METHODS FOR INCREASING ENERGY HARVEST WITH PV MODULE INTEGRATED POWER CONVERTERS

BY

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THESIS

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Abstract

Increasing energy harvest from PV systems and reducing overall PV system costs are important to the continued adoption of solar energy. In an effort to achieve this, power converters are being integrated into PV modules. These power converters allow for more flexibility in PV system design by enabling each PV module to operate independently. The physical integration of these power converters creates new possibilities to improve the energy harvest. This thesis proposes methods and circuits that leverage this physical integration to further enhance PV module integrated power converters.

A steady-state, SPICE-like, modified nodal analysis based (MNA) simulation tool is developed to study the effects of PV module mismatch and shading on PV systems. This simulation tool is used to calculate the power output of a PV system under varying conditions. This facilitates the comparisons of different algorithms and circuits for increasing energy harvest.

Certain assumptions can be made when it is known that a power converter will only be operating on a single PV module, and extra voltage nodes are accessible when a power converter is physically integrated into a PV module. Two global maximum power point tracking (MPPT) algorithms are proposed that leverage this fact to improve energy harvest.

Different circuit architectures are proposed to enable MPPT for a smaller subsection of PV cells called PV submodules. By tracking the MPP for PV submodules, further energy harvest improvements can be made. The proposed circuits include smaller power converters and multiple input converters for full PV submodule power processing as well as differential power processing (DPP) converters to handle the difference in power between PV submodules.
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1. Introduction

Solar energy provides an excellent source of renewable energy that decreases our need for fossil fuels, reduces greenhouse gas emissions, and decreases air pollution. Despite this, only 0.1% of the United States’ electricity was supplied by solar in 2010. The U.S. Department of Energy has recognized the need for solar energy and has created the SunShot Initiative to reduce the price of photovoltaic (PV) energy systems by about 75% between 2010 and 2020. The goal of this cost reduction is to make the unsubsidized cost of solar energy competitive with the cost of conventional energy sources. In this way, solar could meet 14% of energy demand by 2030 [1].

The goal of the SunShot Initiative is to reduce the cost of PV until there is adequate return on investment (ROI) from the installation of PV systems. Levelized cost of energy (LCOE) is a useful metric for determining the effect of energy production on the ROI of a PV system. LCOE is the ratio of electricity generation costs to the electricity generated by the system over its lifetime. The cost includes installation and operations costs. The LCOE is usually given in cents per kilowatt-hour. The LCOE should be below the price of electricity in order for the PV system to have a good ROI. In order to reduce the LCOE and increase the ROI, either the lifetime energy harvested needs to increase or the system costs need to decrease.

To increase energy harvest and decrease costs, there is a trend in the PV industry to integrate power converters into the PV module. Examples of integrated power converters are TrueAC™ modules with integrated microinverters from SolarBridge Technologies and Smart Modules with integrated dc optimizers from SolarEdge and Tigo Energy [2], [3], [4]. Collectively, these converters will be described as integrated microconverters.

Integrating the power converters directly into the PV module gives new opportunities to increase the energy harvest of PV systems and therefore reduce the LCOE. The focus of this thesis is to show how these integrated power converters can increase energy harvest by monitoring and processing power from groups of PV cells in the PV module. These groups of cells will be known as PV submodules. To date, commercially available integrated microconverters process the entire PV module power as a single power source.

The following paragraphs provide overviews of the subsequent chapters of this thesis.

Chapter 2 introduces the PV models and simulation tools used to analyze energy harvest. The PV models are based on a single-diode model of a PV cell. It is shown how the parameters of this model can be extracted from the PV module’s datasheet. This model is then integrated into a SPICE-like, modified nodal analysis (MNA) based simulation. This simulation gives steady-state data to be used in energy harvest comparisons between different PV systems.

Chapter 3 describes how PV mismatch develops and the effect of mismatch on energy harvest. Mismatch can be caused by manufacturing variation, shading, and cloud cover. When PV submodules are connected together electrically, mismatch causes each PV submodule to operate away from its maximum power point (MPP). The goal of the MPP tracking (MPPT) methods and power converters
presented in this work is to ensure that PV submodules operate closer to their MPPs to increase overall energy harvest.

Chapter 4 describes methods that integrated microconverters can implement to detect the formation of multiple local MPPs. Because the microconverters are integrated into a single PV module and can measure the PV submodule node voltages, algorithms can be developed to detect local MPPs and ensure the PV module is running at the global MPP.

Chapter 5 describes power converters that process full PV submodule power and therefore enable tracking of PV submodule MPPs. To use these converters, the series-connection between PV submodules must be detached. Candidate power converters include smaller microconverters and multiple-input converters.

Chapter 6 describes differential power processing (DPP) converters. DPP converters enable tracking of PV submodule MPPs but only process the difference in power between the PV submodules. These DPP converters can be integrated into the entire PV system or used as a front-end for a module integrated converter. Chapter 6 will examine the advantages and disadvantages of each approach.

Chapter 7 concludes with a summary of the thesis and suggestions on future work.
2. PV Modeling and Simulation

The fundamental piece of a PV installation is the PV cell. The shape of the I-V curve of the PV cell and how connected PV cells interact is what affects energy harvest of the overall system. For this reason, having a suitable model for a PV cell is the fundamental building block of a PV system simulation.

2.1 Single and Double-Diode Models

Two common models are the single-diode model and the double-diode model. The double-diode model takes into account changes in diode ideality with voltage. Near the open-circuit voltage, $V_{oc}$, recombination is predominately in the surface and bulk regions and the diode ideality is close to one; near 0 V, recombination is predominately in the junction and space charge region, and the diode ideality is closer to two [5].

Despite the double-diode’s ability to correctly model some of the second-order effects of the semiconductor in the PV cell, the single-diode model still gives good results. When the single-diode model is corrected with series and shunt resistances, its main weakness is at low irradiance [5]. The effect is minimal in energy harvest studies due to the fact that a higher percentage of energy is harvested at high irradiance. The main advantage of the single-diode model is that it requires fewer parameters to define an I-V curve than the double-diode model. The double-diode and single-diode models are shown in Figure 1.

![Figure 1](image-url)

(a) Single and (b) double-diode models.

