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Smart Two-Stage Solar Microinverter

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A Major Qualifying Project submitted to the faculty of the Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science.

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ABSTRACT

The goal of the project was to design and build a two-stage solar microinverter that can be used as a testbench for MPPT algorithms and control structures. Testing these algorithms and control structures will give future researchers the ability to test their various ideas to further develop solar energy research. A prototype microinverter consisting of a flyback DC-DC converter and a full bridge DC-AC inverter was designed, assembled and tested. The converter and inverter sections function individually, but further work is needed to combine the two sections into a full microinverter.
ACKNOWLEDGEMENTS

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A microinverter is a small inverter used to extract and convert energy from a singular PV module. One method that is currently used to improve the efficiency in microinverters is the use of Maximum Power Point Tracking (MPPT). MPPT adjusts the operating voltage of the PV Module such that it’s operating at its highest efficiency possible given the current conditions [1].

The goal of this project is to design and build a two-stage solar microinverter that can be used as a testbench for MPPT algorithms and control structures. From research into microinverter topologies, a single switch flyback boost converter was identified as the most suitable topology to boost the PV voltage up to 170Vpk. For the DC/AC inverter, an H-bridge topology with an LCL filter was chosen for providing a sinusoidal output. An LCL filter was used to filter the output of the h-bridge into a 60Hz sinusoidal waveform.

Prior to implementing the physical system, the microinverter circuit was simulated using Simulink. The simulation results included the PV current and voltage, the MOSFET current and voltage, the transformer current and voltage, the DC link voltage, the grid current, and voltage waveforms, and the converter duty cycle. After creating the Simulink model of the PV microinverter, considerations were made to bring the simulation into a practical circuit. Measurement subcircuits were implemented to measure voltage and current across the microinverter. The converter and inverter were driven using gate drivers. A TI Delfino MCU was used to control the operation of the microinverter, taking in measurements, providing PWM for the gate drivers, and running MPPT algorithms.
The microinverter consists of multiple dependent functional blocks. During assembly of the system, each block was assembled and brought up separately to reduce the likelihood of a malfunctioning block from damaging other components on the PCB or producing misleading results. Issues encountered during the testing of each functional block were corrected before the assembly of the next dependent block.

To verify the functionality of the MPPT algorithm on the DC/DC converter, the DC/DC converter was connected to a 24V DC source with a 12Ω series resistance on the input and a 375Ω load on the output. To gather data in this experiment, two Simulink models were run in external mode to collect Vpv, Ipv, and duty cycle samples from the MCU. From the Vpv vs. Time plot, the system was able to maintain a voltage between 10.8-12.6V, which is close to the Vmp of 12V for this system. The efficiency of the DC/DC converter in this test was about 77%.

To test the DC-AC Inverter, the input to the DC/AC Inverter was connected to a DC power supply, with a voltage of 40V being supplied on the input and a 30Ω resistive load on the output. The oscilloscope image shows the output of the inverter is a 60Hz sine wave, which was anticipated. Measuring the efficiency of the power output vs the power input, the inverter efficiency during this test was 75%. 
Originally, the plan was to control the inverter section of the microinverter, but there were issues with EMI on the inverter side when a significant amount of current is passed through. These issues include voltage spikes on the measurement and voltage references and the interruption of serial and I2C communications to the MCU. Therefore, the EMI issues were documented and suggestions have been made for how to fix them in future iterations of this project.

The prototype microinverter can be used to evaluate MPPT techniques and control schemes to improve the efficiency of photovoltaic systems, and it is able to be modified and customized to fit the needs of the users. The resulted efficiency of the single-switch DC/DC stage was 77%. The DC/AC H-bridge inverter is able to reliably produce a clean 60Hz sine wave from a DC voltage input into a resistive load, with an efficiency of 75% during testing. For standalone use as a grid-tied microinverter, additional future revisions are required.
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A microinverter is a small inverter used to extract and convert energy from a single PV module. One method that is currently used to improve the efficiency in microinverters is the use of Maximum Power Point Tracking (MPPT). MPPT adjusts the operating voltage of the PV module such that it’s operating at its highest efficiency possible given the current environmental conditions [1].

The goal of this project is to design and build a two-stage solar microinverter that can be used as a testbench for MPPT algorithms and control structures. Using a two-stage construction allows for the converter and inverter sections to be used and tested independently. This microinverter was designed with being able to collect runtime data and to easily adjust software parameters in mind. To achieve this goal, the following four steps were completed:

1. Identify different microinverter topologies and control algorithms
2. Simulate the chosen microinverter topology
3. Design and construct the microinverter on a printed circuit board
4. Conduct microinverter testing for functionality

First, research was conducted to determine the most suitable microinverter topology to accomplish the project goal. Once this was determined, the microinverter topology was simulated using Simulink to verify the viability of it and ensure that the selected topology worked as predicted. To realize the design in hardware, additional support circuitry for measurement and gate driving was designed. A microcontroller capable of running real-time control algorithms was selected and interfaced to the measurement and control circuitry. Additionally, the complete circuitry was laid out onto a PCB, which was then fabricated and assembled. Firmware for the microcontroller was developed using the Simulink Embedded Coder functionality in MATLAB. Each section of the microinverter was then tested in a series of steps to eliminate any potential issues that may cause other sections not to work.
2. LITERATURE REVIEW

There are several different ways to connect a photovoltaic system to the grid. To start, the three main inverter configurations that are common are the central inverter, string inverter, and microinverter configurations. Each of these configurations is capable of using an MPPT algorithm to track the optimal PV operating voltage. While there are multiple MPPT algorithms, one of the most common algorithms is the Perturb & Observe (P&O) algorithm [1],[2]. In addition to inverter configurations and MPPT algorithms, the topology of the inverter also contributes to the amount of power that a PV module can deliver to the grid. Inverter topologies can be divided into the categories of two-stage and one stage. In a two-stage topology, a DC-DC converter increases the voltage before inverting the voltage and injecting it into the grid. However, in a one-stage topology, the DC-DC converter is nonexistent, and the voltage is inverted and stepped up to the grid voltage in one single stage.

2.1 PV Module Power Extraction Methods

PV systems can have a variety of characteristics. Some of these include how the system is configured and whether it is a standalone or grid-tied system. The smallest PV configuration is a cell which makes up a PV module. PV modules can have a number of cells, with a common number of cells being 48, 54, 60, or 72. PV modules can then be connected in series to create a PV string [3]. These PV strings can then be configured in parallel to create PV arrays which will also increase the power output of the PV configuration.

2.1.1 Central Inverter

A central inverter is a configuration of inverters that are connected to multiple strings of PV modules in parallel. As shown in Figure 2.1, each string is connected in parallel, and then the inverter is connected to the entire array of PV modules. Central inverters are most commonly used within large scale utility PV farms [4]. This is due to central inverters being low cost and easy to implement which are both appropriate for large scale operations. On the other hand, central inverters do have their disadvantages. One disadvantage of central inverters is how difficult it is to integrate MPPT with them [4]. Due to the combined IV characteristics of each PV module, it is challenging to track the maximum power point (MPP) of the entire PV array. Additionally, partial shading of the array of PV modules can degrade the amount of power that an array can provide. Since each array is producing less than its optimal power output, the entire facility as a result will not reach its full potential due to the type of inverters that are used.
2.1.2 String Inverter

A string inverter, unlike its central inverter counterpart, only converts the DC power of one PV module string to AC power as seen in Figure 2.2. Since this configuration requires an inverter at the end of each string of modules, it will be more expensive. However, in the long run, it will yield higher power outputs [4]. This is mainly because each string will have a dedicated MPPT algorithm tracking the voltage of the string. As a result, the losses due to partial shading or other mismatching causes will be drastically reduced. This will ultimately lead to a higher power output of each string, array, and facility respectively.

2.1.3 Microinverter

A microinverter, when compared to its counterparts, is considered a different method to improve efficiency compared to the previous two topologies. Unlike a string or central inverter, a microinverter converts DC power to AC power at the PV module level as seen in Figure 2.3. The operating voltage of each PV module can be controlled individually. This allows MPPT to be run independently on each module, which is more effective as conditions may vary between modules due to partial shading [5]. If a string or central inverter uses any transformer, then the larger current going through the inverter will
produce more losses than a transformer in a microinverter [6]. Microinverters are not ideal for every installation type, as they have some disadvantages such as the substantial cost to install one for each PV module [7]. This results in microinverters typically being used for smaller scale applications where there are not hundreds of PV modules.

![Figure 2.3. Microinverter Configuration](image)

### 2.2 Maximum Power Point Tracking

A PV module has different IV characteristics depending on varying conditions such as solar radiation, ambient temperature, and photovoltaic cell temperature. MPPT is a method which is used to extract the maximum available power from a PV module under any of the varying conditions. This algorithm is usually implemented on the DC-DC converter, which helps to track the value of the voltage at which the PV module can deliver the maximum power. Although there are many different MPPT algorithms, the main focus of this section will be on the Perturb and Observe algorithm.

#### 2.2.1 Perturb & Observe MPPT Algorithm

P&O is one of the most popular MPPT algorithms used for photovoltaic systems [1],[2]. This algorithm works by changing the voltage value of the PV system in small increments, while also measuring its output power. When the voltage is altered by a small value, the algorithm measures the change in power output of the system and if there is an increase in the power than the voltage perturbation is continued in the same direction. When perturbing the voltage decreases the system’s power output, the algorithm reverses the direction of the voltage perturbation to reach the MPP. One of the advantages of using a P&O algorithm is that it is easy to implement, but on the other hand due to its constant perturbation of voltage it generates a steady state oscillation. Ultimately this steady state
oscillation results in a fair amount of power loss within the system. This algorithm was implemented on the microinverter to verify that the hardware is capable of successfully running an MPPT algorithm.

2.3 Microinverter Topologies

A topology in electrical terms refers to how a circuit is physically connected and configured. The system configuration of microinverters can be separated into two broad types: a one stage topology, and a two-stage topology. A one stage microinverter topology steps up the voltage and converts it to AC power all within a single DC-AC Inverter. On the other hand, a two-stage microinverter topology includes a DC-DC converter to step up the voltage and a DC-AC inverter in a second stage [8]. Although the single stage topology is simpler to construct, it quickly becomes much less efficient with larger power outputs [8]. Additionally, using a two-stage approach allows for the DC-DC converter stage, where MPPT is typically implemented, and the inverter stage, where the grid power output is modulated, to be tested and used separately.

2.3.1 DC-DC Converter

A DC-DC converter serves the purpose of increasing or decreasing the voltage of its input to a higher or lower voltage at its output. The three most common types of converters are boost converters, buck converters, and buck-boost converters. This report will focus on boost converters to increase the voltage output from the PV module.

Conventional Boost Converter

![Figure 2.4. Conventional DC-DC Converter](image)

Figure 2.4 displays a conventional DC-DC converter circuit. For a standard boost converter operating in continuous current mode, it has two different modes of operation. When switch S1 is on, diode D is reversed biased and the current through inductor L increases. When S1 is turned off, D becomes forward biased. Since the current through inductor L is maintained by the previously generated magnetic field, the current flow...
towards the load is maintained. Since the PV module and the inductor act as series voltage sources, an output voltage greater than the input voltage is produced. Hence, the relationship between the input voltage and the output voltage is expressed as

\[ V_o = \frac{V_s}{1-D} \]  

(2.1)

where \( V_o \) is the output voltage, \( V_s \) is the input voltage, and \( D \) is the duty cycle [9]. Due to the output voltage being inversely proportional to \( D \), the duty cycle will never become 1 because the switch needs to be turned off to allow voltage to flow through the inductor; meaning \( P_{in} = P_{out} \). This allows for the load resistance \( R \) to be calculated using Eq. 2.2 and 2.3.

\[ I_{IN}V_{IN} = I_O V_O \]  

(2.2)

\[ R = \frac{V_o}{I_o} \]  

(2.3)

To be in continuous current mode, the inductor value is calculated such that the current through the inductor never reaches zero. Therefore, the minimum inductance value can be calculated by the following equation:

\[ L_{min} = \frac{D(D-1)^2 R}{2f} \]  

(2.4)

where \( R \) is the load resistance, and \( f \) is the switching frequency of the converter. To reduce the voltage ripple when the switch is on, a decoupling capacitor is put in parallel with the load. The capacitance can be found using the following equation:

\[ C = \frac{D}{R(\Delta V_o/V_o)f} \]  

(2.5)

where \( \Delta V_o \) is the output voltage ripple. To reduce further losses due to the equivalent series resistance of the capacitor, it is best to limit the number of capacitors in parallel.

**Single Switch Flyback Boost Converter**

Figure 2.5 shows the circuit configuration of the single switch flyback boost converter. A PWM signal turns on and off the single switch (S1), which controls the flow of current in a flyback transformer. Additionally, the PWM signal that is sent to the gate of the switch will directly dictate the voltage that is seen by the transformers. The primary purposes of the flyback transformer is a storage inductor and a way to isolate the PV
module from the high voltage of the output capacitor. On the secondary side of the transformer, a voltage doubler circuit exists for the sole purpose of increasing the voltage coming from the transformer to grid voltage. Furthermore this circuit consists of two diodes and a capacitor.

![Figure 2.5. Single Switching Flyback DC-DC Converter](image)

**Soft Switching Flyback Boost Converter**

Figure 2.6 shows the circuit configuration of the DC-DC soft switching flyback boost converter. This circuit uses a flyback transformer as the storage inductor while providing added isolation [10]. The turn ratio on the transformer affects the amount that the voltage will be stepped up.

