Northeastern University
College of Engineering

Comparison of Commercially Available Photovoltaic Systems

Wai Kit Ho
Steven Seeberger
Reece Yamamoto

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Professor Lehman

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Introduction

Renewable energy is becoming a necessity as alternative forms of energy generation are needed to meet the world's energy demands. One renewable energy source that is gaining popularity is Photovoltaic (PV) power. The PV industry is currently releasing new technology to improve the efficiency and availability of these PV systems. In this report, the three main current PV system configurations will be discussed and compared in terms of cost, reliability and performance.

The first configuration is the central inverter system. This system consists of multiple PV panels that are linked in series, and their total voltage output is fed to a large central inverter. The second configuration is the DC-DC optimizer system, where each PV panel is fit with its own DC-DC converter to optimize its power output. Each DC output is then combined in series with the optimized voltage output of other PV panels, and the total voltage output is fed to a central inverter. The third configuration is the microinverter configuration, where each PV panel is fit with its own microinverter, which allows each panel to be directly connected to the grid. Each configuration will be discussed further in the report, along with system background information, advantages and disadvantages of each configuration, and a cost and reliability analysis. Lastly, each PV system will be simulated in MATLAB Simulink under various irradiation conditions.

Background

For each of the three systems studied and simulated, it was necessary to design a DC-DC converter, a Maximum Power Point Tracking (MPPT) controller, and an inverter. The DC-DC converter was used for DC-DC optimization in the DC-DC optimizer system and Maximum Power Point Tracking in the microinverter system. The MPPT controller was used to control the duty cycle for Maximum Power Point Tracking in the DC-DC optimizer and microinverter systems. The inverter was used for inverting DC signals to AC signals in both the DC-DC optimizer and microinverter systems. Based on the need to potentially step up or step down the PV panel voltage during MPPT, we determined that a buck-boost converter would be the most suitable topology for our DC-DC converter [1]. The MPPT controller was implemented using the Perturb and Observe algorithm, as this is the algorithm most widely used in the industry [2]. Finally, the inverter was designed as an H-Bridge PWM inverter due to the need for a purely sinusoidal output signal and its ease of implementation. Note that the central inverter system is the only system modeled using different topologies, as this system was our "control" for a working PV system as its design was provided mainly by a MATLAB reference design .

DC-DC Converter

The schematic for the buck-boost converter implemented and the characteristic equation relating the input and output voltage for the buck-boost converter are both shown below [3].

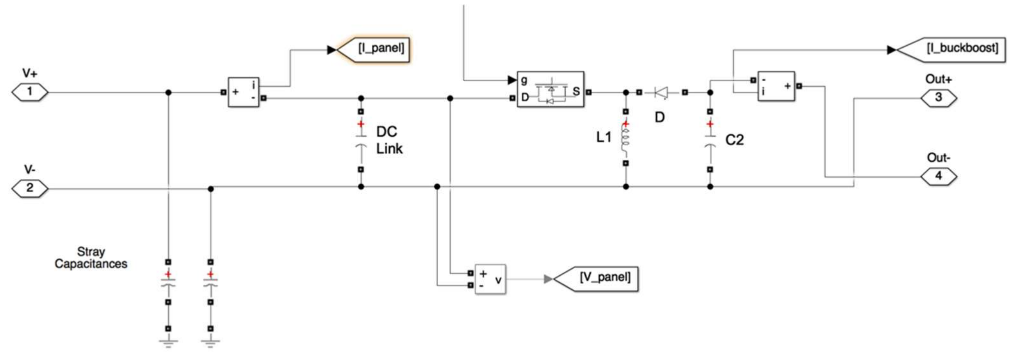

Figure 1: Buck-Boost Converter Simulink Model

(1) $$V_{out} = \frac{-D}{1-D} V_{in}$$

The polarity of the output voltage becomes negative when it converted through a buck-boost converter. This polarity reversal was addressed by connecting the negative terminal of the inverter to the positive terminal of the buck-boost converter.

The following equations were used to design the inductor and capacitor for the buck-boost converter.

(2) $$C_{min} \geq \frac{DTI_{load}}{\Delta V_C}$$

(3) $$L_{min} \geq \frac{V_L DT}{\Delta i_L} = \frac{V_{in} D_{max}^2 T}{\left(\frac{\Delta i_L}{i_L}\right) I_{in}}$$

Here, D is the duty ratio of the MOSFET switch, T is the switching period, I_{load} is the current through the load resistor, V_L is the voltage over the inductor, Δi_L is the allowed inductor current ripple, and ΔV_C is the allowed capacitor voltage ripple.

Maximum Power Point Tracking

In order to ensure that the PV panel was producing its maximum power output, Maximum Power Point Tracking (MPPT) was utilized. The MPPT algorithm in the modeled system employs the Perturb and Observe method, which adjusts the duty ratio of the buck-boost converter by calculating the appropriate duty ratio to maintain peak power output for the PV panel. By measuring the PV panel output voltage and current, the power can be calculated. By comparing the change in power and voltage values to previously measured values, the controller will increase or decrease the duty ratio. The MPPT controller recursively calculates and compares the power and voltage to dynamically adjust the PV panel output power to ensure it is at its maximum [2]. The code for the MPPT algorithm used in the simulations is listed in Appendix A. The following figure shows the logic flow chart of the MPPT algorithm.