Equation (1) gives the PV cell current for the double-diode model. The equation is determined by applying KCL.

$$i = I_{ph} - I_{S1} \left[ e^{\frac{-q(v+iR_s)}{kT}} - 1 \right] - I_{S2} \left[ e^{\frac{-q(v+iR_s)}{kT}} - 1 \right] - V + \frac{v + iR_s}{R_{sh}} \quad (1)$$

Equation (2) gives the current for the single-diode model. It is found by setting $I_{S2} = 0$ in Equation (1).

$$i = I_{ph} - I_{S1} \left[ e^{\frac{-q(v+iR_s)}{kT}} - 1 \right] - \frac{v + iR_s}{R_{sh}} \quad (2)$$

The variables for these equations are defined below. Determining the parameters for the single-diode model is less complicated than the double-diode model. To determine the double-diode model, data must be collected on a PV cell sample over varying irradiance and temperature. With this data, a heuristic curve fitting may be performed to determine the necessary constants for the double-diode model [6]. This requires a great amount of work to model different PV modules.
2.2 Formulation of Single-Diode Model from Datasheet Values

Because the single-diode model does not rely on varying irradiation and temperature, a single data point, such as the values found on a datasheet, can be used to develop a model of a particular PV cell.

2.2.1 Parameter Extraction
The process to extract this model from datasheet values is presented in [7]. There was a mistake in the derivation in [7] that is corrected in [8].

To fully define the single-diode model we need to find the following parameters:

- \( I_{ph} \) = photogenerated current at STC
- \( I_o \) = dark saturation current at STC
- \( R_s \) = series resistance
- \( R_{sh} \) = shunt resistance
- \( A \) = diode ideality factor

The parameters that are needed from the datasheet are:

- \( I_{sc} \) = short-circuit current at STC
- \( V_{oc} \) = open-circuit voltage at STC
- \( V_{mp} \) = voltage at Maximum Power Point (MPP) at STC
- \( I_{mp} \) = current at MPP at STC
- \( k_i \) = temperature coefficient of short-circuit current as a percentage %
- \( k_v \) = temperature coefficient of open-circuit current as a percentage %
- \( N \) = number of series-connected cells in a module

Constants and parameters that are needed are:

- \( k \) = Boltzmann’s constant = 1.38065 \times 10^{-23} \text{ J/K}
- \( T_{stc} \) = temperature at STC in Kelvins = 298 \text{ K}
- \( q \) = the magnitude of electron charge = 1.602 \times 10^{-19} \text{ C}
- \( V_T \) = \frac{kT_{stc}}{q}

Equations (3) - (5) can be simultaneously and iteratively solved for \( R_s \), \( R_{sh} \), and \( A \).

From [8]:

\[
0 = I_{sc} - I_{mp} - \frac{V_{mp} + I_{mp} R_s - I_{sc} R_s}{R_{sh}} - \left( I_{sc} + \frac{I_{sc} R_s - V_{oc}}{R_{sh}} e^{\frac{V_{mp} + I_{mp} R_s - V_{oc}}{NAT}} \right) e^{\frac{V_{mp} + I_{mp} R_s - V_{oc}}{NAT}} \tag{3}
\]
2.2.2 Variation with Temperature and Insolation

With \( R_s, R_{sh}, \) and \( A \) calculated, it is possible to formulate the equations necessary to simulate the PV module and find the PV module’s characteristic I-V curve. The first step is to find the temperature, \( T \), effects on \( V_{oc}, I_{sc}, I_s, \) and \( I_{ph} \). Equations (6) and (7) come from [7] and [8] but are modified for the \( k_v \) and \( k_i \) based on the percentage of \( V_{oc} \) and \( I_{sc} \) rather than the absolute value. Equations (8) and (9) use \( V_{oc}(T) \) and \( I_{sc}(T) \) to find the temperature-dependent diode saturation current and generated photocurrent, \( I_s(T) \) and \( I_{ph}(T) \).

\[
V_{oc}(T) = V_{oc}[1 + k_v(T - T_{STC})] \tag{6}
\]

\[
I_{sc}(T) = I_{sc}[1 + k_i(T - T_{STC})] \tag{7}
\]

\[
I_s(T) = \left( I_{sc}(T) - \frac{V_{oc}(T) - I_{sc}(T)R_s}{R_{sh}} \right) e^{\frac{V_{oc}(T)}{NAT}} \tag{8}
\]

\[
I_{ph}(T) = I_s(T)e^{\frac{V_{oc}(T)}{NAT}} + \frac{V_{oc}(T)}{R_{sh}} \tag{9}
\]

These temperature-dependent equations are then extended to include insolation, or solar irradiance, \( G \). Insolation at the so-called standard test conditions, STC, is \( 1000 \text{ W/m}^2 \), and is denoted by \( G_{STC} \). The equations (10) - (14) are derived in [7] and [8]. Equation (12) for finding \( V_{oc}(G, T) \) is a transcendental equation that must be solved iteratively.

\[
I_{sc}(G, T) = I_{sc}(T) \frac{G}{G_{STC}} \tag{10}
\]

\[
I_{ph}^* = I_{ph}(T) \frac{G}{G_{STC}} \tag{11}
\]

\[
V_{oc}(G, T) = \ln \left( \frac{I_{ph}^*R_{sh} - V_{oc}(G, T)}{I_s(T)R_{sh}} \right) NAT \tag{12}
\]
\[ I_s(G, T) = \left( I_{sc}(G, T) - \frac{V_{oc}(G, T) - I_{sc}(G, T)R_s}{R_{sh}} \right) e^{\frac{V_{oc}(G, T)}{NAVT}} \]  

(13)

\[ I_{ph}(G, T) = I_s(G, T) e^{\frac{V_{oc}(G, T)}{NAVT}} + \frac{V_{oc}(G, T)}{R_{sh}} \]  

(14)

With these equations dependent on insolation and temperature, the characteristic equation for the PV module is defined, Equation (15). The PV module current is defined in terms of voltage and current. Because it is a transcendental equation, it must be solved iteratively.

\[ i = I_{ph}(G, T) - I_s(G, T) \left( \frac{\nu + iR_s}{e^{\frac{V_{oc}(G, T)}{NAVT}} - 1} \right) - \frac{\nu + iR_s}{R_{sh}} \]  

(15)

2.2.3 Reverse Breakdown Characteristic

In order to have a full simulation, the PV module’s characteristics must be modeled for when PV module voltage is negative. This is important when studying shading effects [7]. The equation is defined in [9]. Equation (16) includes the effects of avalanche breakdown of the PV cells in the PV module. This too is a transcendental equation that must be solved iteratively.

- \( \alpha \) = fraction of ohmic current involved in avalanche breakdown
- \( m \) = avalanche breakdown exponent
- \( V_{br} \) = single PV cell junction breakdown voltage

\[ i = I_{ph}(G, T) - I_s(G, T) \left( \frac{\nu + iR_s}{e^{\frac{V_{oc}(G, T)}{NAVT}} - 1} \right) - \frac{\nu + iR_s}{R_{sh}} \left( 1 + \alpha \left( 1 - \frac{\nu + iR_s}{N V_{br}} \right)^{-m} \right) \]  

(16)

2.2.4 Arbitrary Series Connection of PV Cells

Equation (16) is the full characteristic equation for the PV module. The equation needs to be modified in order to simulate strings of an arbitrary number of PV cells connected in series. First, we can define the ratio of the number of PV cells in series to number of PV cells in a module as the ratio \( N_{ratio} \), shown in Equation (17).