![Figure 2.6. Soft Switching Flyback DC-DC Converter](image)

On the primary side of the transformer, the circuit consists of an active-clamp circuit, and on the secondary side, it has a series-resonant circuit. The active clamp circuit has two switches, switch \( Q_1 \) and switch \( Q_2 \), and a clamping capacitor \( C_C \). This capacitor regenerates the energy stored in the leakage inductance and also limits the voltage across switch \( Q_1 \). The clamping capacitance can be solved using the following equation:
\[ C_c > 10 \left( \frac{(1-D_{\text{min}})^2}{L_m(2\pi f_{\text{sDC}})^2} \right) \] (2.6)

where \( D_{\text{min}} \) is the minimum duty cycle, \( L_m \) is the magnetizing inductance of the transformer and \( f_{\text{sDC}} \) is the switching frequency of the DC-DC converter.

Furthermore, both switches have complementary pulse-width modulation (PWM) signals delivered to them, along with zero-voltage switching (ZVS) turn-on to ensure minimal switching losses [11]. This ZVS turn-on is dependent on the magnetizing inductance \( L_m \) and the DC-DC converter output power. Hence, the leakage inductor must meet the following specification:

\[ L_m < \frac{D(D-1)^2T_{\text{sDC}}V_d^2}{2n^2P_{\text{max}}} \] (2.7)

where \( P_{\text{max}} \) is the maximum output power of the DC-DC converter and \( T_{\text{sDC}} \) is the switching period.

The series-resonant circuit on the secondary side of the transformer consists of two rectifier diodes, \( D_1 \) and \( D_2 \), and a resonant capacitor \( C_R \) which represents the series resonant voltage doubler. The capacitance can be solved for using the following equation:

\[ C_R < \frac{D^2T_{\text{sDC}}^2}{\pi^2L_{\text{lk}}} \] (2.8)

where \( L_{\text{lk}} \) is the leakage inductance of the transformer.

Figure 2.7 displays a modified version of the flyback boost converter with two flyback transformers. Although similar to Figure 2.6, having transformers in parallel will allow
current to pass through each transformer at a fraction of the total while keeping the voltage the same. As a result, the total magnetizing inductance will be lower and can be found using Eq. 2.9.

\[ L_{mparallel} = \frac{1}{\frac{1}{L_{m1}} + \frac{1}{L_{m2}}} \]  

(2.9)

### 2.3.2 DC-AC Inverter

A DC-AC inverter converts DC into AC, allowing the power to be used by devices or fed into the grid. Two different types of inverter topologies are the H-bridge inverter and the half-bridge inverter.

**H-Bridge Inverter**

![Figure 2.8. H-Bridge DC-AC Inverter](image)

The H-bridge inverter consists of four MOSFETs. An H-bridge inverter switches the voltage polarity applied to the load. When switches Q1 and Q4 are closed, a positive voltage will be applied to the load. When the switches Q2 and Q3 are closed, a negative voltage will be applied to the load. Furthermore, an H-bridge inverter consists of minimal components and are relatively easy to design which makes it a popular inverter topology.
Half-Bridge Inverter

The half bridge inverter as seen Figure 2.9 consists of two capacitors, and two switches. In most applications due to the power requirement, these switches are MOSFET’s. Here, the DC voltage source charges both capacitors equally to the value of the DC voltage source. When Q1 is conducting the grid will see the voltage from C₁ which is positive. When Q2 is conducting the grid will see the voltage from C₂ which is negative. With this said the grid will see a sine wave created when Q1 and Q2 are turned on and off.

2.3.3 Grid-Tied Filter

The output of the inverter stage is not a true sine wave and must be filtered using a bandpass or lowpass filter before it can be used. An LCL filter can be implemented which consists of two inductors and a capacitor as shown in Figure 2.10.

The first step in designing the LCL filter is to calculate the maximum current \( I_{\text{max}} \) that would be injected into the grid from the microinverter. \( I_{\text{max}} \) can be solved using Eq. 2.10, where \( P_n \) is the nominal power of the microinverter and \( V_{\text{ph}} \) is the grid phase voltage \([12],[13]\).
\[ I_{\text{max}} = \frac{P_a \sqrt{2}}{3V_{\text{ph}}} \]  

(2.10)

Once maximum current to be injected into the grid is calculated, the change in current in the microinverter side inductor can be calculated, as seen in Eq. 2.11 below. The 0.05 represents the design factor, which in this equation accounts for the power factor of the grid varying up to 5%.

\[ \Delta I_{L_{\text{max}}} = 0.05I_{\text{max}} \]  

(2.11)

Using the change in the current of the microinverter side inductor (\( \Delta I_{L_{\text{max}}} \)), the switching frequency (\( f_{\text{sw}} \)), and the DC link voltage (\( V_{\text{DC}} \)) the microinverter inductor can be calculated using Eq. 2.12 below.

\[ L_1 = \frac{V_{\text{DC}}}{6f_{\text{sw}} \Delta I_{L_{\text{max}}}} \]  

(2.12)

To calculate the base impedance of the filter the nominal energy and power of the microinverter can be used as seen in Eq. 2.13 below

\[ Z_b = \frac{E_n^2}{P_n} \]  

(2.13)

where \( E_n \) is the phase-phase voltage and \( P_n \) is the nominal power. Using the base impedance and the grid frequency in radians per second, the base capacitance of the filter can be calculated as seen in Eq. 2.14 below

\[ C_b = \frac{1}{\omega g Z_b} \]  

(2.14)

Using the calculated base capacitance the filter capacitance can be found using Eq. 2.15 below. In this equation the 0.05 design factor accounts for the power factor of the grid varying upwards of 5%.

\[ C_f = 0.05C_b \]  

(2.15)
Using the desired attenuation factor \((k_a)\), the base capacitance \((C_f)\), and the switching frequency in radians per second \((\omega_{sw})\) the grid side inductor can be calculated using Eq. 2.16 below.

\[
L_2 = \frac{\sqrt{1 + \frac{1}{k_a^2}} + 1}{C_f \omega_{sw}^2}
\]  

(2.16)
3. **OBJECTIVES AND SCOPE**

The goal of the project is to design and build a two-stage solar microinverter that can be used as a testbench in solar energy research for testing MPPT and control algorithms. The following objectives were designed to accomplish this goal.

3.1 **Objective 1: Identify different microinverter topologies and control algorithms**

To accomplish this objective, the team needed to answer the following:

- What MPPT Algorithms are most commonly implemented in microinverters?
- What control algorithms are used for inverters?
- What type of topologies are commonly used in DC-DC converters?
- What type of topologies are commonly used in DC-AC inverters?

3.2 **Objective 2: Simulate the chosen microinverter topology**

To accomplish this objective the team followed the following steps:

- Simulate the DC-DC converter with a fixed duty cycle
- Simulate the DC-DC converter with a P&O MPPT Algorithm
- Simulate the H-Bridge inverter with a fixed duty cycle
- Simulate the H-Bridge inverter with a PID controller
- Simulate the entire microinverter connected to a grid system

3.3 **Objective 3: Design and construct the microinverter on a PCB**

To accomplish this objective the team followed the following steps:

- Design support circuitry for the microinverter
- Design and layout the printed circuit board (PCB)
- Populate the PCB with the hardware components
- Develop simulink software for the microcontroller

3.4 **Objective 4: Conduct microinverter testing for functionality**

To accomplish this objective the team followed the following steps:

- Test the functionality of the power rails for both internal and external operation
- Test the functionality of the voltage and current measurement circuits
- Test the functionality of the gate driver circuits
- Test the functionality of the DC-DC converter
- Test the functionality of the DC-AC inverter
4. SIMULATION AND ANALYSIS

Prior to implementing the microinverter in hardware, the microinverter circuit was extensively simulated using Simulink. This allows the behavior of the microinverter system to be predicted before it is fully constructed. Figure 4.1 displays the simulated microinverter circuit while Table 4.1 displays the values that were used in the simulation. The simulation was run for 3 seconds under ideal test conditions while several values were being logged. These values include the PV current and voltage, the MOSFET current and voltage, the transformer current and voltage, the DC link voltage, the grid current and voltage waveforms, and the converter duty cycle.

Figure 4.1. Simulated Microinverter System
Table 4.1. Microinverter Component Values and Models

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbols</th>
<th>Value / Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Voltage</td>
<td>Vin</td>
<td>1-24 V</td>
</tr>
<tr>
<td>Output voltage of DC/DC stage</td>
<td>Vd</td>
<td>180 V</td>
</tr>
<tr>
<td>Rated power</td>
<td>Pmax</td>
<td>180 W</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>f</td>
<td>50kHz</td>
</tr>
<tr>
<td>Decoupling capacitor</td>
<td>Cin</td>
<td>1 mF</td>
</tr>
<tr>
<td>Clamping capacitor</td>
<td>Cc</td>
<td>4.7 µF</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>Lm</td>
<td>20 µH</td>
</tr>
<tr>
<td>Turn ratio</td>
<td>n</td>
<td>1:4</td>
</tr>
<tr>
<td>Leakage inductance</td>
<td>Llk</td>
<td>2.6 µH</td>
</tr>
<tr>
<td>DC link capacitor</td>
<td>Cd</td>
<td>1 mF</td>
</tr>
<tr>
<td>Resonant capacitor</td>
<td>Cr</td>
<td>2 µF</td>
</tr>
<tr>
<td>Rectifying diodes</td>
<td>D1, D2</td>
<td>MSRF1560G</td>
</tr>
<tr>
<td>Inverter side inductor</td>
<td>L1</td>
<td>28 mH</td>
</tr>
<tr>
<td>Grid side inductor</td>
<td>L2</td>
<td>10.1 mH</td>
</tr>
<tr>
<td>LCL Filter capacitor</td>
<td>C</td>
<td>1.8 µF</td>
</tr>
</tbody>
</table>

4.1 PV Module

Figure 4.2. PV Voltage and Current Waveforms
Figure 4.2 displays the characteristics of the input voltage and current from the PV module connected to the microinverter with respect to time. The voltage VS. time graph shows the voltage oscillating around 19V and the current VS. time graph shows the current oscillating around 9A - both of which are near their respective MPP values as shown by Table 5.1.

### 4.2 Switching MOSFET

![Figure 4.3. Expected MOSFET S1 Waveforms](image)

The graphs above represent the voltage and current characteristics of the MOSFET on the primary side of the transformers TF1 and TF2. The voltage VS. time graph shows the two MOSFETs working complementary to one another approximately at a 60:40 ratio.
4.3 Flyback Transformers

The graphs above represent the input current for the two individual transformers and the total input current of both the transformers. The first graph on the top represents the total current which comes out to be approximately 10A peak. The next two graphs display that the individual current flowing through each branch is approximately 5A at peak. Due to the two transformers being in parallel, it is expected that the total current will be divided in half through Kirchhoff’s Current Law (KCL) to flow into each transformer.
Figure 4.5 shows the combined output voltage of transformers TF1 and TF2. Since the transformers are connected in parallel both transformers have the same voltage across them on the secondary. The graph above shows a square wave for the output voltage with a maximum amplitude of approximately 85V.

### 4.4 Rectifying Diodes

![Graph showing expected diode waveforms](image)

Figure 4.6. Expected Diode D1 and D2 Waveforms

The graphs above show the voltage and current values for the rectifier diodes which are on the secondary side of the transformers TF1 and TF2. The voltage vs. time graph shows a square wave of both the diode working complementary to one another. During the forward bias position, the voltage across each diode is approximately 180V. The current vs. time graph shows the maximum current through the diode is approximately 7A.
4.5 DC Link

The graph above displays the output DC link voltage of the DC-DC converter within the microinverter. The graph initially shows the voltage oscillating as it is initially in the transient stage. However, eventually, the oscillation dampens and starts to reach a steady state which is approximately at 180V (DC).
4.6 Grid Measurement

The graphs above show the output voltage and current of the microinverter which is being injected into the grid. The DC power produced by the PV module is converted to AC power to be injected into the grid by the inverter stage. The voltage vs. time graph shows the microinverter outputs approximately 170V (AC) to match the existing grid voltage. The current vs. time graph shows that the microinverter outputs approximately 2A (AC). Both of these waveforms are in phase with each other to ensure grid safety and reliability, and a unity power factor.
4.7 Duty Cycle

Figure 4.9. DC Converter Duty Cycle

Figure 4.9 shows the duty cycle at which the DC-DC converter is operating when the PV module has reached its MPPT. When simulated, the duty cycle of the converter fluctuates around a 58% duty cycle. Under ideal conditions, it can be expected that the duty cycle will oscillate around this point. Although testing of the microinverter prototype may not reach ideal testing conditions, these results show that the P&O algorithm that was implemented works as intended.
5.  CIRCUIT DESIGN AND IMPLEMENTATION

5.1 Introduction
After creating the Simulink model of the PV microinverter, considerations were made to bring the simulation into a practical circuit. There are several limitations to the Simulink simulations that had to be accounted for:

- Measurement blocks for both voltage and current in Simulink output discrete values that exactly correspond to the input across or through the block. In a physical circuit, measurement blocks are implemented using op-amps along with other circuitry to output a voltage proportional to the measurement input.

- While the Simulink model simulated power being generated by the PV module, it does not account for the power needed to run the microinverter. For the physical circuit, a power supply that can provide both the driving and reference voltages is necessary to have a functioning microinverter.

- Also in the model, the MOSFET switches are driven using purely the PWM signal generated by the Simulink blocks. For the practical circuit, gate driving circuitry is necessary to increase the voltage of the PWM signal generated by the microcontroller to fully turn on the MOSFET switches.