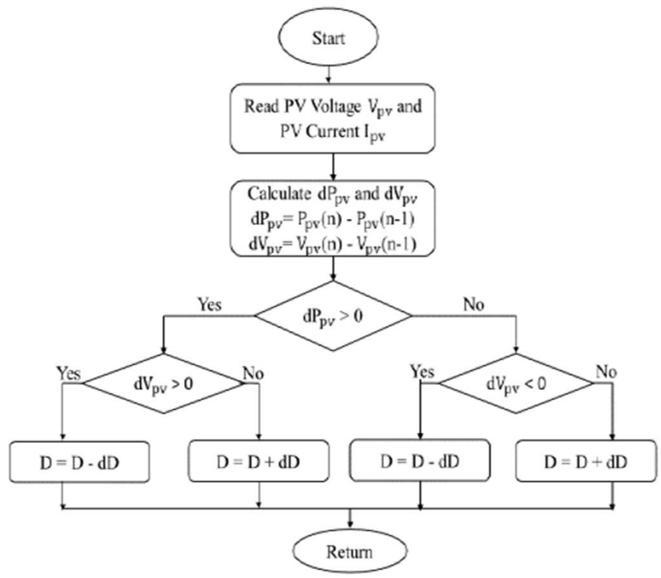

Figure 2: Perturb and Observe Algorithm Flowchart [2]

H-Bridge PWM Inverter

An H-bridge pulse width modulated (PWM) single-phase inverter was used to convert the DC output signal(s) to the desired AC voltage. The inverter was designed to output 240 VRMS, with a frequency of 60 Hz. These values were chosen to simulate integration with the United States power grid, where residential structures are supplied with a 240 VRMS AC signal (for stepping down to 120 VRMS) at 60 Hz. The Simulink model of the PWM inverter implemented is shown below.

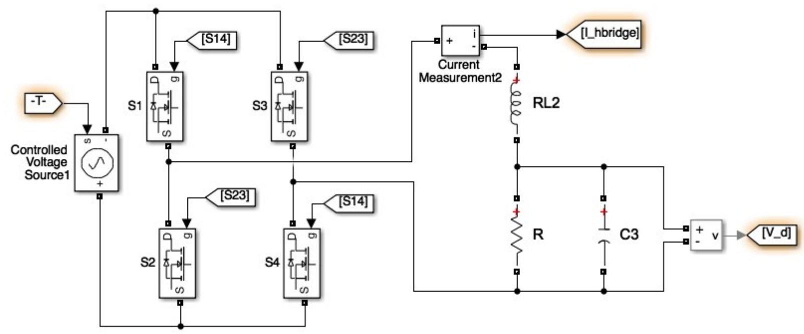

Figure 3: PWM Inverter Simulink Model

The output voltage is determined by the switching frequency of the switches. Given an input voltage value, the inverter was designed to output a particular voltage value by calculating the depth, *k*, as follows:

(4) $$k = \frac{V_{out-p}}{V_{in}}$$

And knowing the relationship that:

(5) $$V_R(t) \approx kV_{in}\cos(\omega_{out}t)$$

The duty cycle for the switches could then be calculated using:

(6) $$D_{14} = \frac{1}{2} + \frac{k}{2}\cos(\omega_{out}t)$$

(7) $$D_{23} = 1 - D_{14}$$

From here, the resistor, inductor, and capacitor values could be chosen. To ensure the output frequency is not attenuated by the low pass filter, the resistor and inductor values are chosen using the following relationship:

(8) $$\frac{R}{L} = 10\omega_{out}$$

To ensure that the switching frequency is much greater than the output frequency, the switching frequency is chosen to so that:

(9) $$\omega_{switch} > 10\frac{R}{L}$$

Finally, to pick a suitable capacitor value, we make use of the relationship:

(10) $$C > \frac{T_{sw}^2 V_{in}}{16 \Delta V_C L}$$

The specific values chosen for the inverter in each application will be discussed in the analysis for that application.

Central Inverter System

Overview

The central inverter configuration is made of PV panels linked in series, forming strings. Each string is connected in parallel to form an array. The combined output of all the strings is fed to a large inverter, which converts the DC voltage to AC and sends it to the grid [4].

System Simulation

The central inverter system was modeled in MATLAB Simulink. To simulate the central inverter system for testing purposes, we downloaded the MATLAB example "Single-Phase, 240 Vrms, 3500 W Transformerless Grid-Connected PV Array" and built our design from it [5]. The main modification we made was splitting the PV Array block (which inherently contained multiple modules strung together in series in the example) into multiple PV Array blocks each only containing one module. By manually placing these single module blocks in series, we were able to individually control the irradiance each module experienced. Such control enabled us to perform partial shading tests, as well as full sunlight tests. We decided on a standard of one string of 10 PV modules in series for our system design, and carried this convention through later to the DC-DC optimizer and microinverter systems. Aside from modifying the number and format of the PV Array modules, we also had to place capacitors across each module in our model with initial voltages of the MPPT voltage for the module. This capacitor placement ensured that the PV module output voltage started in a well-defined state, which was necessary for the MATLAB PV Array block implemented. We also had to modify the expected reference voltage range for the MPPT controller used (based on the Perturb and Observe algorithm, which will be explained in further detail in the DC-DC optimizer system analysis). No further changes needed to be made to the central inverter system, and as such we were able to perform testing with it to determine the system outputs under various irradiance conditions. The MATLAB model for our central inverter system is shown below, and our results are as follows:

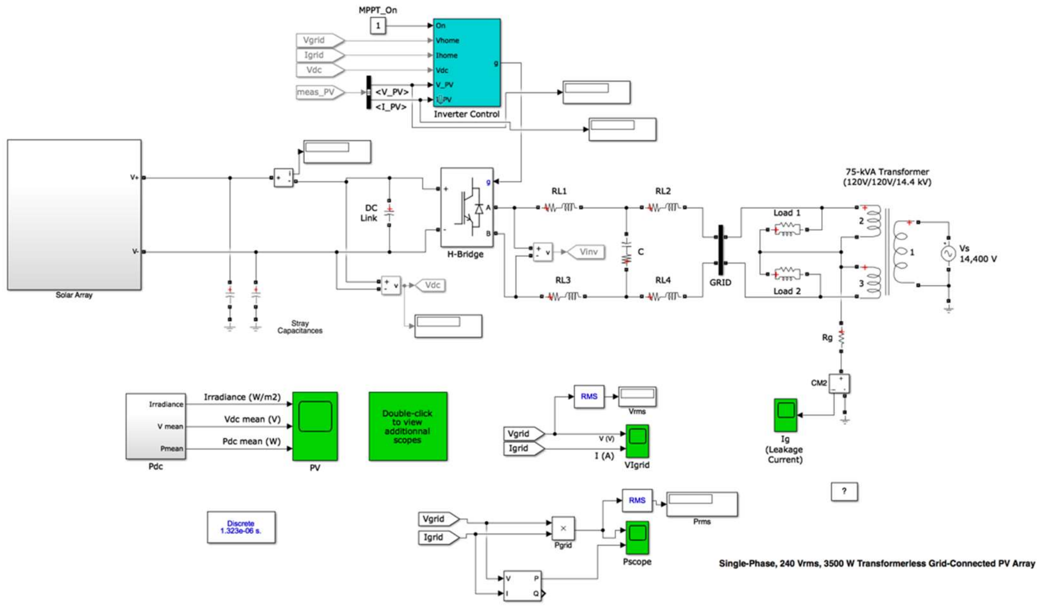

Figure 4: Central Inverter System Model

The resulting grid voltage waveform generated from our central inverter system is shown below for the $1000\frac{W}{m^2}$ irradiance condition. The power results under varying shading conditions are listed to follow. The shading factor used was a 25% reduction in irradiance (so an irradiance value of $750\frac{W}{m^2}$), which corresponds to a heavy shade condition [6]. The shade factor was implemented on 5 of the 10 solar modules, while the other 5 were held at $1000\frac{W}{m^2}$.

Figure 5: Central Inverter System 100W/m^2 Voltage

Table 1: Central Inverter System Power Results

Power Condition	No Shade - 100W/m^2	Heavy Partial Shade - 750W/m^2
Power Value	2471	1690

From this we can see there is a 31.6% drop on overall power output of the array with half of the PV panels shaded, from 2471 to 1690. These values will be used for comparison later in the report.

Advantages & Disadvantages

Some advantages of this configuration are reliability, simplicity, and cost efficiency. This configuration has a proven track record, as it is the oldest configuration in the world that is still used. Also, being a single central inverter, this configuration is the simplest (has the least components) compared to the other two configurations, which allows for better reliability. The minimalism in power conversions leads to fewer points of fault in the PV system, and thus more ease in monitoring each component. If a PV system in this configuration is not functioning properly, it is somewhat straightforward to diagnose and resolve the problem. Having fewer components also allows for the system to be cheaper.

Several disadvantages of this configuration include interdependency in the PV array, high voltage output and difficulty in expanding the system. Interdependence in the array means that when one PV panel is not producing as much power as the other panels (usually due to shading), this single panel will limit the output of the entire array. Also, since the PV panels are all connected in series, there will be high voltages in the PV system (maximum 600Vdc for households [7]), which heavily increases the risk for fire or shock. Additionally, it would be difficult to expand the system since a new string of PV panels would have to match the old strings exactly (same angle, location, exposure) in order to output the same power, or else one of the strings would limit the entire array. Lastly, if the central inverter fails, the whole PV system fails until the inverter is repaired or replaced, which is costly and time consuming [8].

Cost Analysis

A typical central inverter costs between $1500 and $2500 and usually includes a 10 year warranty and an expected 10 year service life, although the service life can be extended to 20 years with a proactive monitoring and maintenance plan [9]. A typical household PV system in the Massachusetts is 7kW, which can consist of 28, 260W PV panels and a central inverter [10]. A solar panel costs $217, so the total cost of a system is $7576 (assuming the inverter costs $1500) [11]. This cost estimate is only used for comparison and does not include labor and other installation components (mounting, balance of system, etc).

DC-DC Optimizer System

Overview

The DC-DC optimizer system consists of a series of PV panels, with each panel connected to a DC-DC optimizer. Each optimized output is connected in series and then fed to a large central inverter which is connected to the grid.