- \( N \) = number of series-connected cells in a module
- \( N_{sim} \) = number of series-connected cells to be simulated

\[ N_{ratio} = \frac{N_{sim}}{N} \]  

(17)

New panel parameters based on different series-connected PV string length must be found. These are:

- \( R_s^\ast \) = series resistance
- \( R_{sh}^\ast \) = shunt resistance
- \( V_{oc}^\ast \) = open-circuit current at STC
- $V_{mp}$ = voltage at Maximum Power Point (MPP) at STC
- $k_v$ = temperature coefficient of open-circuit current as a percentage %

Because the PV cells are connected in series, they have the same current, and their voltages add to produce a total series voltage. The current through the series-connected string of PV cells is the same as the current though the entire PV module. The voltages for the entire PV module and the series-connected string of PV cells differ by a factor of $N_{ratio}$. Likewise the current temperature coefficient, $k_i$, remains unchanged while the voltage temperature coefficient, $k_v$, is multiplied by the factor of $N_{ratio}$ as shown by Equations (18) - (20).

\[
V_{oc}^* = N_{ratio}V_{oc}
\]  
\[
V_{mp}^* = N_{ratio}V_{mp}
\]  
\[
k_v^* = N_{ratio}k_v
\]

Also, for a series connected string of PV cells, the series resistances are in series and add. From [6] we also see that the shunt resistances add. Therefore both $R_s$ and $R_{sh}$ are multiplied by $N_{ratio}$ as shown by Equations (21) and (22). This is shown graphically in Figure 2.

\[
R_s^* = N_{ratio}R_s
\]  
\[
R_{sh}^* = N_{ratio}R_{sh}
\]

Using these new values, the equations for temperature and insolation variations are calculated again, and a new PV characteristic equation is obtained.

### 2.3 Modified Nodal Analysis Based PV Simulation

A Modified Nodal Analysis (MNA) model for an arbitrary length series-connected string of PV cells provides the building block for a system-level simulation. When these PV strings are attached together, they are able to interact. Mismatch between PV strings and shading patterns can be examined. The
effects of different power electronic topologies can also be examined. The system-level simulation provides the means by which to study energy harvest with differing system topologies, power electronics, and conditions.

Because of the non-linear nature of the PV cell, a SPICE-based simulation is chosen as the basis for the system level simulation. SPICE was originally designed for the interconnection of many nonlinear semiconductor devices. The difference between PV cells and simple diode p-n junctions is that PV cells are exposed to light. This light can be modeled as an independent current source with the current dependent on the intensity of the light.

SPICE is based on MNA. In MNA, admittances, current sources, and voltage sources are stamped into the admittance matrix. Nonlinear devices are linearized into admittances, current sources, and voltage sources. For further information on MNA, see reference [10] or [11].

2.3.1 Admittance Matrix Stamp
Each different part in a circuit must be stamped into the admittance matrix. Nonlinear parts must first be linearized before being stamped into the admittance matrix. The matrix Equation (23) is then solved for using the Newton-Raphson method [10].

\[ v = Y^{-1} j \]  

1. Initialize: Guess circuit voltages and currents
2. Linearize: Calculate linearized Norton equivalent circuits for all non-linear components around the presumed operating points.
3. Solve the system for the new operating points.
4. Return to step 1 with new operating points. If the change between the new and the old operating points is small, the system is solved within a given error.

An example of a diode matrix stamp is shown in Figure 3. The diode is linearized into a current source and admittance. The linearization of a diode is stamped into the admittance matrix by adding the stamp to corresponding elements of the admittance matrix [10].

Figure 3 Stamp for linearized diode model.
2.3.2 Formulation of PV Admittance Matrix Stamp

An equivalent stamp must be made from the PV string equation. $G_s$, $G_{sh}$, and $I_{ph}$ are already linear. The current through the diode must be linearized. This diode model must include the current for the forward conduction and the reverse breakdown characteristics of the PV string. When a PV string is stamped, an extra node, $n + 1$, must be added to the admittance matrix. This is to account for the node in which the photogenerated current source, the shunt resistance, and diode attach to the series resistance.

The characteristic equation for the PV string can be modified for use in the PV stamp. Two changes must be made from this equation. First, only the current though the diode portion of the module must be accounted for. Second, the voltage at the extra node, $n + 1$, is a variable. By relying on the voltage at node $n + 1$, the equation for $I_{eq}$ is no longer transcendental. Equation (24) shows the PV characteristic which is formulated in terms of the voltage at node $n + 1$ in Equation (25).

$$i = I_{ph}(G,T) - I_s(G,T)\left(\frac{v + iR^*}{e^{NAV_T} - 1}\right) - \frac{\alpha}{R_{sh}^*} \left[ 1 + \frac{v + iR^*}{N V_{br}} \right]^{-m}$$  \hspace{1cm} (24)

$$I_{eq}(v_{n+1}) = I_s(G,T)\left(\frac{v_{n+1} + 1}{e^{NAV_T} - 1}\right) + \frac{\alpha}{R_{sh}^*} \left[ 1 - \frac{v_{n+1}}{N V_{br}} \right]^{-m}$$  \hspace{1cm} (25)

In order to find $G_{eq}$, the equation for $I_{eq}$ must be differentiated as shown in Equation (26). With Equations (25) and (26), the PV stamp can be defined. This linearized PV string stamp is shown in Figure 4.

$$G_{eq}(v) = \frac{dI_{eq}(v_{n+1})}{dv_{n+1}} = \frac{v_{n+1} I_s(G,T)e^{NAV_T}}{NAV_T} + \frac{\alpha}{R_{sh}^*} (1 - \frac{v_{n+1}}{N V_{br}})^{-m} + \frac{v_{n+1}}{R_{sh}^* N V_{br}} (1 - \frac{v_{n+1}}{N V_{br}})^{-m-1}$$  \hspace{1cm} (26)

Figure 4 Stamp for linearized PV string model.
2.3.3 Power Converters in Admittance Matrix

To complete the PV system, a load is needed. This can be as simple as a voltage source, current source, or resistor. To find the I-V characteristic curve of a PV array, this load must be swept to provide data from short circuit to open circuit. The stamps for these various loads can be found in [10] and [11].