- The MPPT and PID controller logic were implemented as blocks in Simulink. For the physical circuit, the logic for the MPPT algorithm, PID Controller, and other microinverter logic will have to be managed by a microcontroller.

- When measuring the waveforms at various points in the microinverter, stray capacitance and inductance distorted waveforms in the physical circuit, which does not occur during a simulation, as the simulation assumes ideal conditions.
5.2 System Block Diagram

Figure 5.1. Overall System Block Diagram

Figure 5.1 shows the system block diagram for the whole microinverter system. Each block represents either a separate component or circuit block(s) that provides a given function to the system. The specifications of each block are to be as followed:

**PV Module**

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Generates power to be delivered by the system using sunlight.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input(s)</td>
<td>Sunlight</td>
</tr>
<tr>
<td>Output(s)</td>
<td>Power: 180 - 200W; Voltage: 0 - 25V; Current: 0 - 10A</td>
</tr>
</tbody>
</table>

**DC/DC Converter**

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Boost PV voltage to grid voltage.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input(s)</td>
<td>Power: 180 - 200W; Voltage: 0 - 25V; Current: 0 - 10A; Control: ~12V PWM Signal</td>
</tr>
<tr>
<td>Output(s)</td>
<td>Power: 180 - 200W; Voltage: 180V; Current: 1A</td>
</tr>
</tbody>
</table>

**DC/AC Inverter**

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Convert DC grid voltage to AC grid voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input(s)</td>
<td>Power: 180 - 200W; Voltage: 180Vdc; Current: 1A; Control: ~12V PWM Signal</td>
</tr>
<tr>
<td>Output(s)</td>
<td>Power: 180 - 200W; Voltage: 170Vpk; Current: 1A</td>
</tr>
<tr>
<td><strong>Grid Connection</strong></td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td><strong>Functionality</strong></td>
<td>Filter and control inverter output</td>
</tr>
<tr>
<td><strong>Input(s)</strong></td>
<td>Power: 180 - 200W; Voltage: 170Vpk; Current: 1A; Unfiltered Signal</td>
</tr>
<tr>
<td><strong>Output(s)</strong></td>
<td>Power: 180 - 200W; Voltage: 170Vpk; Current: 1A; Filtered Sine Wave</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>PV Voltage Sense</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Functionality</strong></td>
<td>Measures PV module voltage</td>
</tr>
<tr>
<td><strong>Input(s)</strong></td>
<td>Voltage: 0 - 25V</td>
</tr>
<tr>
<td><strong>Output(s)</strong></td>
<td>Voltage: 0 - 3.3V (proportional to PV voltage)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>DC Link Voltage Sense</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Functionality</strong></td>
<td>Measures DC Link Voltage (voltage between converter and inverter sections)</td>
</tr>
<tr>
<td><strong>Input(s)</strong></td>
<td>Voltage: 0 - 200V</td>
</tr>
<tr>
<td><strong>Output(s)</strong></td>
<td>Voltage: 0 - 3.3V (proportional to DC link voltage)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Grid Voltage Sense</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Functionality</strong></td>
<td>Measures Grid Voltage</td>
</tr>
<tr>
<td><strong>Input(s)</strong></td>
<td>Voltage: 0 - 170 Vpk</td>
</tr>
<tr>
<td><strong>Output(s)</strong></td>
<td>Voltage: 0 - 3.3V (proportional to Grid voltage)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>PV Current Sense</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Functionality</strong></td>
<td>Measures PV current</td>
</tr>
<tr>
<td><strong>Input(s)</strong></td>
<td>Current: -3 to 3A</td>
</tr>
<tr>
<td><strong>Output(s)</strong></td>
<td>Voltage: 0 - 3.3V</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th><strong>Grid Current Sense</strong></th>
<th></th>
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<tbody>
<tr>
<td><strong>Functionality</strong></td>
<td>Measures Grid current</td>
</tr>
<tr>
<td><strong>Input(s)</strong></td>
<td>Current: -3 to 3A</td>
</tr>
<tr>
<td><strong>Output(s)</strong></td>
<td>Voltage: 0 - 3.3V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Flyback Gate Driver</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Functionality</strong></td>
<td>Controls switches in the DC/DC Converter and isolates MCU from microinverter.</td>
</tr>
<tr>
<td><strong>Input(s)</strong></td>
<td>+3.3V PWM signal</td>
</tr>
<tr>
<td><strong>Output(s)</strong></td>
<td>+12V PWM signal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Inverter Gate Driver</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Functionality</strong></td>
<td>Controls switches in the DC/AC Inverter and isolates MCU from microinverter.</td>
</tr>
<tr>
<td><strong>Input(s)</strong></td>
<td>+3.3V PWM signal</td>
</tr>
<tr>
<td><strong>Output(s)</strong></td>
<td>+12V PWM signal</td>
</tr>
</tbody>
</table>
**Power Supply Units**

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Provide voltage sources for microinverter.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input(s)</td>
<td>PV power or external power</td>
</tr>
<tr>
<td>Output(s)</td>
<td>Primary Side: +12V, +5V</td>
</tr>
<tr>
<td></td>
<td>Secondary Side: +12V, +5V, +3.3V, +2.5V, +1.65V</td>
</tr>
</tbody>
</table>

**Microcontroller**

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Control microinverter operation. Sensing, MPPT, PWM control.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input(s)</td>
<td>ADC input: 0 - 3.3V</td>
</tr>
<tr>
<td>Output(s)</td>
<td>PWM output: 0 - 3.3V</td>
</tr>
<tr>
<td></td>
<td>GPIO output: 0 - 3.3V</td>
</tr>
</tbody>
</table>

**Display**

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Displays runtime information of microinverter.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input(s)</td>
<td>General Purpose Input Output (GPIO) from MCU: 0 - 3.3V</td>
</tr>
<tr>
<td>Output(s)</td>
<td>Sensor Measurements; Power Output; Efficiency;</td>
</tr>
</tbody>
</table>

**5.3 Detailed Block Descriptions**

For each of the circuit blocks in the microinverter, a detailed description of the block’s function is provided along with design schematics, calculations, and major components being used. Revisions to the design as the project progressed are included in each detailed description.

As a disclaimer, the net names in the final report may differ from what is on the actual schematic/PCB files. This was done to simplify the explanation of different circuit blocks.
5.3.1 PV Module

Figure 5.2. Grape Solar 180W Solar Module [14]

The main component used to generate electrical power is a PV module. The microinverter was designed around a PV module with the specifications of a Grape Solar 180W US solar panel. Table 5.1 displays the electrical specifications for this PV module that were important with regards to this project.

Table 5.1. Solar Module Specifications [15]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power (P_{max})</td>
<td>180W (0%, +3%)</td>
</tr>
<tr>
<td>Voltage at Maximum Power Point (V_{mpp})</td>
<td>19.67V</td>
</tr>
<tr>
<td>Current at Maximum Power Point (I_{mpp})</td>
<td>9.15A</td>
</tr>
<tr>
<td>Open Circuit Voltage (V_{oc})</td>
<td>24.06V</td>
</tr>
<tr>
<td>Short Circuit Current (I_{sc})</td>
<td>9.77A</td>
</tr>
<tr>
<td>Temperature Coefficient of V_{oc}</td>
<td>-0.28 %/°C</td>
</tr>
<tr>
<td>Temperature Coefficient of I_{sc}</td>
<td>+0.04%/°C</td>
</tr>
<tr>
<td>Temperature Coefficient of P_{max}</td>
<td>-0.38%/°C</td>
</tr>
</tbody>
</table>
5.3.2 DC/DC Converter

On the primary side of the switching converter, IRFB4310 MOSFETs are used due to their low $R_{DS_{-ON}}$ (5.6mΩ), high $V_{DS}$ (100V), and $I_D$ (130A) [16]. These ratings are necessary to increase the efficiency of the DC/DC converter and allow for up to 200W of power to go through this section. The NA5919-AL transformers are 1:4 flyback transformers that boost the voltage from the PV module [17]. For the switching circuit of the DC/DC converter, C2 and Q2 in figure 5.3 can be removed when soft switching is not being used. Due to issues encountered while having the soft switching (active clamp) MOSFET connected to the inverter gate driver, C2 and Q2 were removed in the current version of the microinverter PCB.

On the secondary side of the DC/DC Converter is a voltage doubler circuit and the DC Link capacitor. The voltage doubler circuit consists off a 2µF capacitor, which was chosen based on the previous simulations, and two MRF1560G power rectifier diodes, which have a low forward voltage (1.5V), with high voltage (600V) and current (15A) ratings [18]. The DC
link capacitors, two 1mF capacitors in parallel, ensure that there is a significant voltage buffer between the converter and inverter sections of the microinverter.

For the PV capacitor and the DC link capacitor, bleeder resistors were added to drain the capacitors when the microinverter is turned off. The value for the DC link bleeder resistor was calculated using the following formula:

\[
V_{\text{Safe}} = V_{\text{Capacitor}} \cdot e^{\frac{t}{RC}}
\]  

(5.1)

Where \( V_{\text{Safe}} = 50V \), \( V_{\text{Capacitor}} = 200V \), \( C = 2\text{mF} \), and \( t = 300s \). With these values, the calculated \( R = 108.202\text{k}\Omega \). For simplicity, two 200k bleeder resistors were used in parallel for the DC bus, which results in a discharge time of 277s. This is still acceptable for working around the microinverter. Two 1mF capacitors were used to provide an additional buffer between the converter and inverter sections.

A neon indicator bulb (LED1) is included on the secondary side to indicate whether there is a voltage over approximately 60V on the DC link capacitors or not. This is used as a safety feature while working on the microinverter. The resistor R5 was used to limit the amount of current that would go through the bulb. 150K\Omega was chosen based on the datasheet for the neon indicator bulb [19].

FUSE1 is used to isolate the converter section from the inverter section when the converter section is being tested independently.

### 5.3.3 DC/AC Inverter

![DC/AC Inverter H-bridge and LCL Filter](image-url)
The DC/AC inverter section of the microinverter consists of an H-Bridge and an LCL filter. The switches used for the H-Bridge are SIHP25N40D Power MOSFETs, which feature a high $V_{DS}$ (450V) and $I_{DS}$ (24A) [20]. The LCL filter (L1,L2,R6,C6) uses the values specified in the simulation section.

### 5.3.4 Grid Connection

The grid connection circuit is used to connect/disconnect the microinverter from the grid. This can be done in case the microinverter is not operating as intended or if abnormal conditions are detected on the grid. The ST2-DC12V-F relay is controlled by the microcontroller and the grid current limiting circuitry. LED2 is used to indicate when the relay is turned on. Resistor R7 limits the current through the LED to a reasonable value. The neon indicator bulb LED3 is used to indicate when there is a high voltage on the grid connection (>60V). LED3 uses the same series resistance of 150K for R8 as the neon indicator bulb across the DC link capacitor. FUSE2 and FUSE3 are used to protect the
microinverter if more than 3A is drawn from the grid, which could happen in the event of a malfunction [21].

Figure 5.7 shows the circuitry used to switch the relay. The GRID_RLY_CTRL signal coming from the overcurrent protection section, which is controlled by the microcontroller activates a MOSFET, which allows current to flow from the secondary +12V rail, through the relay coil, through the MOSFET [22], and into ground. Because the relay coil is an inductive load, freewheeling diode D3 [23] was added to protect the MOSFET from damages caused by voltage spikes.

### 5.3.5 PV Voltage Sense

*Original*

![Figure 5.8. PV Voltage Sense](image)

To measure the voltage of the PV module, the circuit in Figure 5.8. is used. Features of this voltage sensing circuit include a voltage divider, an isolation amplifier, and voltage clamping. Voltage division is done using two resistors, R3 and R1. The scaled down voltage is 0.006 of the voltage at PV+, the PV voltage. This was done to get the max input voltage to the isolation amplifier, 150mV, within the specified voltage range of the amplifier input, 250mV. An isolation amplifier, the AMC1200SDUB [24], is used to keep the primary and secondary grounds of the circuit separated, reducing the amount of noise that occurs in the voltage measurements. The output of the isolation amplifier, VPV_SEN, is the voltage that will be read in by the microcontroller to measure the PV Voltage. The Schottky diode array, D1, is used to protect the microcontroller by preventing VPV_SEN from going beyond the 0V to 3.3V range of the microcontroller ADC. Additional capacitors were added throughout the
circuit to reduce the amount of noise occurring on the amplifier’s supply rails and inputs. Two test points are included, IN_VPVSEN and OUT_VPVSEN, to measure the voltage on each side of the amplifier. Resistor R2 is used to limit the current going to the MCU in the case there is an overvoltage condition on the voltage sense circuit. C1-4 are used as decoupling capacitors to limit noise.

Revision
During testing, there were issues discovered with this design. The specific isolation amplifier ordered had an 8-SOP package while the footprint used in the PCB design was mislabeled as an SOP, when it was really an SOIC. An SOIC package is smaller than the SOP package, therefore the SOP amplifier could not be attached without using a significant number of bodge wires. To alleviate these issues, a breakout PCB that has the same schematic as that in Figure 5.8 was made to accommodate the larger SOP package. The breakout PCB attaches to the main microinverter PCB using the connections shown in Figure 5.8.