System Simulation

The DC-DC optimized system was modeled in MATLAB Simulink. Using chosen irradiance and temperature inputs, the output power was determined. The following figures show the system model and relevant subsystems.

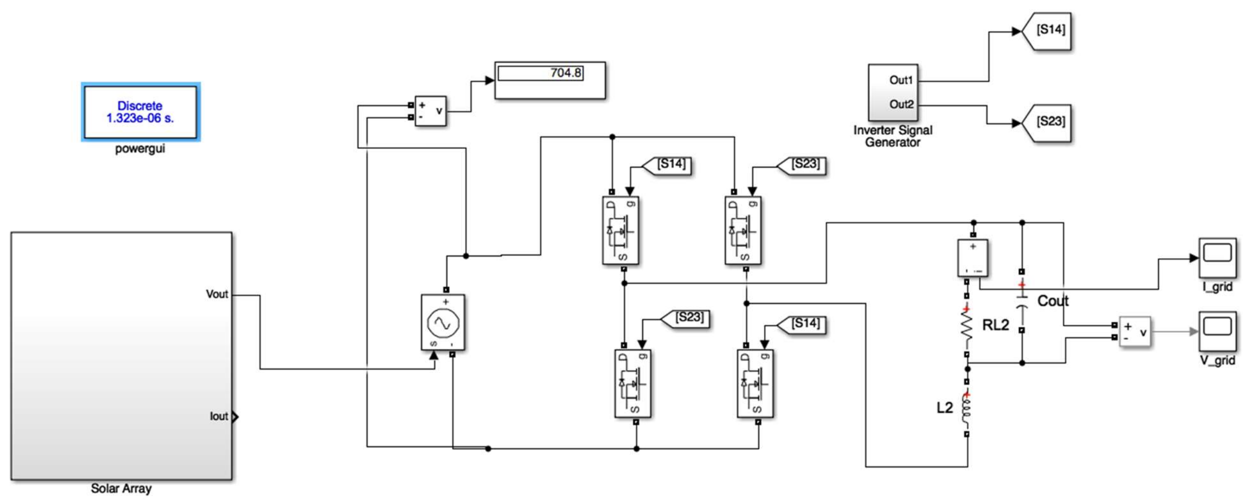

Figure 6: DC-DC Optimizer PV System Model

As in the central inverter system, ten PV panels were connected in series for this system. A DC-DC optimizer was connected to each panel and with the optimized outputs connected in series, as seen in the following images.