Power converters installed to help balance the system must also be included in the MNA. A stamp for a power converter is developed in [11]. This converter stamp shown in Figure 5 has an input and output port. The stamp fixes the ratio of output voltage and input voltage, shown in Equation (27). The converter stamp also fixes the ratio of input current and output current, shown in Equation (28). This way, the input power and output power are kept equal. Therefore, this is the stamp of an ideal converter with 100% conversion efficiency. The stamp can be modified to include losses, but for this thesis only ideal converters are modeled.

\[
\begin{bmatrix}
1 & -1 & -K & K \\
1 & -1 & -K & K \\
\end{bmatrix}
\]

Figure 5 Stamp for an ideal power converter.

\[
\begin{align*}
V_j - V_{j'} &= K(V_k - V_{k'}) \\
I &= l_j = -l_{j'} = \frac{1}{K} l_k = -\frac{1}{K} l_{k'}
\end{align*}
\]

(27)  (28)

2.3.4 Steady State Energy Harvest Analysis

For the energy harvest studies presented later in this thesis, it is assumed that the system dynamics are much faster than changes in insolation and temperature. The system would spend the vast majority of time in steady state and the effects of system dynamics would be insignificant. Therefore, this implementation of MNA does not include system dynamics, and a transient solver is not yet implemented. In order to include all system dynamics, the cell capacitances, converter energy storage, and switch events would need to be modeled. A transient solver would have to be implemented such as in [10] and [11].

2.4 Verification of PV Simulation

To verify the PV module simulation is correctly working, a PV module’s I-V characteristic is measured and compared to a PV module’s simulated I-V characteristic. The PV module tested is the Sunpower SPR-225-BLK [12]. The PV module’s I-V characteristic was measured using a programmable load. During the
test, the load was swept from 0 V to open circuit voltage. The simulation was corrected with
temperature and insolation by using the measured short circuit current and open circuit voltage of the
PV module. In Figure 6, the measured data from the test and simulated I-V characteristics are shown to
be very similar in shape. The datasheet derived model provides a good approximation of a PV module
for simulation purposes.

![Figure 6 Measured and simulated I-V characteristics.](image-url)
3 Mismatch in PV Systems

PV modules are constructed by connecting PV cells into a single series string. Commonly there are 60-72 PV cells in this series-string. Figure 7 shows a PV module that is divided into three PV sub-modules, each with a bypass diode in parallel. This bypass diode is placed to prevent reverse biasing of shaded cells. This helps to increase energy harvest and reduced localized heating of shaded PV cells.

![Figure 7 PV module construction.](image)

Because the PV cells are connected in series, differences between PV cells cause a loss in performance. This is because the conditions for MPP of the PV module might not correspond to the MPP conditions for every individual PV cell. Each cell will operate slightly off of its MPP, and the MPP of the module will be less than the sum of the MPPs of the individual cells. This relationship is shown in Equation (29).

\[ MPP_{\text{module}} < \sum MPP_{\text{cell}_n} \] (29)

This mismatch can occur for a number of reasons. Small sources of mismatch include manufacturing variation, uneven aging, and uneven soiling. Larger sources of mismatch include differences in PV module orientation, shading from clouds, and shading from nearby obstructions.

3.1 Sources of Small Mismatch

Small sources of mismatch force each PV submodule to operate slightly off of its MPP. In Figure 8, three slightly mismatched PV submodules are operating at \( I_{mp} \) of the PV module. Potential energy harvest is lost because each PV submodule is forced to operate off of its MPP. Sources of small mismatch can be caused by manufacturing variation, uneven aging, and uneven soiling.
The mismatch from manufacturing variation can be measured before an array is installed. Over the lifetime of a PV system, the mismatch from uneven aging and uneven soiling can also be measured. In order to do this, the individual PV modules are disconnected from the PV array and an I-V curve trace is run to find the MPP of the panel [13].

![Diagram of small PV submodule mismatch.](image)

In a reliability study by the Schatz Energy Research Center (SERC), the initial mismatch in power had a standard deviation of 2.3% [13]. SunPower produced 7000 PV cells for a solar car built by Honda R&D. 91% of these cells had an efficiency between 20%-22.1% [14]. In general, the power tolerance given by the PV module’s datasheet can be assumed to fall within ±3σ of the average specified output power, assuming a normal distribution [15]. A common power tolerance is ±5% which translates to a standard deviation of 1.67% [15].

Over the lifetime of the PV system these deviations increase. In the SERC system, the standard deviation is initially 2.3%, increases to 4.4% after 10 years, and after 20 years reaches 8.8% [13]. This is quite a large deviation. In most systems, the differential degradation rate varies from 0% - 0.167% per year [15]. This results in a maximum of 6.7% after 30 years. Because of the non-linear nature of PV
cells, this 6.7% mismatch does not necessarily lead to a 6.7% reduction in energy harvest. Near MPP, the power is at its least sensitivity to changes in operating voltage and current. By the first order necessary condition of optimality, the MPP occurs when change of power versus voltage or current is zero as shown by Equation (30).

\[
\frac{dP}{dV} = \frac{dP}{dl} = 0
\]

Energy harvest simulation must be run to see the true effect this mismatch may have on energy harvest.

### 3.2 Sources of Large Mismatch

Large mismatches are caused by differences in PV module orientation and shading. In these two cases, the amount of insolation reaching the PV cells is significantly different. Take for example a partially shaded module shown in Figure 9. The shaded cells produce significantly less photocurrent compared to the fully illuminated cells. This can cause the cells to reverse-bias and turn on the bypass diode. When this happens, two local MPPs are formed, shown in Figure 10. One local MPP is at low current with the diode off, and one local MPP is at high current with the diode turned on. The global MPP is the larger of the two local MPPs.

![Illustration of severe mismatch](image)

**Figure 9** Illustration of severe mismatch.
Ensuring operation at the global maximum will provide greater energy harvest; however, not every PV submodule is at its MPP. The shaded PV submodule can actually sink power [16]. Even though the PV module may be operating at its global MPP, more energy harvest is still possible. The theoretical maximum power available (that is, the global MPP) from the panel is the sum of the MPPs of the individual PV cells.

![Shaded PV characteristic curve.](image)

*Figure 10  Shaded PV characteristic curve.*

With an understanding of how mismatch occurs, microconverters can be designed to mitigate the effects of mismatch.
4 Global MPP Search Algorithms

In residential and commercial installations, PV modules may be partially shaded by nearby objects causing irregular illumination patterns on the PV modules. This partial shading causes multiple local MPPs in the PV module’s P-V curve, as shown in Figure 11, that MPPTs can track. Only one of these possible local MPPs is the true global MPP. Any time PV modules operate away from the global MPP, energy harvest is reduced.