5.3.6 DC Link Voltage Sense

![Diagram of DC Link Voltage Sense](image)

Figure 5.9. DC Link Voltage Sense

To measure the voltage at the DC link, a differential op-amp circuit based on the OPA2171 [25] with a Schottky diode voltage clamp is used. The output of the differential op-amp is:

\[ V_{out} = \frac{R_i (V_2 - V_1)}{R_{in}} \]  

(5.2)
Where \( R_f = 15k\Omega \) (R9-10 on the schematic), \( R_{in} = 1.9M\Omega \) (R1-4 and R5-8 on the schematic), \( V_2 \) is VBUS and \( V_1 \) is GND_SEC. Using this equation, the expected voltage on the op-amp output for the DC Link Voltage Sense is expected to be between 0 - 1.58V.

This differential op-amp circuit scales the VBUS voltage down so it can then be read in by the ADC at VBUS_SENS. The Schottky diode array D1 is used to clamp the voltage at VBUS_SENS, preventing the voltage from going beyond the 0-3.3V range of the microcontroller ADC. R11 is used to limit the current going to the MCU in the case of an overvoltage condition. C1-C3 as decoupling capacitors to limit noise.

5.3.7 Grid Voltage Sense

To measure the grid voltage, the DC link voltage measurement circuit was slightly modified and used again. The only significant change made to the grid voltage measurement circuit compared to the DC link voltage measurement is the \( R_f \) value for the voltage divider is 7.5K (compared to 15K for the DC link voltage). This is due to the grid voltage having both positive and negative values, being an AC source. For the non-inverting input, since \(_L\) is an AC voltage, a 1.65V reference voltage (1_65V_REF) is used instead of GND_SEC to bias the input to the op-amp to 1.65V. Therefore, the output voltage of the op-amp is between 0.86V - 2.44V.
An important part of the grid voltage sense circuitry is the zero cross detection system, based on the LMV7235M5 [26] shown in figure 5.11. This will toggle a digital input pin on the microcontroller when the grid voltage crosses the zero point. This can trigger an interrupt on the microcontroller, allowing for the frequency and phase of the grid AC voltage to be precisely measured, ensuring the output of the inverter remains in sync with the grid voltage, which is critical for a system capable of feeding power back into the grid. The comparator is configured in an inverting configuration with hysteresis. High and low threshold voltages of 1.6582V and 1.6418V respectively were designed using resistors R13 and 14. Resistor R12 is used for input protection to limit current in the case of overvoltage. Resistor R16 is used as a pull-up resistor and R15 is used as input protection for the MCU. Capacitor C4 is used as a decoupling capacitor for filtering.

Figure 5.11. Zero Crossing Detection
5.3.8 PV Current Sense

To sense the amount of current coming from the PV module, the PV current measurement circuit in Figure 5.12 is used. The component that allows for current measurements to take place is an ACS723 [27], which is a hall-effect, galvanically isolated current sensor. The ACS723 outputs a voltage that is proportional to the amount of current going through PV- and PGND_PRI, with the output voltage scaled by 100mV/A and centered at 2.5V when there is no current. C1 and C2 are used as decoupling capacitors to filter noise in the +5V_SEC and GND_SEC lines.

The op-amp circuit shown in figure 5.13 is used to scale the output voltage of the current sensor to within the range of the microcontroller ADC. The first op-amp circuit removes the 2.5V bias that was introduced by the current sensor, and the second op-amp circuit scales the voltage to within the full range of the ADC. Using Eq. 5.2, with $R_f = 24.9k\Omega$, $R_{in} =$
24.9kΩ, V2 = 2.5 - 3.5V, and V1 = 2.5V, the expected output voltage of the first op-amp is between 0V - 1V. For the second op-amp, using Rf = 4.87kΩ, Rin = 2.2kΩ, V2 = 0-1V and V1 = 0V, the expected output of the second op-amp is between 0 - 2.21V, going to IPV_SEN.

5.3.9 Grid Current Sense

To measure the amount of current going into the grid, the microinverter used a LTSR 6-NP [28] current transducer. This component outputs a voltage that is proportional to the amount of current going through the transducer on VCS_IOUT. When there is zero current on the grid, the transducer outputs a voltage of 1.65V, using IGRID_SEN_REF as the zero current voltage, with the voltage varying by 104.16mV/A. It was connected using one of the recommended configurations in the part’s datasheet. R1 is used to limit current in the case of an overvoltage condition. Capacitor C1 is used as a decoupling capacitor to limit noise.

Figure 5.14. Grid Current Sense Transformer
The op-amp circuit shown in figure 5.15 is used to scale the output voltage of the current transducer to within the range of the microcontroller ADC. The first op-amp circuit removes the 1.65V bias that was introduced by the current transducer, and the second op-amp circuit scales the voltage to within the full range of the ADC. The first op-amp circuit, following equation 5.2, uses $R_f = R_{in} = 24.9k\Omega$, with $V_2 = 1.65V$ and $V_1 = 1.34V - 1.96V$, therefore the expected output at VCS_TPT_INTMD is 1.34V to 1.96V. For the second-op amp circuit, $R_f = 3.32k\Omega$, $R_{in} = 1.47k\Omega$, $V_2 = 1.34V$ to 1.96V and $V_1 = 0V$, resulting in an output voltage of between 3.03V - 4.43V.

As configured, the grid current sense circuit will not work, since the gain on the second stage was set too high. This was a mistake in the design. It can be fixed by decreasing the resistance of R8-9 or increasing the resistance of R6-7. Since there were issues with the current transformer, this solution was not explored, but can be used should this op-amp circuit be used again.
Overcurrent protection circuitry is built into the grid current sensing to prevent erroneously large grid currents from causing damage to the microinverter. If the reference sine wave of the inverter control system becomes out of phase with the actual grid voltage, or the microcontroller locks up, causing a MOSFET to become stuck on, an effective short across the grid through the MOSFETs and filtering circuitry will result, causing large amounts of current to flow. This could cause severe damage if it is not interrupted quickly. The overcurrent protection circuitry operates independently of the microcontroller, so it will still operate even if software errors are present.

The overcurrent protection system disables the grid connection relay by default. In order to initially enable the relay or clear an overcurrent fault, a signal labeled OVERLOAD_RST is sent from the microcontroller to the Set pin of IC4, which is a standard digital S-R latch. When the latch is sent, the grid connection relay is no longer disabled and can be opened or closed from the microcontroller with the GRID_RLY_CTRL_MCU signal. This was implemented by ANDing the microcontroller relay enable signal with the output of the S-R latch. If the latch is not set, the relay is disabled and will remain open regardless of the status of the GRID_RLY_CTRL_MCU signal. To actually detect an overcurrent situation, the voltage from the grid current sense transformer is compared to an adjustable threshold voltage using a LMV7235 comparator IC [28]. This threshold voltage must be set properly before the overcurrent protection will operate. If an overcurrent condition exists, the grid current sense voltage will exceed the threshold voltage. This will reset the latch, disabling the relay and cutting the current flow. The IGrid_Trip LED will also be illuminated. The MCU
is also notified that an overcurrent event occurred, and the rest of the microinverter will automatically power down and display an error on the LCD. After the cause of the overcurrent condition is corrected, the latch can be reset, re-enabling the relay. If desired, the overcurrent protection circuitry can be manually overridden by changing the position of the BYPS_OVLD_GRID slide switch.

Revision
During testing, the current transformer was not behaving as expected. Since it would have been cost prohibitive to replace the current transformer, grid current sensing was done using an off-the-shelf ACS723 all effect current sense module, which operates similarly to how current sensing is done for the PV module. A schematic of the current sense module is shown below in Figure 5.17.

![Figure 5.17. Grid Current Sense with ACS IC](image)

The op-amp circuit that was originally used to scale the voltage to within the range of the ADC was removed and replaced with a simpler voltage divider circuit, with VCS_IOUT connecting to the VCS_TPT_INTMD trace of the original op-amp circuit. The voltage level at VCS_IOUT corresponds to the grid current, according to this relationship:
\[ VCS_{OUT} = 2.5 + (0.4 \times I_{\text{grid}}) \]  \hspace{1cm} (5.3)

If the unscaled input was passed directly to the ADC, the ADC would clip if \( I_{\text{grid}} \) exceeds two amps. The voltage divider scales down the output voltage to 69.3\% of its original value, according to the following equation:

\[ I_{\text{GRID\_SEN}} = \frac{VCS_{OUT} \times R_8}{(R_8 + R_6)} \]  \hspace{1cm} (5.4)

Using the circuit in figure 5.18, the output voltage for \( I_{\text{GRID\_SEN}} \) is between 0.90V - 2.56V. The diode array D1 is used to protect the MCU from voltages beyond 0-3.3V. Resistor R10 is used to limit current in case of overvoltage conditions, and capacitor C3 is used as a decoupling capacitor to limit noise.

### 5.3.10 Flyback Gate Driver

**Original**

The flyback gate driver consists of two major component sections, an isolation IC and a gate driving IC. The circuit in Figure 5.19 shows the isolation circuit, which utilizes an ISO7240 [30] isolation IC. This chip is used to keep the primary and secondary grounds separated while still sending the PWM signal to the gate driver. Pull down resistors (R1-4) are used are included on each input of the isolation IC, even unused inputs, to prevent noise from triggering the outputs. R5-6 are used to limit current going to or from the ePWM in the case of an overvoltage condition.
For the gate driving section, an SM72295 Photovoltaic Full Bridge Driver is used. This IC increases the voltage going to the MOSFET gates in the flyback converter [31]. It provides a $+12V$ gate voltage with respect to the source of each MOSFET being driven, with a bootstrap configuration used to elevate the gate voltage of the clamping MOSFET with respect to that MOSFET source. R11-12 are used as pull-down resistors to keep the PWM input pins on the SM72295 from floating and R13-14 are used to limit the current to or from the ISO7240 in the case of an overvoltage condition. Diodes D1-2 and resistors R7-10 are used to decrease the turn-off time of the MOSFET.

**Revision**

Since the design of the flyback converter has been reverted to a single switch flyback topology, FLYBACK_DRV_1B was disconnected from the flyback converter, with the components on that line removed and the IC pin lifted. In Figure 5.20, R9, R10, and D2 were removed on the current microinverter PCB.

### 5.3.11 Inverter Gate Driver

**Original**

For the inverter gate driver section, two types of driver circuits are used, a low side, and a high side driver circuit. The reason for having a high and a low side driver circuit is due to gate voltages being referenced to different sources. While the low side MOSFET source is the secondary ground, the high side MOSFET source is on the grid.
Figure 5.21. Low-Side Inverter Gate Driver

For the low side driver circuit, a UCC27324 Low Side MOSFET driver IC is used. This component is used to increase the efficiency of switching the low side MOSFETs by providing a high peak current [32]. The UCC27324 takes the PWM signals for the low side MOSFETs, INV_PWM_1L and INV_PWM_2L, and outputs them on INV_DRV_1L and INV_DRV_2L. Resistors R1 and R2 are used as pull-down resistors to keep the inputs to the UCC27324 from floating, and diodes D3 and D4 are used to clamp the output voltage to ground in the event a negative voltage appears on the outputs of U1 due to undershooting or ringing. Resistors R3-4 and diodes D1-2 are used to decrease the turn off time of the low side MOSFETs.

Figure 5.22. High Side Inverter Gate Driver

For the high side driver circuit, due to the reference source voltage of the high side MOSFET being different from the secondary ground, an isolation IC and a MOSFET gate driver IC is used. This is done to keep $V_{gs}$ high enough with respect to the source of the high side MOSFET to drive it. The isolation IC, an ISO7420D, keeps the secondary ground and the source of the MOSFET separate [33]. The MOSFET driver IC, a UCC27531, is used to drive the MOSFET with high peak currents efficiently [34]. The circuit in Figure 5.22 is used to
drive one of the high side MOSFETs. A separate, but identical circuit is used to drive the other high side MOSFET. Resistors R5 and R6 are used to dampen oscillations on the MOSFET. Capacitors C1-3 are used as decoupling capacitors to filter noise.

Revision:
Issues were discovered with the design seen in figure 5.22, primarily that the footprint for the UCC27531 component on the PCB was incorrect and that even when the footprint was corrected, the circuit was not providing a PWM output. To fix these issues, a new design was made for the inverter gate driver based on the bootstrap driver topology instead of the isolated driver topology of the original design. Looking into potential gate drivers, a new IC was found that could replace the ISO7420D, the UCC27531, and the UCC27324D. The new design uses two UCC27710 ICs, one for each high-low side MOSFET pair, driving the MOSFETs in isolation [35]. These driver ICs, as well as all required passive components, are installed on a small custom PCB mounted on top of the main PCB. A schematic of the UCC27710 driver circuitry for one high-low pair is shown below, following the reference design from TI [36].

![Schematic of UCC27710 Driver Circuitry](image)

Figure 5.23. New Inverter Gate Driver

The operation and construction of the new gate driver circuitry found in Figure 5.23 is simpler than the original design. The inverter PWM signals are supplied through PWMIN and PWMINX from the MCU. The UCC27710 drives the MOSFET pair using HO + HS to drive the high side MOSFET and LO + GND to drive the low side MOSFET. +12V_SEC is connected to both the VDD pin and the HB pin, stepping up the PWM signal from +5V to +12V.
5.3.12 Power Supply Units

Original

To provide power to the microinverter, multiple different circuits are used to provide reference voltages and power supplies.

![Figure 5.24. Schematic for Original Primary Side Power Rails](image)

To provide power for primary side components, the circuit in Figure 5.24. is used. To provide a +12V primary supply, a slide switch is used to allow for switching between +12V coming from the PV module or +12V from an external power supply. To provide a +5V primary supply, a PTH08080WAH switching voltage regulator is used to drop +12V to +5V [37]. Resistor R2 was selected to be 330Ω to get the voltage of the output to 5V. Capacitors C6-7 are used to make sure the capacitance at the input is at least 100µF, and C10 is used for decoupling on the output to filter noise.