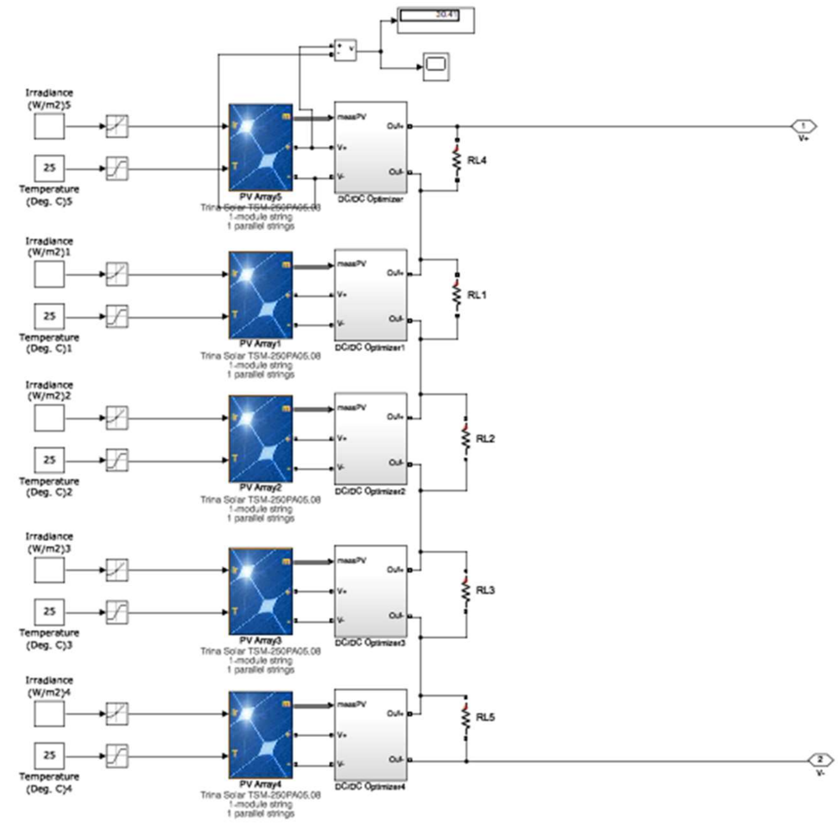

Figure 7: 5 PV Panel String with DC-DC Optimizers

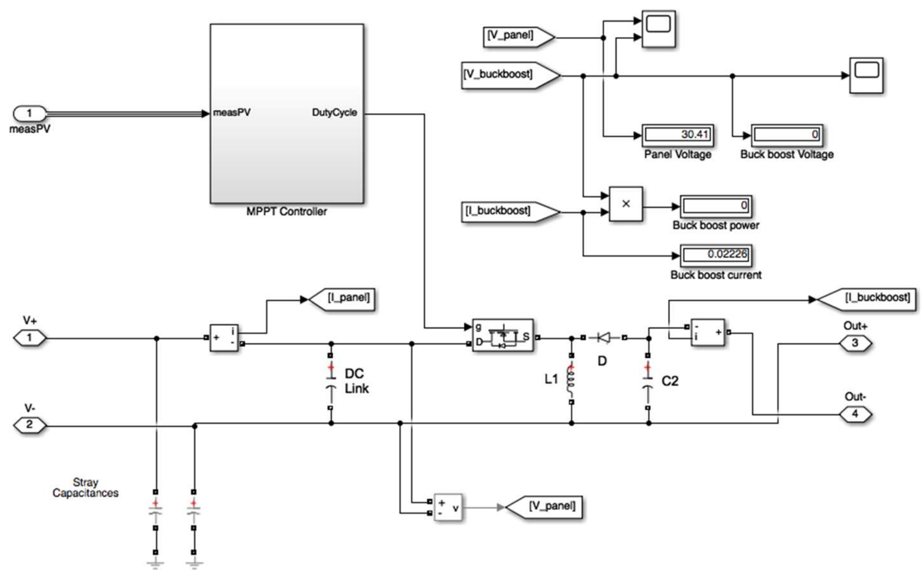

Figure 8: DC-DC Optimizer Circuit with Buck-Boost Converter

The inductance and capacitance values were designed using the Buck-Boost design equations. As the output voltage was intended to be unregulated according to the MPPT algorithm, we simply designed the inductor and resistor values. Equation 3 was used to determine the inductor value under worst case conditions. The worst case ratio $\frac{V_{in}}{I_{in}}$ occurs when the panel is experiencing a $100\frac{W}{m^2}$ irradiance (the worst typically for a poor weather day), at which point the MPPT for the panel input is $V_{in} = 29.28V$ and $I_{in} = 0.805A$. The worst case duty cycle is the duty cycle at the MPPT for the highest tested irradiance ($1000\frac{W}{m^2}$), which was determined to be about 0.6 from Equation 1 assuming a 45V converter output. We also decided to use a switching frequency of 100kHz and a maximum allowed inductor ripple percentage of 20% pk-pk based on reasonable estimations. These values lead to an inductance calculation of about $0.7mH$, which was the value implemented in the model. The capacitance value was chosen using Equation 2 and a worst case load current of 6A (which would be the load current modeled for all cases). The worst case duty ratio and output voltage could then be solved for based on the panel power output when the panel is experiencing its worst irradiance condition ($100\frac{W}{m^2}$). We also assumed a maximum 1% pk-pk voltage ripple. Using this method, we determined our capacitance value to be $0.2mF$. A link capacitor for the panel was also chosen nominally as $3mF$. As seen in Figure 6, we also had to include output resistors for each DC-DC converter. We understand that this resistor would not be included in practice, as instead impedance matching would be performed with the output load of the inverter the DC-DC converter output feeds to. However, here we were unable to perform the correct impedance matching as we could not correctly determine the output of the DC-DC converter using the load of the inverter. Therefore, we included a resistance of 20Ω at the output of each DC-DC converter to properly set its output voltage to approximately 70V.

The inverter was designed by first using Equation 4 to properly determine a depth of 0.485 for a V_{in} of 700V (ten 70V outputs in series) and a V_{out} of $240\sqrt{2}$. This depth value allowed us to set our duty ratios using Equations 6 and 7. From here, we chose a resistor value of 40Ω based on a P_{out} of 2495 (10 panels at 249.5 W each) and a V_{out} of $240\sqrt{2}$. Equation 8 allowed us to pick a correct inductance value of $10.36mH$ based on the remaining specifications. Using Equation 9, we decided on a switching frequency of 20kHz. Finally, Equation 10 allowed us to pick the correct capacitance value assuming a ΔV_C of 5V.

The PandO block contains the MPPT Perturb & Observe function (Appendix A), that controls the duty ratio of the buck-boost converter to ensure that the PV panel power output is maximized. The implementation of this block is shown below.