![Figure 11 Example of MPPs in a PV module.](image)

4.1 Limitations of MPPT Algorithms

There are many known MPPT algorithms. Because they rely on localized data for optimization, most conventional MPPTs can only guarantee the tracking of a local MPP [17]. To guarantee finding the global MPP, a search of the P-V curve must be performed. However, this search comes at a cost. Because energy is the integral of power over time, any time spent searching for another MPP means energy harvest is reduced. A balance must be reached between the energy harvest lost while searching and energy harvest gained by operating at the global MPP.

Two algorithms that heuristically search the P-V characteristic curve are explored in this thesis. The first assumes that the integrated microconverter can measure PV module voltage and current but not the PV submodule voltages. Given the possible operating conditions of the PV modules, this MPPT algorithm only searches under specific conditions. The second MPPT algorithm assumes the microconverter can measure the PV submodule voltage across the bypass diodes.

4.2 Global MPPT Search Algorithm

The first algorithm aims to optimize the balance of energy harvest lost searching and the energy harvest gained by operating at the global MPP. This enhanced MPPT minimizes searching while increasing the likelihood each search will result in finding the global MPP. This algorithm is outlined in [18].
The search algorithm assumes the microconverter is only attached to one PV module. Currently, the rated power of these PV modules is 200-300 W. When the PV module is operating near rated power, it is unlikely the PV module is partially shaded and unlikely that multiple local MPPs exist. It is also unlikely that the PV modules would be installed in such a way as to create partial shading near solar noon.

Figure 12 shows two P-V curves from a simulated PV module illuminated at $600 \frac{W}{m^2}$. One has PV submodule shaded at $200 \frac{W}{m^2}$, and the other does not. It is clear that the local MPP is much lower than the unshaded MPP. This lower power can be used to define a power range in which multiple local MPPs are more likely and where a search for the global MPP is more effective.

![Figure 12 Comparison of shaded and unshaded PV modules.](image)

### 4.2.1 Formulation of Global MPPT Search Algorithm

Figure 13 shows the state diagram of the enhanced MPPT. In the “MPPT” state, the inverter uses a standard MPPT algorithm. Once the input power falls below $P_{low}$, the “MPPT Wait $T_1$” state is entered. From this state, the microconverter will return to the “MPPT” state if the input power rises above $P_{high}$; else it will enter the “Search” state after $T_1$ seconds. This $T_1$ second wait is used to prevent false positives from noise or quick shading events. Before entering the “Search” state, the commanded voltage and input power, $V^*$ and $P$ are saved as $V^*_{prev}$ and $P_{prev}$. 


In the “Search” state, the microconverter scans for a new global MPP. In the case of voltage control, $V^*$ is decremented by $V_{step}$. This continues until either the input power increases to $P_{lim}$ above $P_{prev}$, or $V^*$ reaches $V_{min}$, this microconverter’s minimum operating voltage. If $V^*$ reaches $V_{min}$, no new global MPP was found and the microconverter enters the “Return” state. In this state, $V^*$ is incremented by $V_{step}$ until the microconverter returns to $V_{prev}$.

If the input power increases to $P_{lim}$ above $P_{prev}$, the microconverter enters the “MPPT Wait $T_2$” state. This state releases control back to the MPPT but contains another timer. It is similar to the “MPPT Wait $T_1$” state; however, $T_2 > T_1$. When $T_2$ seconds pass, the microconverter searches again for a new global MPP.

4.2.2 Example of Global MPPT Search Algorithm

An example implementation of the global MPPT search algorithm is shown in Figure 14. $P_{low} = 50$ W, $P_{high} = 120$ W, $P_{lim} = 5$ W, $T_1 = 10$ s, $T_2 = 600$ s, $V_{min} = 24$ V, and $V_{step} = 0.1$ V. These values are based on a typical 250 W, 72 cell PV module. The power limits are chosen with the assumptions from the previous section to maximize the benefit of each search while minimizing unnecessary searches. Below 50 W, the likelihood of partial shading increases. If the low MPP is around 50 W, the global MPP is likely above 120 W. If this were the case, the microconverter would not search minimizing energy harvest lost to searching. The state machine operates at the 60 Hz line frequency. $V_{step}$ is chosen to limit the power change while searching.
4.2.3 Operation of Global MPPT Search Algorithm

Figure 15 shows the algorithm working late in the afternoon. During this time, the PV module becomes shaded due to a simulated dormer. The power drops below 50 W for more than 10 seconds, initiating a search. The search finds a new MPP with higher output power at a lower voltage. This search ensures energy harvest increases when shading occurs.
4.3 Diode Triggered MPP Search Algorithm

The second search algorithm takes advantage of access to the PV submodule voltages. These voltage measurements are taken across the bypass diode. This work is detailed in [19]. By measuring this voltage, the microconverter can detect when the diode turns on due to reverse biasing of the PV cells caused by partial shading. When this occurs, the search is initiated.

A boost converter implementing this global MPPT algorithm is attached to a PV module [19]. Hardware results show the functioning of this algorithm. The boost converter is attached to a resistive load. Maximizing output voltage also maximizes output power when the load is a constant resistance, where the power $P$ is given by Equation (31) [19].

$$P = \frac{V^2}{R}$$

Figure 16 shows the hardware results of shading one PV submodule. When the shading occurs, $V_1$ becomes less than 0 V. This initiates the search algorithm. When this happens, the search finds the global MPP. The algorithm effectively detects the possible local maximum by using microconverter accessible voltage measures to initiate a search and find the global maximum.

Figure 16 String-level shading scenario: (a) shading condition, (b) $V_{out}$ as a function of $V_{in}$, (c) $V_1$ as a function of $V_{in}$ [19].
5 Full PV Submodule Power Processing

While the algorithms in the previous chapter increase energy harvest by searching for the global MPP, there is still more potential energy harvest. The PV submodules are attached together and must operate with the same current. With mismatch, the PV submodules do not operate at their individual MPPs. The global MPP is still less than the sum of the MPPs of the individual PV submodules.

5.1 PV Module Modification

In order have the PV submodules operate independently, they must be disconnected. The series connection between the PV submodules can be broken and the bypass diodes removed. An original and modified SS-SP-120, 120-W PV module is shown in Figure 17 [20].

![Figure 17 Disconnection of PV submodules: (a) Original connection of PV cells in the PV module, (b) Modified PV module with independent PV submodules [20].](image)

5.2 Full PV Submodule Power Converter

With the PV submodules disconnected, a module-integrated power converter with full power processing on the individual PV submodules can be installed. There are many different options for implementing these module-integrated converters. Series-connected microconverters, parallel-connected microconverters, or multiple-input converters are all candidates for PV submodule power processing [17]. An example of a series connected microconverter is a dc-dc optimizer using a small synchronous buck converter, which can achieve a low part count and efficiency greater than 98% [21]. A PV system implementing these small dc-dc optimizers is shown in Figure 18.