![Figure 5.25. Schematic for Original Secondary Side Power Rails](image)

To provide power for secondary side components, the circuit in Figure 5.25 is used. The +12V secondary and +5V secondary supplies are provided in the same manner as those used for the primary supplies. To provide a +3.3V secondary supply, a TPS79533DCQR
linear regulator is used [38]. Capacitors C3-C5 are used as decoupling capacitors to filter noise.

Figure 5.26. Original Voltage Reference Schematics

To provide a 2.5V reference, a TL431AIDBZR shunt regulator [39] is used. Resistor R3 was calculated to be 510Ω so 1.5mA can be used by the 2.5V reference. To provide a 1.65V reference, a voltage divider is used with the 2.5V reference (2.5V * 0.6598 = 1.6495V).

Figure 5.27. Original MOSFET Driver Isolated Supply Schematic

To power each of the high side MOSFETs on the inverter, a PCSA1-S12-S12 isolation converter is used to provide a +12V reference with respect to the source of the MOSFET as
opposed to the secondary ground [40]. An LM317 voltage regulator is used to provide a +5V reference with respect to the source of the MOSFET [41]. There are two pairs of isolators and voltage regulators to provide separate references for each high side MOSFET. Capacitors C8-9 and C11-12 are used as decoupling capacitors coming from the +12V_SEC reference and between the isolation converter and voltage regulator. Resistors R8-11 were chosen to get the LM317 to output a voltage close to 5V (4.94V according to the equations in the LM317 datasheet).

![Original Schematic for PV Derived Primary and Secondary Side 12V Rails](image)

Figure 5.28. Original Schematic for PV Derived Primary and Secondary Side 12V Rails

To allow for the option of providing two stable, isolated +12V rails from the PV module, an LM5017MR/NOPB Buck Regulator is utilized [42]. An MSD1278-273ML coupled inductor is used to provide the two isolated +12V rails [43]. This allows for the option to operate the microinverter in standalone mode, not connected to the grid. Most of the components use values suggested in the LM5017 datasheet to create an isolated supply. Resistors R15 and R16 were selected to get a voltage approximately around 12V (11.57 according to the equations in the datasheet).
Revision

Figure 5.29. Revised Schematic for Original Primary Side Power Rails

Figure 5.30. Revised Schematic for Original Secondary Side Power Rails

During testing, there were issues with the PTH08080WAH, primarily that the component would quickly fail and not provide a stable +5V. To alleviate this issue, LM7805 linear regulators were substituted in for the nonfunctional switching regulator modules [44]. The PTH08080WAH was switched out in both the primary and secondary PSU.
For the 2.5V reference, the shunt regulator did not work during testing and was substituted with an LM385 shunt regulator [45]. Resistor R3 was also substituted with a 51Ω resistor instead of a 510Ω, to improve the stability of the voltage reference if it is loaded.

Since the original inverter driver circuit was not working as intended, and with the UCC27710 based circuit replacing it, there is no need to have dedicated +12V isolation converters. Therefore, the circuit in Figure 5.27 was removed in the final design.
During testing, it was found that the PV power supply circuit as seen in Figure 5.28 did not function as intended. To overcome this issue the off-the-shelf modules seen in Figure 5.32 and Figure 5.33 were used. For the primary side power, the DC-DC buck-boost converter in Figure 5.32 was used to supply 12 volts to the circuit in Figure 5.29. This boost converter input is connected directly to the PV module, and testing confirmed that it was capable of deriving a stable 12V rail off of PV voltages ranging from two volts through the module’s open circuit voltage. For the secondary side, the isolation buck converter in Figure 5.33 was used in conjunction with the converter in Figure 5.32 to supply the circuit in Figure 5.30 with an isolated 12 volt rail. The use of the PV derived 12V rails allows for the microinverter to be operated in an off-grid configuration during future experimentation. A block diagram showing the final PV-derived power rail system is shown below in Figure 5.34.
5.3.13 Microcontroller

The microcontroller is used to control the operation of the microinverter. The microcontroller takes in measurements from the five measurement blocks. From these measurements, an MPPT algorithm is run to make adjustments to the operation of the microinverter. The microcontroller outputs PWM signals to the flyback and inverter gate driver blocks.

For the microcontroller, a TI C2000 Delfino based LaunchPad [49] is used. This microcontroller was selected for multiple reasons. First, it has a 200 MHz dual-core processor that can simultaneously run two independent Code Composer Studio (CCS) projects. This is useful for being able to run different types of MPPT algorithms and control schemes. Second, Simulink has a package available for generating CCS projects from Simulink blocks. This will streamline the development process for the microinverter firmware and make the program more accessible for future development. Third, the Delfino has enough digital I/O to support the microinverter and extra peripherals, such as connecting to a laptop over USB to run the MPPT externally.

Figure 5.35. TI F28379D Delfino MCU Launchpad Development Board [48]
5.3.14 Display

Original

![128x64 KS0108 LCD Display Schematic](image)

Figure 5.36. Original KS0108 Display Schematic

The microinverter is equipped with a display to allow important data such as the PV module voltage, current, and power, as well as the system’s current operating mode, to be viewed at a glance. A 128x64 pixel monochrome dot matrix LCD was selected as the display. The use of this display allows for large amounts of information to be displayed simultaneously and offers much more flexibility than other common display types such as seven segment LED displays. This display along with the four pushbutton switches located nearby also allow for the implementation of a simple graphical user interface (GUI), where various parameters and operating modes can be adjusted without having to reprogram the microcontroller. The schematic for this implementation of a 128x64 pixel display showing the parallel data interface is shown in Figure 5.36.

Revision

It was discovered after the PCB had been manufactured, however, that it would be impractical to implement the code needed to control such a dot matrix display using the Simulink environment and the Delfino microcontroller. This was due to the difficulty in generating the control signals for this LCD without an existing library compatible with the Simulink programming environment. As a result, the display subsystem was completely redesigned. The new display system utilizes a 4-line text display based on the HD44780 driver IC [50] in place of a dot matrix display. Instead of driving the LCD directly from the main microcontroller programmed in Simulink, a separate small 8-bit microcontroller programmed using the Arduino programming environment serves as an interface between
the LCD and the Delfino MCU. This Atmel ATMega328P microcontroller communicates with the main Delfino MCU over the I2C communication protocol and controls the LCD over a 4-bit parallel interface.

Figure 5.37. LCD Adapter Board Schematic

Figure 5.38. LCD Adapter Board PCB Layout
An additional printed circuit board allowing for the LCD and accompanying ATMEGA328P microcontroller to be mounted on the main microinverter PCB in place of the original dot matrix LCD was designed and fabricated. This adapter board has a 6-pin ICSP header allowing the ATMEGA328P microcontroller to be programmed. A simple user interface was implemented using the display and the four push buttons allowing for the operating mode of the inverter and the information displayed to be changed on the fly. Every screen capable of being displayed on the LCD is predefined in the ATMEGA328P code, and the main MCU sends each piece of data to be displayed on the LCD as well as control state information as a separate packet over the I2C bus to the interface MCU. In the event that this communication is unsuccessful, an error message is displayed on the LCD to avoid outdated information from being mistaken for correct information. The Arduino code for this ATMEGA328P, as well as more details on the operation of the display system, can be found in Appendix D.

![Figure 5.39. Functional LCD with Adapter Board on the Main PCB](image)

### 5.4 PCB Design

Using the design schematics in section 5.3, a PCB was laid out and manufactured. Assembling the microinverter circuit on a PCB for this project has multiple advantages over other prototyping bases, such as breadboard or protoboards:

1. PCBs can handle a higher current going through them compared to breadboards.
2. Keeping the project on one board removes issues that can arise due to the lack of structural integrity (disconnecting wires, pins, etc).
3. Option to use both through-hole and surface mount device (SMD) type components.
While PCBs are regarded as more professional and reliable compared to prototyping boards, there are some disadvantages with PCBs that may cause some issues later in the project.

1. PCBs can become expensive to manufacture and have a comparatively long lead and shipping time.
2. It is difficult to fix mistakes (such as mismatching footprints or missing PCB traces) on the PCB after the PCB has been manufactured.

The PCB that was manufactured is a two-layer FR4 board with 2oz copper. The board’s dimensions are 450 mm by 200mm. To calculate the minimum trace width to support different currents, an online calculator was used. On the PV side, 8mm traces were used to support the PV short circuit current of 9.15A. On the grid side, 2mm traces were used to support a maximum grid current of 3A. For voltage and data lines, trace widths varying from 0.5mm - 1mm were used depending on their uses and lengths.

![Figure 5.40. Annotated Microinverter PCB](image)

For the PCB layout, a best effort was made to keep the components in each circuit block together. Figure 5.40. shows an annotated version of the PCB layout. The original PCB design can be found in Appendix A. The main microinverter blocks (red), such as the DC/DC converter and DC/AC inverter, are put across the bottom half of the PCB. The digital blocks (yellow), such as the display and the MCU, are placed in the upper right-hand corner. The measurement blocks (green) and the gate drivers (blue) are placed between the power section of the microinverter and the digital section of the microinverter. This was done to keep the MCU and display isolated from the sections that have a significant amount of
power going through them, making the microinverter safer to work around while experimenting with it. The PSUs (purple) are placed close to the sections they have to provide the supply voltages to.

For the PCB design, additional capacitor and inductor footprints are included on the PCB design compared to the schematics in the previous sections. This was done in the case any of the capacitor or inductor values needed to be adjusted.

5.5 Safety Considerations

While the microinverter is operating, there is both high voltage and current potential on the board. These conditions create potential safety issues that need to be mitigated.

The microinverter was designed to keep the primary side and the secondary side of the transformer isolated from one another, using separate power supplies and grounds for each side, ensuring the PV module is always galvanically isolated from the grid. This was done to adhere to site safety standards for power supplies [51]. A significant amount of clearance between the primary and secondary sides was given. The PCB for the microinverter was designed to keep the power components away from the digital components.

Fuses have been included in the design. A fuse is located on the DC link to provide a method of isolating the DC/DC converter from the DC/AC inverter. Fuses were also added to the grid connection to protect the microinverter in the case of a sudden current spike. The overcurrent protection circuit also prevents a larger than intended amount of current from entering or leaving the microinverter, triggering the grid relay to disconnect when high current is detected.

Bleeder resistors are added to the major capacitors in the design to safely discharge them while experimenting with the design. Without bleeder resistors, the capacitors may continue to hold a charge after the microinverter is shut down, leading to an unintended, high voltage shock. Warning labels were placed on the microinverter to warn about the potential for high voltage. Additionally, an overvoltage condition, created by running the boost converter with no load, on the high voltage DC rail can create a hazardous condition, with excessive energy being stored in the main capacitors. This increases the potential shock hazard and can even damage the large electrolytic capacitors, which in extreme cases could cause an explosion. To prevent this from happening, all versions of the MCU firmware contain hard-coded logic which shuts down the boost converter completely if the DC link voltage exceeds 250v.
5.6 PCB Assembly

Once the PCB for the microinverter was completely laid out, it was manufactured by JLCPCB in China and sent back so it could be assembled and tested. Each section was built up and tested individually, as outlined in the experimental results section. Most of the components were SMD components, which were attached using hot air and solder paste. The rest of the components were through-hole components. The microinverter was placed onto standoffs and an acrylic base and top cover were used to help protect the microinverter.

Figure 5.41. PCB Fully Assembled
6. EXPERIMENTAL RESULTS

The microinverter consists of multiple dependent functional blocks. During assembly of the system, each block was assembled and brought up separately to reduce the likelihood of a malfunctioning block from damaging other components on the PCB or producing misleading results. Issues encountered during the testing of each functional block were corrected before the assembly of the next dependent block. Assembly and testing of the subsections occurred in the following order:

1. Primary and secondary +12V, +5V voltage rails
2. Secondary +3.3V, +2.5V, +1.65V voltage rails
3. Primary and Secondary PV-derived feeder +12V rail
4. PV Voltage Sense
5. PV Current Sense
6. DC Link Voltage Sense
7. Grid Voltage Sense
8. Grid Current Sense
9. Microcontroller
10. Flyback Gate Driver
11. Inverter Gate Driver
12. DC-DC Converter
13. DC-AC Inverter

For the experimental results section, test point names are taken directly off the Eagle schematic/PCB files for the main microinverter PCB and may differ from the published schematics in Section 5.

6.1 Primary Rails
To test the primary +12V and +5V voltage rails, the input of the primary rail block was connected to an external +12V wall adapter. On the PCB, 12VPRITST and 5VPRITST were probed using a voltmeter to confirm the primary rails were supplying the correct voltages. LEDs that correspond with each of the different voltage rails also illuminated when the voltage rail was live. As mentioned in Section 5, the original design of the voltage rail supply blocks included the use of buck converter modules to drop 12V down to 5V. These modules were found to be unreliable and were substituted with linear voltage regulators, greatly improving reliability for a slight expense of efficiency. After this modification was made, the primary voltage rails worked reliably. The measured output voltages of these rails are shown in Figure 6.1.
6.2 Secondary Rails

The secondary rails were tested in a similar manner to the primary side. The difference is that on the secondary side, there are +3.3V, +2.5, and +1.65V on top of the +12V and +5V rails. On the PCB, 12VSECTST, 5VSECTST, 3V3SECTST, 2_5_REF_TST, and 1_65V_REF were probed to confirm the correct voltages were present. After assembly and testing, it was found that the 2.5v voltage reference was unreliable. A modification to the design explained in Section 5 was performed, and the 2.5v and 1.65v references were again tested. The outputs of each of these sections are shown below in Figure 6.2.