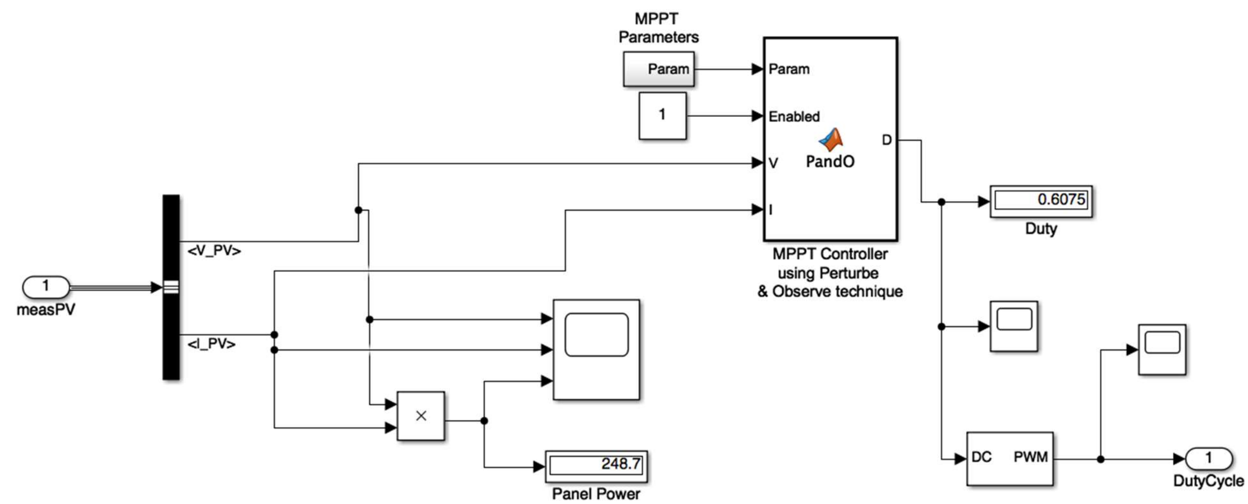

Figure 9: MPPT Controller with Perturb & Observe Functional Block

The resulting grid voltage waveform generated from our DC-DC optimizer system is shown below for the $1000\,\frac{W}{m^2}$ irradiance condition. The power results under varying shading conditions are listed to follow. The shading factor used was the same 25% irradiance reduction.

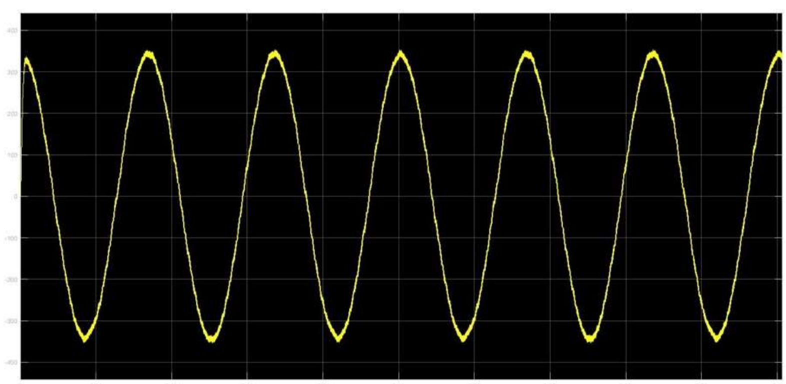

Figure 10: DC-DC Optimizer $100W/m^2$ Voltage

The peak voltage is 339.411 volts which is the amplitude of 240 VRMS waveform. There are six periods over the 0.1 second interval, confirming the frequency is 60Hz.

Table 2: DC-DC Optimizer System Power Results

Power Condition	No Shade - 100W/m^2 (W)	Heavy Partial Shade - 750W/m^2 (W)
Power Value	1451	1281

From this we can see there is a 11.7% drop on overall power output of the array with half of the PV panels shaded, from 1451 to 1281. Comparing this to the 31.6% power drop for the central converter system, we can conclude DC-DC optimizer lessens the effect of individual PV panels that are under performing.

Advantages & Disadvantages

Advantages of this configuration include less interdependence between each individual PV panels. This means that each PV panel is operating at its highest power point based on the irradiance and temperature input. Each panel is optimized individually so that a lower power output from one panel does not limit the power output of the entire array [12].

Some disadvantages of this configuration include high voltage output since the panels are still connected in series and the total voltage is the sum of the optimized DC voltages, and high single failure risk since the panels are connected in series. The DC-DC optimizer configuration has an added component at each panel so there is a higher risk of component failure due to the increase in complexity of the system [12].

Cost Analysis

This system is more expensive than the central converter system. For example, each PV panel must be fit with its own DC-DC converter, which ranges in cost from $50-75 each, depending on functionality. For a 7kW system, twenty eight 260 W PV panels are required. Using 28 SolarEdge P320 Power Optimizers, which cost $71, 28 Sunspark 260 W PV panels that cost $217 each, and a $1500 central inverter—the total of this system comes out to $9564, which is $1988 more than the central inverter system [9].

Additionally, the system is more difficult to install since each PV panel needs to be fitted with a DC-DC optimizer, which results in greater labor cost. Most manufacturers offer a 25-year warranty on their DC-DC converters, but considering the central inverter has a shorter working life/warranty, the DC-DC converter will still be functional by the time the central inverter need to be fixed or replaced [12].

Microinverter System

Overview

The microinverter configuration consists of an array of PV panels where each panel has a microinverter that converts the panel's DC output voltage into an AC voltage. Each panel is connected in parallel and each string is connected directly to the grid [13].

The micro-inverter model topology utilizes the same buck-boost DC-DC converter and the H-bridge PWM inverter as the DC-DC optimizer. However, the DC-DC converter and inverter were redesigned slightly at the component level to meet the new power specifications of the system. MPPT is still applied at the DC-DC converter level. Micro-inverters combine the DC-DC optimizer and inverter, connecting directly to individual PV panel. The micro-inverter AC output voltages have the same frequency and voltage, as well as the same phase. This allows them to be connected in parallel, and then ultimately connected to the grid. When connected in parallel, the regulated voltage remains at 240 VRMS for each microinverter output, but the power for each is added together.

System Simulation

The Microinverter PV system was modeled using MATLAB Simulink. The buck-boost converter was used as the DC-DC converter, and the PandO function was used for MPPT control. The following figure shows the overall Microinverter system.