There are many feasible multiple-input converters that can be used for module-integrated converters [22]. A multiple input buck-boost converter (MIBB) implementing ripple correlation control (RCC) for MPPT can be used for PV applications [23]. The MIBB circuit topology is shown in Figure 19. A multiple...
input boost converter (MIB) avoids the inverted output voltage of the buck-boost converter. The MIB has been specifically used for PV submodule power processing under partial shading conditions [20]. The MIB circuit topology is shown in Figure 20. The results for the MIB work are examined as an example of the energy harvest gains possible by processing the PV submodule power independently.

![Diagram of PV submodule integrated dc-dc optimizer](image1.png)

**Figure 18** PV submodule integrated dc-dc optimizer [21].

![Diagram of multiple input buck-boost converter attached to 2 PV submodules](image2.png)

**Figure 19** Multiple input buck-boost converter attached to 2 PV submodules.

![Diagram of multiple input boost converter attached to 2 PV submodules](image3.png)

**Figure 20** Multiple input boost converter attached to 2 PV submodules.

### 5.3 MIB Energy Harvest Simulation

Simulations are performed to demonstrate the impact of using the MIB to independently process the PV submodule power. The simulations compare the power output of the PV module with the independent power outputs of the PV submodules. These simulations are described in [20]. In Figure 21, both strings
are matched with an insolation of 1000 $\frac{W}{m^2}$. The sum of the power from the two PV submodules is equal to the power from the PV module at 121.8 W. Figure 22 shows the effects of shading by reducing the illumination to 250 $\frac{W}{m^2}$. In this case, there are two local MPPs: the global MPP at 52.33 W and the other local MPP at 32.64 W. PV submodule 1 has an MPP of 60.9 W, and PV submodule 2, the shaded PV submodule, has an MPP of 13.72 W. The sum of the PV submodule MPPs is 74.62 W.

![Figure 21](image1.png)

**Figure 21** (a) PV submodule1 and (b) PV submodule2 illuminated at 1000 $\frac{W}{m^2}$ [20].

![Figure 22](image2.png)

**Figure 22** (a) PV submodule1 illuminated at 1000 $\frac{W}{m^2}$, (b) PV submodule2 illuminated at 250 $\frac{W}{m^2}$ [20].

By using the MIB to operate the PV submodules independently, a large improvement in energy harvest is achieved. The MIB provides a 42.6% improvement over the global MPP and a 128.6% improvement over the local MPP. By processing the PV submodule power independently, the effects of multiple local MPPs are eliminated. The two local MPPs of the PV module have been eliminated leaving only one operating point which gives the maximum energy harvest.

Having only one operating point giving maximum energy harvest provides many additional benefits. The need to scan the P-V curve for additional local MPPs is eliminated. Also, in order to track the global MPP, the converter must work at a fraction of the voltage of the unshaded $V_{mp}$. The SS-SP-120 module only has two PV submodules, so when the bypass diode is on, the voltage is half the normal $V_{mp}$. If the
panel has three bypass diodes, the global MPP can occur at one-third or two-thirds of the nominal \( V_{mp} \). By using the MIB, the relative input voltage range can remain smaller, and the MIB converter can be better optimized.

5.4 MIB Hardware Implementation

The increase in energy harvest is verified with a hardware implementation of the MIB. The SS-SP-120 module is placed in the sun with one cell fully shaded, as shown in Figure 23. With a normal boost converter, 32.22 W are extracted from the panel; with the MIB, 43.74 W are extracted [20]. This shows a 35.8% improvement when using the MIB.

Figure 23 Experimental setup depicting the shading condition investigated [20].
6 Differential PV Submodule Power Processing

The previous chapter demonstrated how energy harvest can be improved by independently tracking the individual PV submodule MPPs. However, the topologies presented in the previous chapter require modifying a PV module by disconnecting the series-connected PV submodules. This chapter proposes new PV system architectures that track individual PV submodule MPPs by processing the difference in power between PV submodules. Because of this, PV module modification is unnecessary.

6.1 DPP Architectures

A number of different DPP architectures are proposed in literature. Three architectures will be explored here: PV-PV, PV-bus, and PV-virtual bus [24], [25]. These DPP architectures along with the dc optimizer architecture from Chapter 5 are illustrated in Figure 24. Similar DPP architectures, such as switched capacitor architectures and generation control converter architectures exist but will not be explored in this thesis [26], [27].

Figure 24 (a) Conventional dc optimizer architecture, (b) PV-PV architecture, (c) PV-bus architecture, and (d) PV-virtual bus architecture.
The different DPP architectures share many common features. In each, the PV array with the DPP converters is attached to a central converter. Usually this central converter is a large inverter (e.g., rated for more than 10 kW). The large converter handles the bulk energy conversion and MPPT for the entire PV array. The DPP converters handle the difference in power between PV submodules and provide MPPT for each individual PV submodule.

The PV-PV architecture, shown in Figure 25 (a), consists of a bidirectional buck-boost converter attached to two PV submodules [24]. The converter is able to transfer power from one PV submodule to the other. When cascaded, the PV-PV converters can move energy around the PV system from PV submodule to PV submodule. This PV array with cascaded PV-PV converters is attached to a central converter. The number of PV-PV converters in this system is one less than the number of PV submodules.

![Figure 25](image)

**Figure 25** (a) PV-PV buck-boost converters, (b) PV-bus boost converters, (c) PV-bus flyback converters [24].

The PV-bus architecture can be implemented with isolated or non-isolated converters, shown in Figure 25 (b) and (c) [24]. The input of the PV-bus converter is attached to a single PV submodule. The output of the PV-bus is attached to the PV array, which is attached to the central converter. This allows power to be transferred between the PV modules through the bus. Because the bus is attached to the central converter, it also allows for direct transfer of the differential power to the central converter. An example of a non-isolated PV-bus converter is a boost converter [24]. An example of an isolated PV-bus converter is a flyback converter [24], [25]. The number of PV-bus converters in this system can be one less than or equal to the number of PV submodules. If the number is equal to the number of PV submodules, multiple operating points give the same global MPP [25].