Figure 6.1. Primary Voltage Rail Measurements

Figure 6.2. Secondary Voltage Rail Measurements
6.3 PV Sourced Primary and Secondary

After assembly of the PV sourced primary and secondary generator, it could be tested. To test this, the slide switch 12V_SEC_SRC(switch) and 12V_PRI_SRC(switch) were both moved into the “PV” position. The PV_12V_Supply switch was then be moved into the “Enabled” position. A DC power supply was connected to the PV input connector, and a voltage of 12V was applied. If the block was functional, all the power rail indicator LEDs should illuminate, and the correct voltage levels should have been able to be measured at the corresponding test points. The original design iteration of this block did not operate correctly, so the design was revised to utilize external voltage converter modules. A description of this revised design, which was tested and confirmed to work, is contained in Section 5. The ability to generate the primary and secondary rails off of the PV module voltage is necessary in order to operate the microinverter system in an “off-grid” configuration. This is not within the scope of the project, but this option is provided for future experimentation.

6.4 PV Voltage Sense

To test the PV Voltage Sense block, the AMC1200B voltage sense IC was installed. As mentioned in Section 5, this IC was mounted on a custom breakout board which was then connected to the main PCB. The rest of the PV voltage sense circuitry was populated. A lab bench power supply was then connected to the PV+ and PV- connections. A +12V supply was connected to the primary side power jack while the PV_12V_SUPPLY switch moved into the “disable” position. The voltage applied to the PV rail was ramped up, while the voltage out of the PV voltage sense block fed into the ADC of the microcontroller was measured with a benchtop multimeter. Measurements comparing the output and the input at various voltage points were taken and graphed. The linear nature of the graph indicates that this circuitry is working well. This data was used to create a scale factor mapping the measured voltage at the ADC to the actual PV voltage. This graph, showing the calculated scale factor, is shown in figure 6.3.
6.5 PV Current Sense

To bring up the PV current sense block, U1, the ACS723ELCTR-20A current measurement IC, as well as U2, an isolated op-amp, were both installed. At this stage, switches Q1 and Q2 were not installed. A wire was connected between the FYBK_PRI_TST1 test point and PGND_PRI to short the PV voltage rail, allowing current to be measured. A controlled DC current source was connected between PV+ and PV-. The PV_12V_SUPPLY switch was moved into the “off” position. 12V supplies were connected to the primary side power jack and the secondary side power, and the 12_PRI_SRC and 12V_SEC_SRC switches were moved into the “External” positions. The DC current source, a bench power supply, was turned on, and the voltage levels on the VCS_IPV and IPV_SEN points with respect to the secondary ground were measured with multimeters. The output of the PV current sense block that feeds into the ADC of the microinverter was measured at several different input voltage points in order to create a scaling factor. A graph of this data plus its trendline is shown in figure 6.4.
6.6 DC Link Voltage Sense

To bring up the DC link voltage measurement block, all of the circuitry needed was populated. Afterwards, the system was powered up in the way described above, and a controllable DC voltage source was connected across the DC rail. The output of the DC rail sense block was measured as various input voltages were applied. This data and its corresponding scaling factor are shown in Figure 6.5.
6.7 Grid Voltage Sense

To bring up the Grid voltage measurement block, U2, an op-amp, will be installed, as well as the remaining passive components required for grid voltage sensing. A controllable voltage source was connected across the grid connections on the main PCB. The test was conducted in a very similar way to the other tests described here, except that negative input voltages were also utilized since this block will be measuring AC voltages. The results of this test are shown in the chart below in Figure 6.6.
6.8 Grid Current Sense

When the grid current sense block was being brought up, the current transformer, as well as other components, were installed. A wire was connected between the HBRIDGE1 and HBRIDGE2 test points. The +12V Secondary rail was powered with an external power supply. A DC current source was connected to the grid connection terminals, and various currents were applied, while the current sense output signal was monitored. The original revision of the grid current sense block involved a current transformer with integrated signal processing circuitry, which failed during testing. The current sense block was revised to utilize a hall-effect isolated current sense IC, as described in Section 5. The test was then repeated, and the results are shown in figure 6.7.
6.9 Flyback Gate Driver

To test the flyback gate driver, the ISO7240 (IC5) and an SM72295 (U22) was attached to the PCB. Then the flyback PWM signals were supplied using the microcontroller PWM. It was verified that +12V PWM signals were being supplied by the flyback gate driver.
6.10 Inverter Gate Driver

To test the inverter gate driver, all components were populated. Both the high side and low side inputs were provided with PWM signals using the microcontroller PWM outputs. The outputs were observed on an oscilloscope, to ensure that the MOSFET gates would be receiving a level shifted version of the driver input signals. Significant testing, debugging, and design revisions involving switching from an isolated driver topology to a bootstrap driver topology described in Section 5 were required in order to get the gate driver to a point where it operated reliably. After this was completed, the gate driver was confirmed to work reliably, allowing for future tests involving the actual inverter to be conducted.

![Figure 6.9. Test Output of Revised Inverter Gate Driver Board](image)

6.11 DC/DC Converter

![Figure 6.10. DC/DC Converter Test Circuit](image)
To verify the functionality of the MPPT algorithm on the DC/DC converter, the setup in Figure 6.10 was used. On the PV input to the microinverter, a DC power supply of 24V and a series resistance of 12Ω was connected. Using this setup, a PV Module with a Vmp = 12V and Imp = 1A can be emulated. The maximum power point occurs when the resistance of the DC/DC converter is the same as the series resistance. To gather data in this experiment, two simulink models were run in external mode to collect Vpv,Ipv, and duty cycle samples from the MCU. The first model did a sweep of the duty cycle from 0-100, producing the plots in figures 6.11-13. The second model used P&O MPPT to track the maximum power point of the IV curve, producing the plots in figures 6.14-16.

The Ipv vs. Vpv plot of Figure 6.11 shows the change in input current being linear to the change in the operating voltage of the flyback converter. There were a few outlier points when operating at between 14-16V. This could be due to the duty cycle changing the voltage more rapidly when the duty cycle is lower compared to higher duty cycles.
Figure 6.12. $P_{pv}$ vs. $V_{pv}$ of Series Resistance and Constant DC Voltage

The $P_{pv}$ vs. $V_{pv}$ plot of Figure 6.12 shows how the amount of power input into the DC/DC converter reaches a $P_{mp}$ of 11.5W. At this point, the $V_{mp}$ is 11.59V and $I_{mp}$ is 0.99A, which is close to the designed maximum power point for this system.

Figure 6.13. $V_{pv}$ vs. Duty Cycle of Series Resistance and Constant DC Voltage
The $V_{pv}$ vs. Duty Cycle plot of Figure 6.13 shows how the operating voltage changes as the duty cycle increased from 0-100. When the duty cycle was below 12%, the operating voltage of the DC/DC converter changed more rapidly, which is why the slope on the Figure 6.13 is greater in this area and why the data points are spaced out in figures 6.12 and 6.13.

![Figure 6.14. Vpv vs. Time Running MPPT](image)

For the MPPT test, the $V_{pv}$ vs. Time plot of figure 6.14 shows the voltage oscillating between approximately 10.8 - 12.6V, with the trendline between 11.3-11.6V after 125 seconds. This is expected, as the actual Vmp of the system is 11.5V.
The Duty Cycle vs. Time plot of Figure 6.15 shows how the duty cycle varies between 27-33% around the maximum power point of the system.

The Ppv vs. Time plot of Figure 6.16 shows how the Pmp is reached and stays relatively constant between 11.3-11.7 W. Overall, the actual MPPT algorithm is working as expected.
on the microinverter. The algorithm was able to track the maximum power point that was found in Figure 6.12.

While the oscillations of figures 6.14 and 6.15 are normal for P&O MPPT, it would be preferred to reduce their amplitude to increase the power efficiency. In the case of MPPT test, this could be done by reducing the duty cycle step, as the duty cycle step was set to 1% when it might have been more appropriate to set the step to 0.5% or lower. Also, the accuracy of the PV voltage and current sense modules along with the associated ADCs can affect how well the MPPT is tracked. The PV Power vs. Time curve of figure 6.12 shows that a slight variation in the calculated power compared to the maximum power point can greatly affect the calculated operating voltage. This is opposed to an actual PV module, where the maximum power point width is narrow. This issue can be fixed by either testing on a real PV module, improving the accuracy of the PV voltage and current sense modules, and/or reconfiguring the ADCs to improve accuracy.

Since the inverter section of the microinverter still needed to be tested, that section was prioritized over optimizing MPPT due to a lack of time.

Figure 6.17. Output Voltage and Current at MPPT

To get the efficiency of the DC/DC converter with the test setup in figure 6.17, a voltmeter and ammeter were connected to the load to determine the output current and voltage when the system was operating at the maximum power point. The output voltage was measured to be 56.9V and the output current was measured at 0.155A, while the input voltage and current were measured previously to be 11.5V and 1A respectively. With this information, the efficiency of the DC/DC converter in this test was about 77%. This is expected since the
soft switching MOSFET was removed from the DC/DC converter, leading to power dissipation in the main switching MOSFET. Also, the efficiency may increase if more power was pushed through the DC/DC converter.

6.12 DC/AC Inverter and Filter

![DC/AC Inverter Test Circuit](image)

To test the DC-AC Inverter, the input to the DC/AC Inverter was connected to a DC power supply, with voltages between 0-40V being supplied. The MCU was programmed to generate a modulated 60Hz sine wave using PWM to drive the four switches in the H-Bridge, with the amplitude of the output sine wave controlled by an M-constant. The output voltage of the inverter, as measured at the HBRIDGE1 and HBRIDGE2 test points (pre-filtering) and AC_L_OUT and AC_N_OUT points (post-filtering) were observed on an oscilloscope to see that a sinusoidal output is capable of being produced. After a substantial amount of debugging and design changes related to the MOSFET gate drivers were required, as described in Section 5, the inverter stage is capable of creating a filtered sine wave output. A scope image showing the voltage at the AC output of the inverter, which is driving a resistive load, is shown in figure 6.20.
Figure 6.19. Inverter Output Voltage Waveform - Pre Filtered

Coming directly off the h-bridge output, HBRIDGE1 and HBRIDGE2, the output shown in figure 6.19 is a PWM signal that is has a constantly changing duty cycle, due to the modulation of the 60Hz sine wave. This PWM voltage has to be filtered to output a 60Hz sine wave.

Figure 6.20. Inverter Output Voltage Waveform - Amplitude Measurement

From the output voltage waveform of Figure 6.20, the output of the DC/AC inverter after the filter is a 60Hz sine wave. With an input voltage of 40V, a load of 300Ω, and the M-constant at 0.5, the amplitude of the output waveform is 16.4V.
Using the same test conditions as those in figure 6.21, the frequency of the sine wave was measured. The frequency of the sine wave is 59.52Hz, which is close to the 60Hz.

To measure the current waveform at the output, a shunt resistance of 1Ω was put in series with a load resistance of 20Ω and an input voltage of 30V. The voltage across the shunt resistance was then measured to get the current waveform. The RMS of the current measured on the scope was 346mA, and the measured RMS on the ammeter was 361mA. The current waveform is also in phase with the voltage waveform. Sources of error, in this case, include the resistance of the rheostat not staying exactly at 1Ω.
Figure 6.23 shows the data that was used to calculate the efficiency of the inverter. The left image shows the input voltage and current on the DC power supply and portable ammeter respectively. The left image also shows the output RMS current on the bench ammeter. The right image shows the output RMS voltage. Measuring the efficiency of the power output vs the power input, the inverter efficiency during this test was 75% \( \left( \frac{12.3V \times 0.391A}{40.9V \times 0.156A} \right) \). This is considered normal for lower-end inverters, and the efficiency should increase under a greater power load, as the inverter was only outputting 6.4W.

**Inverter Noise Issues**

While testing the inverter section of the microinverter, irregularities were observed in the support circuitry of the microinverter. These irregularities arise when a significant amount of current is passed through the inverter. Issues observed include the serial communication from the MCU to a laptop prematurely cut, the I2C communication between the MCU and the display being cut, and the output voltage waveform becoming distorted once these issues occur. It was also observed that a computer monitor nearby became distorted when the inverter was operating and had current going through it. Upon further investigation, voltage spikes were observed at various locations on the secondary side of the microinverter.
The oscilloscope images of Figure 6.24 show the voltage output of the grid voltage sense block when there is a peak voltage of 16V on the inverter output. The image on the left was obtained by connecting the inverter output without the MOSFETs connected to an isolation transformer and a variac, to get a reference sine wave at 16Vpk. The image on the right was obtained by operating the inverter with an input of 40V, a resistive load of 300Ω, and an M-constant of 0.5. Comparing the two images, there are significant voltage spikes while the inverter is operating, with the maximum and minimum voltages observed being 3.5V and -0.5V respectively. The output current was 0.370A RMS in this case.

The oscilloscope images in Figure 6.25 show the output voltage of the DC link voltage sense block when 40V is supplied to the DC link (the input of the inverter). When the MOSFETs are disconnected, effectively turning off the inverter, the DC link voltage remains constant.
When the MOSFETs are connected, turning on the microinverter, voltage spikes are observed at the output of the DC link sense block, with the peak voltages of 4.5V and -3V.

The oscilloscope images in Figure 6.26 show the +3.3V and +5V secondary reference voltages while the inverter is turned on. As observed, significant voltage spikes occur on these rails when power is passed through the inverter.