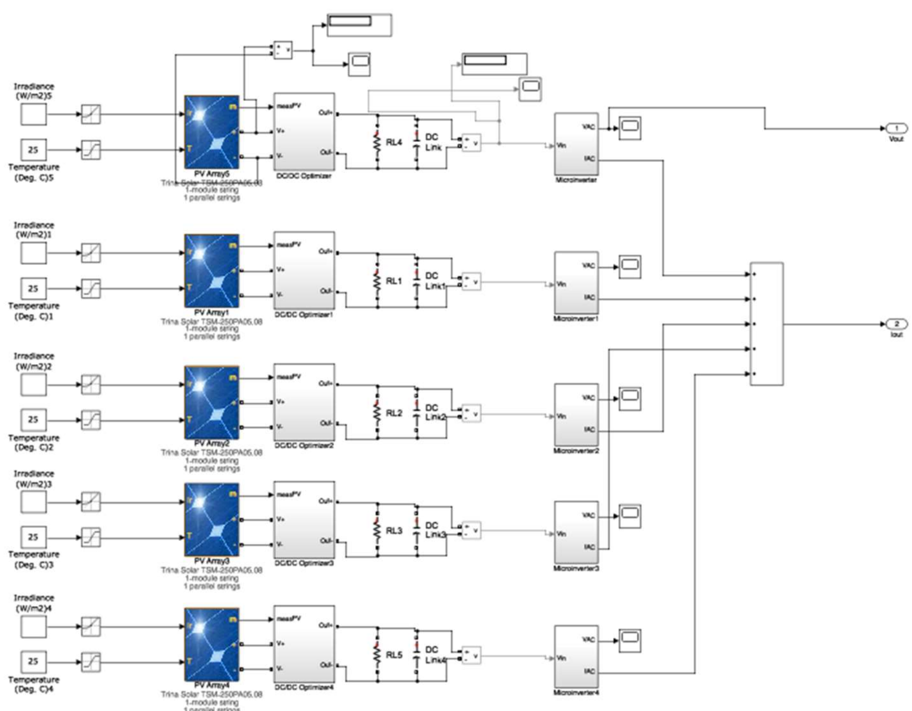

Figure 11: 5-Panel String with Microinverters

Two of the above 5-panel configurations with microinverters were connected in parallel. The microinverters were configured to output 240 VRMS at 60Hz. The buck-boost converter used here was identical to the converter used for the DC-DC optimizer system. Only the load resistance for each converter was modified to be 600Ω to regulate the outputs of the converters to about 385V. This allowed each microinverter to be designed as the larger PWM inverter was designed for the DC-DC optimizer system, assuming and input voltage to each inverter of 385V and an output voltage of 240 VRMS AC. The respective inverter parameters are therefore simply listed for convenience in Table 3 below. The voltage of one panel was output to simulate the voltage sent to the grid, while the currents of each microinverter were added to simulate the current output to the grid. Again it should be noted that this does not perfectly model a true PV system, as the loading effect of the inverters on the DC-DC converters is effectively eliminated. However, for the purpose of this report and of generating a valid relative comparison between the three systems, we determined the methodology implemented to be acceptable.

Table 3: Microinverter Parameters

Parameter	Depth (k)	Switching Frequency (kHz)	Resistor (Ω)	Inductor (H)	Capacitor (μF)
Value	0.882	20	463	0.123	0. 4902

The resulting grid voltage waveform generated from our microinverter system is shown below for the $1000\frac{W}{m^2}$ irradiance condition. The power results under varying shading conditions are listed to follow. The shading factor used was the same 25% irradiance reduction.

Figure 12: Microinverter $100W/m^2$ Voltage

The peak voltage is 339.411 volts which is the amplitude of 240 VRMS waveform. There are six periods over the 0.1 second interval, confirming the frequency is 60Hz.

Table 4: Microinverter System Power Results

Power Condition	No Shade - 100W/m^2 (W)	Heavy Partial Shade - 750W/m^2 (W)
Power Value	1231	1060

From this we can see there is a 13.89% drop on overall power output of the array with half of the PV panels shaded, from 1231 to 1060. Comparing this to the 31.6% power drop for the central converter system, we can conclude microinverter lessens the effect of individual PV panels that are under performing. However, there is a more significant power drop in the microinverter configuration (13.89%) compared to the 11.7% of power drop in the DC optimization configuration. Theoretically the microinverter should have a smaller power drop because each PV panel is its own independent system while this is not the case in a DC optimization configuration. This deviation from theory may be due to inaccurate values we chose to build the microinverter or the buck boost converter. Also, the output of each configuration was changed as we went through the modeling process – we should have had a similar No-shade power value for each configuration, but instead we have 2471 for the central inverter, 1451 for the DC optimizer, and 1231 for the microinverter, which may have further skewed our conclusions.

Advantages & Disadvantages

The advantages of this configuration include no high DC voltages (which eliminates the risk of shock and fire hazard), no interdependence between PV panels, the ability to expand an existing PV array with relative ease, and increased reliability [14]. In a microinverter system, each PV panel performs independently and at its own optimal peak, so a shaded panel within the array has no bearing on other panels. As independents units, PV panels with microinverters can be added to an existing array at any time and will only increase the total solar energy generated in the array. This benefit allows homeowners to start will a small microinverter array and expand it over time, compared to central and DC-DC optimized configurations where a big investment is made up front. Also, microinverters are marketed as being more reliable than central inverters, as they are typically sold with a 25 year warranty [14] to match the expected lifetime of the PV panels they are installed on, which is also typically 25 years [6]. This projected lifetime can be compared to that of a standard central inverter, which is typically only 10-20 years.

