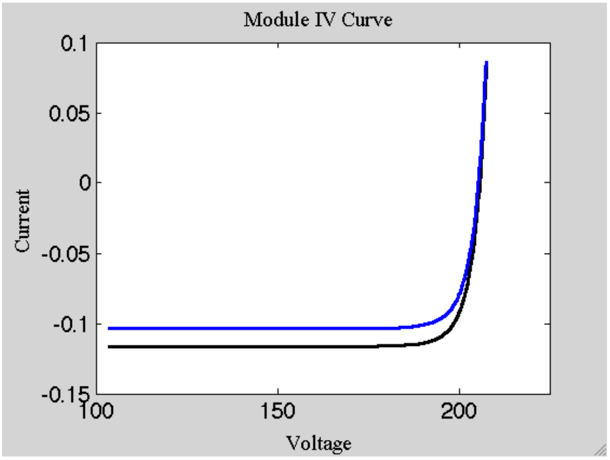

Figure 9: MEPV module IV characteristics for AM1.5 (black) and AM3.0 (blue) incident solar spectra.

individual IV characteristics and the appropriate circuit combinations. The results shown in Figure 9 are from a small module (~ 0.3 m per side), but the result for a larger 1m square module is a simple multiplicative factor (~8-10) times that which we calculated.

Lastly, in figure 10, we calculate the maximum power tracking point for both the series connected triple junction (magenta curves in figure 8) or the combined module (figure 9) as a function of several spectra. The results are normalized to the sum of the individual maximum power tracking points for all the diodes (3 in the case of the triple junction and 12960 for the MEPV module).

We can observe that there is about 7% degradation in the performance of the triple junction from the AM1.5 to AM3.0 spectrum. However, with the series-parallel connections described here, there is less than 1% degradation compared to optimum individual cell maximum power point tracking. That is, even if we had an individual inverter on each cell, we could gain no more than 1% additional efficiency over the technique described here.

CONCLUSION

We have presented connection techniques and simulations highlighting the flexibility of MEPV modules in terms of spectral variations, shading and reliability performance. MEPV is suitable for direct high voltage modules, potentially eliminating the need for DC-DC converters or micro-inverters that are now becoming available for today's PV modules. We presented more detailed calculations of the spectral dependence based on spectral response of the cells and IV characteristics.

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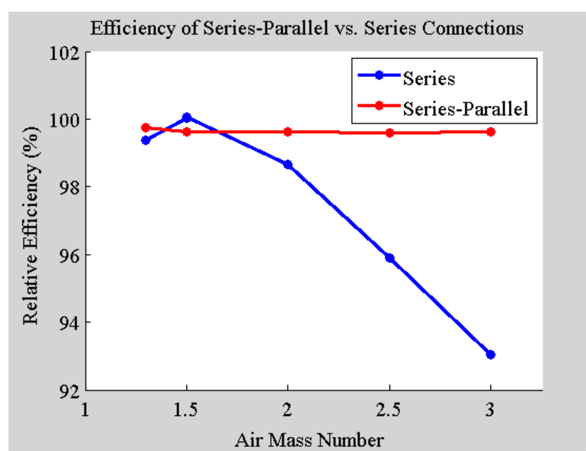

Figure 10: Comparison of the relative efficiency of series and series-parallel connections for varying input spectra