The oscilloscope images in Figure 6.27 show the I2C SCL line when the inverter is off vs. when the inverter is on. As shown on the left, when the inverter is turned off, the I2C communication happens normally. When the inverter is turned on, the communication is stopped and voltage spikes are observed on the I2C SCL line.
While the inverter is operating, oscillations occur at the $V_{DS}$ of the MOSFET. These oscillations are around 13-14 MHz in frequency. While it is not believed these oscillations are causing the larger noise issues occurring, the switching oscillations were documented for future reference.

The source of the EMI is believed to be due to the physical layout of the PCB. Design considerations that were not strictly adhered to such as avoiding long traces, right angles and the significant number of vias are potential sources for the EMI. This can cause signals from one trace to be inadvertently coupled to nearby traces. The lack of dedicated ground plane layers also increases the effect of EMI on sensitive circuitry on the PCB. The large off-board inductor potentially could be a source of radiated EMI emissions as well. EMI is also an inherent issue with inverters and is designed around with EMI filters and shielding [52].

![Figure 6.28. Inverter MOSFET switching oscillations](image)
7. CONCLUSION AND RECOMMENDATIONS

From the results, it can be concluded that the individual circuit blocks of the microinverter are working and functional. PSUs were able to maintain their intended voltages and data was read and recorded from the microinverter sensors onto the Delfino microcontroller to create proper scaling factors. The gate driving blocks were able to properly maintain a duty cycle given a P&O MPPT algorithm. As a result of these subsections working properly, the DC/DC flyback converter is able to track and operate at the maximum power point voltage and step up the input voltage to high voltage on the DC link. The resulted efficiency of the single-switch DC/DC stage was 77%. The DC/AC H-bridge inverter is able to reliably produce a clean 60Hz sine wave from a DC voltage input into a resistive load, with an efficiency of 75% during testing. When the inverter is in operation, voltage spikes and noise can be observed on the secondary side sensors, reference voltages, and communication traces, which affects the operation of the system. This is believed to be due to EMI caused by the switched current passing through the inverter while it is operating. As a result, the prototype microinverter can be used to evaluate MPPT techniques to improve the efficiency of photovoltaic systems, and it is able to be modified and customized to fit the needs of the users. For use as a complete grid-tied microinverter, there are a number of revisions that are recommended.

7.1 Future Recommendations

To continue work on the development of an experimental microinverter for PV system research, it is recommended that the main PCB be revised and remanufactured to include the circuitry revisions discussed in this report and to mitigate issues related to EMI and signal crosstalk that were encountered during testing. Over the course of testing and debugging, a number of significant circuitry revisions were made, such as switching from an isolated inverter gate driver topology to a bootstrap topology and replacing the failure-prone current transformer module with a robust hall-effect current sense IC. When these changes were made, small custom PCBs were created to house the new circuitry, which were then mounted on top of the main PCB. In the new main board revision, these new subsections can be integrated directly on the new board.

The most important reason why it is recommended to revise the PCB is that in the existing design, electromagnetic interference and signal crosstalk between traces on the board significantly affect the operation of the system. Switching noise and PWM noise from the boost converter, and especially the inverter stage, is introduced onto the analog measurement signals and the display’s I2C lines, and even the MCU’s USB communication. This results in detrimental effects such as noisy ADC readings, display glitches, MCU lockups, and dropped USB connections while data logging. Before a complete control
system allowing for grid connection can be implemented, these EMI issues must be mitigated. Therefore, the revised PCB should be designed from the start with EMI and signal integrity in mind. The revised board may need to be a four-layer board, to permit the use of multiple ground planes and shorter traces. The layout should be designed to minimize crosstalk between signals and between power traces and to avoid excessive radiated emissions. Additional hardware filtering and clamping should be included on the analog signals prior to ADC measurement, to remove high-frequency signal components resulting from switching noise. During the design stage, it is recommended to use of PCB design software that includes simulation tools for evaluating the EMI properties of the board. Due to the complexity of the entire system, it is also recommended that the design be reviewed in detail by an experienced PCB design expert prior to manufacturing to ensure that EMI mitigation and signal integrity measures taken during design are sufficient. Addressing these issues in the revised PCB design will greatly improve the functionality and reliability of the microinverter.

The system was originally designed to include support for operating the flyback converter in an active clamping or soft switching topology. Persistent issues were encountered with the flyback converter gate driver IC failing when driving the second switch, which would also lead to the failure of other components. For this reason, the DC/DC converter was reverted to a single switch configuration, which reduces efficiency. It is recommended that the boost converter gate driver circuitry be replaced with a UCC27710-based design, in order to allow for active clamping to operate reliably. This bootstrap topology gate driver IC is used in the revised grid gate driver and was found to work reliably, and its suitability in driving the two flyback converter switches should be investigated. Once the hardware is capable of supporting active clamping and soft switching, the MCU program can be fine-tuned to optimize the operation of the active clamp by adjusting parameters like deadtime and duty cycles to improve efficiency and reliability.

Another recommendation for the revised PCB is the inclusion of an RC or RCD snubber across the main boost converter MOSFET. When the existing system is operated in single switch configuration, high Rds voltages exist on the MOSFET, which in some cases exceed the component’s absolute maximum ratings, accelerating its failure. A RC or RCD snubber would safely dissipate this voltage, preventing damage to the switch. The inclusion of such a snubber is less important when operating the system in an active clamp or soft switching mode, but should still be included if possible.

Additionally, there are several subsections that should be revised during the board redesign to enhance the performance of the microinverter. The grid overcurrent protection circuitry should be updated so that it is completely independent of the microcontroller
programming, and can only be reset by a manual button press, to prevent a MCU lockup from allowing for an overcurrent situation to occur. The reference voltage and power supply rail sections should be updated to account for the revised circuitry and new packages used. Also, PV derived voltage rail option should be revised so that it will operate on the main PCB without the need for external modules. This originally was to be the case, but the original dual output boost converter was nonfunctional, and the external module approach was used instead.

Once the PCB revisions are completed, and the board has been assembled and tested, improvements can be made to the firmware running on the MCU. The user interface can be improved and more fully implemented, and additional operating modes can be added. Proper synchronization between the grid voltage and the inverter voltage can be achieved, as well as PID control of the DC-DC link voltage. Different MPPT algorithms can also be implemented in the firmware for evaluation and testing. Communication between a PC running MATLAB and the microinverter can be added, and camera based MPPT can also be implemented.
8. REFERENCES


[34] Texas Instruments, “2.5-A and 5-A, 35-VMAX VDD FET and IGBT Single-Gate Driver” UCC2753x datasheet, Jul. 2015.


[38] Texas Instruments, “Ultralow-Noise, High-PSRR, Fast, RF, 500-mA Low-Dropout Linear Regulators” TPS795 datasheet, May. 2015.


APPENDIX A: MANUFACTURED PCB
APPENDIX B: MCU SIMULINK PROGRAM

The TI C2000 Delfino microcontroller used in this microinverter is a complex device, and programming the device in C using the Code Composer Studio IDE would have a large learning curve. Fortunately, Texas Instruments and Mathworks developed a MATLAB extension allowing for C code to run on the microcontroller to be generated from a Simulink model, using the Matlab Embedded Coder. This allows for the microinverter firmware to be developed more more rapidly and intuitively than using conventional embedded programming techniques. Most standard Simulink blocks are compatible with Embedded Coder and can be used to generate C code for the microcontroller. The microcontroller interfaces (GPIO, ADCs, PWM, etc.) are implemented using blocks from the TI C2000 library.

To take voltage and current measurements, an ADC block is used to configure the appropriate ADC module and channel for reading in analog voltages ranging from 0 - 3.3V. The output of the ADC block is an integer value ranging from 0 - 4095 (the maximum value that can be stored at 12-bit resolution), which is proportional to the voltage read by the ADC. This integer value is multiplied by the ADC Step to map the integer value to the output voltage of the measurement block. A scaling function is then applied to the voltage to convert from the output voltage to the actual voltage or current measured. The current or voltage measured is stored in a Goto block for the value to be available to the rest of the model. Similar blocks were used for implementing measurements for PV, DC Link, and Grid Voltage along with PV and Grid Current.
To perform MPPT, a MATLAB function block is periodically read in the PV voltage and current. The function block outputs the duty cycle the DC/DC converter operates at. The saturation block prevents the duty cycle of the DC/DC converter from reaching 0% or 100% due to the MPPT. A fixed duty cycle can also be supplied by disconnecting the saturation block and connecting a constant block.

To generate a PWM signal, the ePWM block is used, which is used to control a specific ePWM module on the microcontroller by feeding the block with a duty cycle from 0 - 100. The duty cycle used for the flyback PWM comes from the blocks in the image above. VBUS_SEN and boostEnable are used for logic to determine whether the flyback PWM is turned on. The flyback PWM is turned off when boostEnable is false or VBUS_SEN is greater than 250V. This is done as a safety measure to prevent excessive voltage on the DC link if the boost converter is operated in an open loop with no load or a very small load.
The finished microinverter will have various operating modes, some of which have not yet been implemented. In order for a user to control the operation of the microinverter without the need for a connected PC, a simple user interface was implemented using the LCD display and four tactile buttons on the main PCB. The firmware of the microinverter is can be described as a finite state machine. The Stateflow control logic tool in Simulink was utilized to define every possible operating state, as well as the transitions that lead from one state to another. This Stateflow flowchart is also where the control logic associated with each state is implemented. Each state is also associated with a value for “Mode” so that the correct screen is displayed on the LCD screen for that state. (The operation of the LCD display subsection is described in Appendix D).
To implement complementary PWM signals for the inverter, the above Simulink blocks are used. The sin block provides a 60Hz sine wave with an amplitude of 50 (which gives a pk-pk value of 100 for a 100% duty cycle). This sine wave is then multiplied with an m-constant, which adjusts its amplitude. An offset of 50 is then applied to the adjusted sine wave, which being the duty cycle range of the sine wave from -50 to 50, up to the 0 to 100% duty cycle that is needed for the inverter PWM. The ePWM provide a 30kHz PWM based on the input duty cycle at WA and ensure that the PWM waveforms are both complementary within each block and in phase between the two blocks. There is also an option to provide the duty cycle from the INV_DUTY From block, which is currently attached to an implementation of a PID controller for the inverter.
Above is an attempted implementation of a PID controller for the microinverter. The PID Inverter Controller block takes the measurements for Vgrid, Igrid, and Vbus. The controller attempts to keep the DC link operating at the input reference voltage and keep Igrid in phase with Vgrid.

Above is the PID controller that was attempted to be used on the microinverter. This is the same controller as that used for the microinverter Simulink model in section 4. Due to the EMI issues affecting grid voltage, grid current, and DC link voltage measurements, work on the PID controller was ended prematurely in favor of documenting the EMI issues.
APPENDIX C: SCALE FACTOR TESTS

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0595</td>
<td>0</td>
</tr>
<tr>
<td>0.0836</td>
<td>0.1086</td>
</tr>
<tr>
<td>0.1025</td>
<td>0.1938</td>
</tr>
<tr>
<td>0.139</td>
<td>0.3362</td>
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<td>0.1495</td>
<td>0.4068</td>
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<td>0.5141</td>
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<td>0.7257</td>
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<td>0.95</td>
<td>4.0185</td>
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<td>1.4368</td>
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### PV Voltage Sense

<table>
<thead>
<tr>
<th>Vin (V)</th>
<th>Vout (V)</th>
</tr>
</thead>
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<tr>
<td>-0.0045</td>
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<td>1.998</td>
<td>1.331</td>
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<tr>
<td>3.983</td>
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<td>6.0095</td>
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<td>7.999</td>
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<tr>
<td>9.996</td>
<td>1.525</td>
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<tr>
<td>11.97</td>
<td>1.5727</td>
</tr>
<tr>
<td>14.045</td>
<td>1.627</td>
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<tr>
<td>15.975</td>
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<tr>
<td>17.911</td>
<td>1.7158</td>
</tr>
<tr>
<td>20.007</td>
<td>1.7666</td>
</tr>
<tr>
<td>22.03</td>
<td>1.8152</td>
</tr>
<tr>
<td>23.984</td>
<td>1.8623</td>
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<tr>
<td>25.98</td>
<td>1.9104</td>
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</table>

### DC Voltage Sense

<table>
<thead>
<tr>
<th>Vdc Sense (V)</th>
<th>VDC in (V)</th>
</tr>
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<tr>
<td>-0.009</td>
<td>0.00635</td>
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<tr>
<td>4.81</td>
<td>0.03773</td>
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<tr>
<td>14.31</td>
<td>0.11289</td>
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<td>21.18</td>
<td>0.16721</td>
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<tr>
<td>28.95</td>
<td>0.22865</td>
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<tr>
<td>37.4</td>
<td>0.29577</td>
</tr>
<tr>
<td>51.1</td>
<td>0.40375</td>
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<tr>
<td>62.9</td>
<td>0.49731</td>
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<tr>
<td>Grid Voltage Sense</td>
<td>Voltage Out (V)</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Vgrid in (V)</td>
<td></td>
</tr>
<tr>
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<td>-31.49</td>
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<tr>
<td>-22.08</td>
<td>1.5642</td>
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<tr>
<td>-13.66</td>
<td>1.599</td>
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<tr>
<td>-4.68</td>
<td>1.638</td>
</tr>
<tr>
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<td>1.826</td>
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<td>53.7</td>
<td>1.86</td>
</tr>
<tr>
<td>62.9</td>
<td>1.907</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Grid Current Sense</th>
<th>Voltage Out (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Igrid in (A)</td>
<td></td>
</tr>
<tr>
<td>-3</td>
<td>0.915</td>
</tr>
<tr>
<td>-2.5</td>
<td>1.03</td>
</tr>
<tr>
<td>-2</td>
<td>1.17</td>
</tr>
<tr>
<td>-1.51</td>
<td>1.3</td>
</tr>
<tr>
<td>-1.01</td>
<td>1.43</td>
</tr>
<tr>
<td>-0.5</td>
<td>1.58</td>
</tr>
<tr>
<td>0</td>
<td>1.71</td>
</tr>
<tr>
<td>0.5</td>
<td>1.83</td>
</tr>
<tr>
<td>1.01</td>
<td>1.96</td>
</tr>
<tr>
<td>1.51</td>
<td>2.11</td>
</tr>
<tr>
<td>2</td>
<td>2.25</td>
</tr>
<tr>
<td>2.5</td>
<td>2.36</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
</tr>
</tbody>
</table>
APPENDIX D: DISPLAY COMMUNICATION BOARD

As mentioned earlier in the report, a custom display communication board was designed and fabricated, and installed between the 4-line alphanumeric character LCD and the main PCB. This board is necessary because the main PCB originally was designed to accommodate a 128*64 pixel dot matrix display. After the board had been fabricated, it was determined that it would be impractical to program an interface for such a display using Simulink. This new board connects between the LCD module and the TI Delfino microcontroller. An 8-bit Atmel ATMEGA328P microcontroller on the adapter board reads in the system mode state and measurement data sent from the Delfino MCU over I2C, stores these measurements as local variables, and formats the data into the various screens displayed on the LCD.