The PV-virtual bus architecture is similar to the PV-bus architecture. In [25], it is referred to as the “Isolated-Port SubMIC PV Architecture.” In the PV-virtual bus system, the outputs of the PV-virtual bus converters are attached together as a floating node rather than to the PV array. This allows for an adjustable virtual bus voltage rather than being fixed to the output voltage of the PV array. Because this PV array can vary in size, this PV-virtual bus architecture solves system scaling issues associated with the
PV-bus system. Unlike the PV-bus system, the differential power cannot be directly delivered to the PV array. The sum of the power into and out of the virtual bus must be zero [25]. This means that more power will need to be processed in the PV-virtual bus system than in the PV-bus system. The number of PV-virtual bus converters in this system must be equal to the number of PV submodules.

6.2 DPP Simulations

The power processed in a central inverter system, dc optimizer system, PV-PV system, and PV-virtual bus system is analyzed for multiple cases with a series-connected string of 40 PV submodules. Three mismatch cases are studied. The first case simulates mismatch from manufacturing and degradation. The second case simulates the effects of one module being badly mismatched. The third simulates cloud cover shading half of the PV array. The PV-PV and PV-virtual bus DPP converters are run in voltage equalization mode rather than a full implementation of MPPT.

6.2.1 Random Mismatch Simulation

To investigate manufacturing mismatch and differential degradation, a randomized insolation is applied to a string of 40 PV submodules. The insolation for each PV submodule is randomly selected from a normal distribution with a mean of $\frac{1000}{W/m^2}$ and a standard deviation of $\frac{50}{W/m^2}$. The converters are simulated as ideal converters.

Table 1 Results from random mismatch test.

<table>
<thead>
<tr>
<th></th>
<th>Base Array</th>
<th>Dc optimizer</th>
<th>PV-PV</th>
<th>PV-virtual bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power</td>
<td>3206 W</td>
<td>3291 W</td>
<td>3291W</td>
<td>3291W</td>
</tr>
<tr>
<td>Power Processed</td>
<td>0 W</td>
<td>3291W</td>
<td>294 W</td>
<td>153 W</td>
</tr>
<tr>
<td>Estimated Conversion Efficiency</td>
<td>-</td>
<td>98%</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td>Estimated Improvement</td>
<td>-</td>
<td>0.60%</td>
<td>2.19%</td>
<td>2.41%</td>
</tr>
</tbody>
</table>

The results for the simulation, summarized in Table 1, show how dc optimizers, PV-PV converters, and PV-virtual bus converters can track the MPP of every individual PV submodule. This results in a 2.65% improvement in energy harvest; however, some of this energy will be lost in power conversion. The dc optimizers must process the full amount of power from the PV array. The dc optimizer is estimated to have a conversion efficiency of 98% using results from [21]. This reduces the harvest gain to 0.60%. The DPP converters are estimated to have an efficiency of 95% using results from [28]. This reduces the energy harvest to 2.19% for PV-PV and 2.41% for PV-virtual bus. The individual PV submodule power outputs are shown in Figure 26. Figure 27 and Figure 28 plot the power processed by each PV-PV converter and PV-virtual bus converter, respectively.
Figure 26 Random mismatch: PV submodule power output.

Figure 27 Random mismatch: power processed by each PV-PV converter.
6.2.2 Single Shaded PV Submodule Simulation

To investigate the effects that one shaded PV submodule may have on the array, the insolation on the 20\textsuperscript{th} PV submodule is set as $500 \frac{W}{m^2}$ while the rest of the PV submodules are kept at $1000 \frac{W}{m^2}$. The results are tabulated in Table 2. The energy harvest increase from tracking the individual PV submodule MPPs is 1.35%. There is a local MPP in the base array’s P-V characteristic plotted in Figure 29 that is eliminated from the array’s P-V characteristic by the DPP converters shown in Figure 30. The output power from each PV submodule is shown in Figure 31.

From Table 2, we can see that the total power processed by the PV-PV converters is much higher than the PV-virtual bus converters. The PV-virtual bus converters are able to transfer power from each panel to the virtual bus while the PV-PV converters must transfer power through neighboring PV submodules. The effects of this are shown in Figure 32 and Figure 33.

Table 2  Results from single shaded PV submodule test.

<table>
<thead>
<tr>
<th></th>
<th>Base Array</th>
<th>Dc optimizer</th>
<th>PV-PV</th>
<th>PV-virtual bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power</td>
<td>3181 W</td>
<td>3224 W</td>
<td>3224W</td>
<td>3224W</td>
</tr>
<tr>
<td>Power Processed</td>
<td>0 W</td>
<td>3224W</td>
<td>428 W</td>
<td>83 W</td>
</tr>
<tr>
<td>Estimated</td>
<td>-</td>
<td>98%</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td>Conversion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated</td>
<td>-</td>
<td>-0.68%</td>
<td>0.68%</td>
<td>1.22%</td>
</tr>
<tr>
<td>Improvement</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 28  Random mismatch: power processed by each PV-virtual bus converter.
To balance the power, approximately 40 W needs to be added to the 20th PV submodule. This power comes equally from the rest of the 39 PV submodules. In the PV-virtual bus system shown in Figure 33, we can see approximately 40 W are transferred into the 20th PV submodule and approximately 1 W is transferred out of the other 39 PV submodules. In the PV-PV system shown in Figure 32, 20 W is supplied to the 20th PV submodule from the 19th and 21st PV submodules. In order to get 20 W from each PV submodule, 19 W had to come from the 18th and 22nd PV submodules. This cascaded connection greatly increases the amount of power need to be processed in the PV-PV system.

Figure 29 Single shaded PV submodule: base array P-V characteristic curve.

Figure 30 Single shaded PV submodule: array P-V characteristic with DPP converters.
Figure 31 Single shaded PV submodule: PV submodule power output.

Figure 32 Single shaded PV submodule: power processed by each PV-PV converter.
6.2.3 Shaded Array Simulation

To investigate the effects cloud cover may have on the array, half the array is illuminated at 500 W/m² while the other half is illuminated at 1000 W/m². This shading pattern is shown in Figure 34. The results are tabulated in Table 3. The energy harvest increase from tracking the individual PV submodule MPPs is 38.0%. There is a local MPP in the base array’s PV characteristic plotted in Figure 35 that is eliminated by the DPP converters as shown in Figure 36. The output power from each PV submodule is shown in Figure 37.

Table 3 Results from array shading test.

<table>
<thead>
<tr>
<th></th>
<th>Base Array</th>
<th>Dc optimizer</th>
<th>PV-PV</th>
<th>PV-virtual bus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Power</strong></td>
<td>1753 W</td>
<td>2419 W</td>
<td>2414 W</td>
<td>2414 W</td>
</tr>
<tr>
<td><strong>Power Processed</strong></td>
<td>0 W</td>
<td>2419 W</td>
<td>8485 W</td>
<td>848 W</td>
</tr>
<tr>
<td><strong>Estimated Conversion Efficiency</strong></td>
<td>-</td>
<td>98%</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td><strong>Estimated Improvement</strong></td>
<td>-</td>
<td>35.2%</td>
<td>13.8%</td>
<td>35.6%</td>
</tr>
</tbody>
</table>
Figure 34 Shading pattern.