Cost Analysis

The main disadvantage of the microinverter configuration is the cost. For a 7kW system, 28 260W Panel and 28 microinverters are required. Using 28 Enphase iQ6+ microinverters (IQ6PLUS-72-2-US), which cost $265 each [15], and 28 Sunspark 260 W solar panels, which cost $217 each [16], the total price of this system can be projected as $13,496. This total cost is $5,920 more than the central inverter configuration and $3,932 more than the DC-DC power optimization configuration.

Conclusion

In this report we compared three types of PV inverter configurations: central inverter, DC optimization, and microinverters, on basis of cost, performance, and reliability.

For a model 7kW PV system that consists of 28 260W Panel and the inverter specified for each configuration, we have the central inverter system coming out to $7576 (28 $265 PV panels and a $1500 central inverter), the DC optimization configuration at $9564 (28 $265 PV panels, 28 $71 DC optimizers, and a $1500 central inverter), and the microinverter configuration at $13496 (28 $265 PV panels, and 28 $217 microinverters). Using the central inverter cost as a reference, the DC optimization configuration represents a 26.2% increase and the microinverter configuration represents a 78.4% increase, although the higher costs of the latter two configuration might be justified by their improvement in performance.

A central inverter configuration has its entire output limited by a single, underproducing PV panel (which is usually due to shading). A DC optimization configuration is better because a single panel will not limit the system's output as much. A microinverter configuration produces the best power output because no one panel affects any other panel in the array. Each panel will operate at its maximum power. In our model, for the central inverter system, we got a power drop of 31.6% from no shading conditions to partial shading on half the panels. For the DC optimization, we got a 11.7% power drop, and for the microinverter, we got a 13.89% power drop. This shows that for a central inverter, the PV output is very constrained due to individual panels underperforming, while for the DC optimization and microinverter systems, there is less of an effect. Theoretically, the microinverter configuration should have a smaller power drop than the DC optimizer, which may be due to our modified method for modeling the DC-DC optimizer and microinverter systems. In a real system, impedance matching would be performed so that the full power from the DC converters would be transferred through the inverter(s). As here we only modeled voltage output from the DC converters and used that to control a separate voltage being sent to the inverter(s), the power conversion between the DC converter and the inverter is not completely correct (we did not account for current properly). Therefore, we expect larger power drops and worse efficiencies than theoretical predictions. However, our analysis is still applicable in relative system comparison, as the relative drops in power for partial shading conditions are still mostly valid based on the configurations.

Lastly, in terms of reliability, the central inverter system is adequate with a working life and warranty of 10 years, which can be extended up to 20 years, and there are fewer components that could fail. Although, running high DC voltages presents a shock and fire hazard. The DC optimization system is less reliable in that there are more components that can cause failure, the central inverter still has the same 10-20 year warranty/lifetime, and there is the high DC output which is a shock and fire hazard. The microinverter configuration is the most reliable in that each component failure does not affect other PV panels in the array, the microinverter has a warranty/lifetime of 25 years, and there is no high DC voltage, which reduces the risk of shock and fire.

In conclusion, the chosen configuration depends on many variables – space (on a roof), weather, finances, risk adversity, etc., so there is no configuration that is the best. Each has their advantages and disadvantages, although several conclusions can be drawn. If the homeowner is in a consistently sunny location, a central inverter system would be the most feasible. If the homeowner is in a partially sunny location with inconsistent shading, a DC optimization configuration would be the most feasible. If the homeowner is in a partially sunny location with inconsistent shading and has a lot of money, a microinverter system would be best for its additional advantages (no high DC output, longer working life, ease of expansion).

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Appendix A

```
function D  = PandO(Param, Enabled, V, I)

% MPPT controller based on the Perturb & Observe algorithm.

% D output = Reference for DC link voltage (Vdc_ref)
%
% Enabled input = 1 to enable the MPPT controller
% V input = PV array terminal voltage (V)
% I input = PV array current (A)
%
% Param input:
Dinit = Param(1);  %Initial value for Vdc_ref
Dmax = Param(2);   %Maximum value for Vdc_ref
Dmin = Param(3);   %Minimum value for Vdc_ref
deltaD = Param(4); %Increment value used to increase/decrease Vdc_ref
%
persistent Vold Pold Dold;

dataType = 'double';

if isempty(Vold)
    Vold=0;
    Pold=0;
    Dold=Dinit;
end
P= V*I;
dV= V - Vold;
dP= P - Pold;

if dP ~= 0 & Enabled ~=0
    if dP > 0
        if dV > 0
            D = Dold - deltaD;
        else
            D = Dold + deltaD;
        end
    else
        if dV > 0
            D = Dold + deltaD;
        else
            D = Dold - deltaD;
        end
    end
else D=Dold;
end

if D >= Dmax | D<= Dmin
    D=Dold;
end
Dold=D;
Vold=V;
Pold=P;
```