Schematic of the display adaptor board. J1 indicates the connections to the LCD, and J2 indicates connections to the main PCB.
4x20 HD44780 LCD module

The LCD used is a standard off-the-shelf 4-line character LCD with a standard HD44780 parallel interface. This LCD is controlled directly from the ATMEGA328p microcontroller. Additional connections for the LCD include an analog voltage signal controlling the contrast, controllable with a potentiometer on the main PCB, and a current limited power supply for the LED backlight, generated with a resistor on the main PCB.

**Programming the ATmega328P Microcontroller**

The ATmega328p microcontroller is programmed using the open-source Arduino IDE. This speeds up the development process as a number of open source libraries were available. The microcontroller is permanently soldered to the display adaptor board, and it can be programmed by connecting a compatible AVR programmer, such as the open-source USBTinyISP programmer board, to the 6-pin ICSP header. To limit the component count of the adapter board, the microcontroller is configured to use its internal 8MHz oscillator as a clock source. As a result, before attempting to upload code to the microcontroller, it is important that the Arduino IDE is configured to support programming a device without an external clock source. Once the USB programming adapter is connected using the ICSP header on the display board, the new code can be uploaded using the “Upload using programmer” option in the Arduino IDE.

**Code design**

In order to display measurement information on the display, the main TI microcontroller is programmed using the Simulink Embedded Coder to take the measurements from the ADCs, scale them to obtain the correct values, then multiply the
values by a factor of 100. These values are formatted into 16-bit floating point numbers. Each variable is associated with a 16-bit integer identifier number. Each variable is formatted into a 32-bit message consisting of the value concatenated with its respective identifier, and each message is sent out through the I2C bus. Table X, showing which identifier corresponds to each piece of information is shown below. Before the values are sent over I2C, There are 10 pieces of data that need to be sent from the main microcontroller to the AVR microcontroller handling the display functions, corresponding to 9 numerical values calculated onboard the main MCU as well as a “mode” variable. The “mode” variable corresponds to which Stateflow state the microinverter is currently operating in, and instructs the AVR MCU controlling the display to show the correct screen.

Each of the screens that can be defined needs to be predefined in the code running on the AVR MCU. After a screen is defined, it is associated with a specific value of the “mode” variable, so that when it needs to be displayed, the main MCU simply needs to set “mode” equal to the screen’s corresponding number. The corresponding “mode” value for each of the screens currently implemented is shown below in the table below.

<table>
<thead>
<tr>
<th>Data:</th>
<th>Scaled up by a factor of 100 on the Delfino</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Identifier</strong></td>
<td><strong>Arduino Variable</strong></td>
</tr>
<tr>
<td>1</td>
<td>float Vpv</td>
</tr>
<tr>
<td>2</td>
<td>float Ipv</td>
</tr>
<tr>
<td>3</td>
<td>float Ppv</td>
</tr>
<tr>
<td>4</td>
<td>float Vg</td>
</tr>
<tr>
<td>5</td>
<td>float Ig</td>
</tr>
<tr>
<td>6</td>
<td>float Pg</td>
</tr>
<tr>
<td>7</td>
<td>float Vdc</td>
</tr>
<tr>
<td>8</td>
<td>float Eff</td>
</tr>
<tr>
<td>9</td>
<td>int duty</td>
</tr>
<tr>
<td>0</td>
<td>int mode</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LCD Screens:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Startup screen (1,2,3,more)</td>
</tr>
<tr>
<td>1</td>
<td>flyback constant duty start</td>
</tr>
<tr>
<td>2</td>
<td>flyback constant duty</td>
</tr>
<tr>
<td>3</td>
<td>calibration mode start</td>
</tr>
<tr>
<td>4</td>
<td>calibration mode (all adc values)</td>
</tr>
</tbody>
</table>
Code for the ATMEGA328P microcontroller on the display adapter board:

```c
#include <Wire.h>
#include <LiquidCrystal.h>
#include <avr/interrupt.h>

// Connections between the LCD and the AVR
const int rs = 12,
    en = 11,
    d4 = 5,
    d5 = 4,
    d6 = 3,
    d7 = 2;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);

int mode = 0; //default should be 1
int oldMode = 0; // used to see if screen should be cleared when changing mode
int16_t value;
float valFloat;
int16_t identifier;
long int lastTime = 0;

float Vpv = 1.23; //identifier 1
float Ipv; //identifier 2
float Ppv; //identifier 3
float Vg = 2.34; //identifier 4
float Ig; //identifier 5
float Pg; //identifier 6
float Vdc; //identifier 7
float Eff; //identifier 8
```
int duty = 10; // ident 9

void setup() {
    lcd.begin(20, 4);
    lcd.clear();

    // Initialize I2C communications. This board is the slave node,
    // the main MCU is the master node
    Wire.begin(80); // join i2c bus with address #8
    Wire.onReceive(receiveEvent); // register event
    Serial.begin(9600); // start serial for output
}

void loop() {
    if (((millis() - lastTime) > 5000)) { // if data hasn't been
        updated in 5s, indicate an error
            lcd.clear();
            lcd.setCursor(0, 1);
            lcd.print("I2C Error");
            lcd.setCursor(0, 3);
            lcd.print("Please reset MCU.");
            delay(600);
    } else {

        switch (mode) {
            case 0:
                updateDisplayMode0();
                break;
            case 1:
                updateDisplayMode1();
                break;
            case 2:
                updateDisplayMode2();
                break;
            case 3:
updateDisplayMode3();
break;
case 4:
    updateDisplayMode4();
    break;
case 5:
    updateDisplayMode5();
    break;
case 6:
    updateDisplayMode6();
    break;
case 7:
    updateDisplayMode7();
    break;
}
}
delay(300);
} // end loop

// This is the routine that is called when new data is available on the I2C bus
void receiveEvent(int howMany) {
    while (4 < Wire.available()) { // loop through all but the last
        char cc = Wire.read(); // clear out excess bytes on the buffer
        // Last four bytes are the important ones
    }
    byte a, b, c, d;
    d = Wire.read();
    c = Wire.read();
    b = Wire.read();
    a = Wire.read();

    value = a;
    value = (value << 8) | b;

    identifier = c;
    identifier = (identifier << 8) | d;
lastTime = \texttt{millis}(); // reset no data warning timeout

\textbf{switch} (identifier) { \\
  \textbf{case} 1: \\
    Vpv = \texttt{float}(value) / 100; \\
    \textbf{break}; \\
  \textbf{case} 2: \\
   Ipv = \texttt{float}(value) / 100; \\
    \textbf{break}; \\
  \textbf{case} 3: \\
    Ppv = \texttt{float}(value) / 100; \\
    \textbf{break}; \\
  \textbf{case} 7: \\
    Vdc = \texttt{float}(value) / 100; \\
    \textbf{break}; \\
  \textbf{case} 4: \\
    Vg = \texttt{float}(value) / 100; \\
    \textbf{break}; \\
  \textbf{case} 5: \\
    Ig = \texttt{float}(value) / 100; \\
  \textbf{case} 6: \\
    Pg = \texttt{float}(value) / 100; \\
    \textbf{break}; \\
  \textbf{case} 8: \\
    Eff = \texttt{float}(value) / 100; \\
    \textbf{break}; \\
  \textbf{case} 9: \\
    duty = value / 100; \\
    \textbf{break}; \\
  \textbf{case} 0: \\
    mode = value / 100; \\
  } \\

  \textbf{if} (mode != oldMode) { // clear screen before moving to a new mode \\
    cli(); // interrupt disable \\
    lcd.\texttt{clear}(); \\
    sei(); // interrupt enable \\
    oldMode = mode;
void updateDisplayMode0() { // Main menu
    lcd.setCursor(0, 0);
    lcd.print("1. Flyback Conv Test");
    lcd.setCursor(0, 1);
    lcd.print("2. Flyback No Clamp");
    lcd.setCursor(0, 2);
    lcd.print("3. ADC Calibration");
    lcd.setCursor(0, 3);
    lcd.print("4. More Options ");
}

void updateDisplayMode1() { // Flyback Constant Duty mode START SCREEN
    lcd.setCursor(0, 0);
    lcd.print("DC-DC Stage Test");
    lcd.setCursor(0, 1);
    lcd.print("HIGH VOLTAGE!");
    lcd.setCursor(0, 2);
    lcd.print("1. Continue");
    lcd.setCursor(0, 3);
    lcd.print("2. Back to menu");
}
void updateDisplayMode2() { // Flyback Constant Duty mode
    lcd.setCursor(11, 0);
    lcd.print("Vpv    V");
    lcd.setCursor(15, 0);
    lcd.print(Vpv, 1);

    lcd.setCursor(11, 1);
    lcd.print("Ipv    A");
    lcd.setCursor(15, 1);
    lcd.print(Ipv, 1);

    lcd.setCursor(11, 2);
    lcd.print("Vdc    V");
    lcd.setCursor(15, 2);
    lcd.print(Vdc, 1);

    lcd.setCursor(11, 3);
    lcd.print("Duty");

    lcd.setCursor(16, 3);
    lcd.print(duty);
    lcd.setCursor(19, 3);
    lcd.print("\%");

    lcd.setCursor(0, 1);
    lcd.print("2.Exit");

    // Increases constant duty cycle
    lcd.setCursor(0, 2);
    lcd.print("3.Duty Up");

    // Decrease constant duty cycle
    lcd.setCursor(0, 3);
    lcd.print("4.Duty Dn");
}
```cpp
void updateDisplayMode3() {  // ADC calibration mode START SCREEN
    lcd.setCursor(0, 0);
    lcd.print("Starting ADC Test");
    lcd.setCursor(0, 1);
    lcd.print("mode.");
    lcd.setCursor(0, 2);
    lcd.print("1. Continue");
    lcd.setCursor(0, 3);
    lcd.print("2. Back to menu");
}

void updateDisplayMode4() {  // ADC calibration mode (all ADCs active)
    lcd.setCursor(0, 0);
    lcd.print("Vpv     V");
    lcd.setCursor(5, 0);
    lcd.print(Vpv, 1);

    lcd.setCursor(0, 1);
    lcd.print("Ipv     A");
    lcd.setCursor(4, 1);
    lcd.print(Ipv, 2);

    lcd.setCursor(0, 2);
    lcd.print("Vdc     V");
    lcd.setCursor(4, 2);
    lcd.print(Vdc, 1);

    lcd.setCursor(11, 0);
    lcd.print("Vg     V");
    lcd.setCursor(14, 0);
    lcd.print(Vg, 1);

    lcd.setCursor(11, 1);
    lcd.print("Ig     A");
    lcd.setCursor(14, 1);
    lcd.print(Ig, 2);

    lcd.setCursor(0, 3);
```

lcd.print("2. Exit ADC Testing");

void updateDisplayMode5() { // More options menu for updateDisplayMode1
  lcd.setCursor(0, 0);
  lcd.print("1. Inverter Gate Tst");
  lcd.setCursor(0, 1);
  lcd.print("2. Grid Voltage Tst");
  lcd.setCursor(0, 2);
  lcd.print("   ");
  lcd.setCursor(0, 3);
  lcd.print("4. Back to menu");
}

void updateDisplayMode6() { // Inverter gate driver test START SCREEN
  lcd.setCursor(0, 0);
  lcd.print("Inverter gate driver");
  lcd.setCursor(0, 1);
  lcd.print("test. DISCONNECT PV!");
  lcd.setCursor(0, 2);
  lcd.print("1. Continue");
  lcd.setCursor(0, 3);
  lcd.print("2. Back to menu");
}

void updateDisplayMode7() { // Gate driver test screen
  lcd.setCursor(0, 0);
  lcd.print("Now testing gate ");
  lcd.setCursor(0, 1);
  lcd.print("drivers. Freq:50KHz");
  lcd.setCursor(0, 2);
  lcd.print(" ");
  lcd.setCursor(0, 3);
lcd.print("2. Back to menu");
}
// End Code