Figure 35 Shaded array: base array PV characteristic curve.
From Table 3, we can see again that the total power processed by the PV-PV converters is over 10x higher than the PV-virtual bus converters. Figure 38 shows that to balance the power in the array, approximately 400 W of power need to be transferred from unshaded half to the shaded half of the PV array. As shown in Figure 38, 400 W must be processed by a single PV-PV converter. For the PV-PV converter to be able to handle his case, it must be built to handle 5x the full power from a PV submodule.

Looking at Figure 39, the PV-virtual bus system seems to eliminate this issue; however, the way the PV-virtual bus converters are connected needs to be considered. The parallel outputs of the PV-virtual bus converters would likely be attached with a trunk and drop cable. This is as opposed to a point-to-point connection. This trunk cable would have to be sized to handle the full 400 W. At approximately 10 V, the PV submodule operating voltage, the trunk cable has to carry 40 A. This would likely require 4 AWG cable at very high cost. This is compared to the series connected dc optimizer, which only has to handle the PV submodule’s short circuit current, approximately 10 A. The voltage could possibly be boosted higher to reduce this current but at the sacrifice of efficiency and safety.
Figure 37 Shaded array: PV submodule power output.

Figure 38 Shaded array: power processed by each PV-PV converter.
For small random mismatches, DPP converters provide an improvement over basic PV systems and dc optimizer systems. The problem is that this improvement does not scale with large mismatches due to shading. With large mismatch, large amounts of power need to be moved around the PV array to balance the system. This leads to converters or cables that must be rated much greater than their dc optimizer counterparts.

6.3 DPP Microconverter Front-end

Another option is to use DPP converters as a front-end to a PV module integrated microconverter, as shown in Figure 40. The DPP converters provide PV submodule power processing, while the microconverter provides the bulk power processing for the PV module. In this way, PV submodule processing can occur with little modification to an ordinary dc PV module. With DPP converters, disconnecting the series-connected PV submodules is unnecessary.

With the integrated DPP microconverter, the number of DPP converters coupled together is lower. For a typical module with three PV submodules, only two PV-PV converters are necessary. This will greatly limit the maximum power the PV-PV converters must process.
When a PV module is partially shaded, this combination of PV-PV converters and a microconverter harvests significantly more energy than a microconverter on its own. In a PV module with three PV submodules, two are illuminated at $1000 \ \text{W/m}^2$, and one is illuminated at $500 \ \text{W/m}^2$. Figure 41 and Figure 42 show that the PV-PV converters eliminate the local MPP from the PV characteristic and increase the energy harvest by 25.5%. Figure 43 shows the power processed by the two PV-PV converters. The PV-PV converters only have to process a total of 56.7 W.
Figure 41  P-V characteristic of three PV submodules illuminated at 1000 $\frac{W}{m^2}$, 1000 $\frac{W}{m^2}$, and 500 $\frac{W}{m^2}$.

Figure 42  P-V characteristic of three PV submodules illuminated at 1000 $\frac{W}{m^2}$, 1000 $\frac{W}{m^2}$, and 500 $\frac{W}{m^2}$ with DPP converters.
The DPP microconverter front-end enables independent MPPT and avoids shortcomings of full PV submodule power processing and system level DPP. Because of DPP front-end, the PV module does not need modification. The series connection between PV submodules can remain intact. Because of the full PV module power processing of the microconverter, the DPP converters do not have to transfer power to balance the entire array. The DPP converters only have to be sized to handle full PV submodule power.

The DPP front-end also eliminates the multiple local MPPs of a shaded PV module. In a shaded PV module with bypass diodes, the global MPP might occur at one-third or two-thirds nominal \( V_{mp} \). With the elimination of local MPPs, the global MPP will occur close to nominal \( V_{mp} \). The DPP front-end reduces the input voltage range of the microinverter which can lead to lower cost and higher efficiency.
7 Conclusion

By integrating converters into PV modules, new methods can be used to increase energy harvest from PV systems. This increase in energy harvest helps decrease the LCOE for PV systems and speeds the adoption of PV as a clean alternative to fossil fuels.

Adding algorithms to ensure tracking of the global MPP is a quick way to improve energy harvest of module integrated microconverters. Greater energy harvest gains are possible by independently tracking PV submodule MPPs. This can be done by processing the full PV submodule power or by processing the differential PV submodule power.

Tracking PV submodule MPPT has many advantages. Local MPPs are eliminated, and power converters need to track only one MPP. When shaded, increases of 25-125% energy harvest are attained. PV submodule MPPT can be done by processing full PV submodule power or by DPP.

To process the full PV submodule power, the PV module must first be modified. After disconnecting the series-connected PV submodules, small microconverters or multiple input converters can be used to process the full PV submodule power. This increases energy harvest and eliminates local MPPs.

DPP converters provide a way to track PV submodule MPPs without major modification to the PV module. DPP converters only process the difference in power between PV submodules, which leads to a reduction in power conversion losses. DPP converters perform well with small mismatch, but do not scale well with large mismatch. Large mismatch requires DPP converters to handle more than full PV submodule power or for the connecting cables to handle more than full PV submodule short-circuit current.

Using DPP converters as a front-end to PV module integrated microconverters provides a good alternative. Modification of the PV module is not necessary when using the DPP converters to handle the differential power. Because fewer DPP converters are coupled, they are not required to handle as much power. Further investigation of this solution is necessary to choose the optimal DPP converter as a frontend to a PV module integrated microconverter.
While the work reported in this thesis focused on energy harvest, ensuring PV submodules operate at their MPPs may also improve reliability. The bypass diodes dissipate a significant amount of energy when conducting. This may pose a long-term reliability risk. Elimination of bypass diodes eliminates this reliability risk. Operating near MPP may also reduce hot-spotting in PV cells [16], [29]. As shown in Figure 44, the severe heating from hot-spotting accelerates PV cell degradation. Eliminating hot-spotting eliminates a wear mechanism in PV modules.

By integrating microconverters into PV modules, increases in energy harvest and reliability can provide significant improvements to PV systems. These improvements lower the LCOE, thus improving the ROI for PV systems. Continued study of PV integrated power converters will be important in bringing the United States closer to its goal of meeting 14% of the nation’s energy demand with solar by 2030. Continued research into the energy harvest increases and reliability improvements enabled by DPP front-end microconverters should be conducted.
References


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