Design and Implementation of a Grid Connected Solar Micro-inverter

Prepared for: ECE 4600

Prepared by:
Raveen Gunarath
Luo Liu
Sarin Rajapakse
Ella Thomson

Advisor:
Dr. Carl Ho

Department of Electrical and Computer Engineering
University of Manitoba
Winnipeg, Manitoba, Canada

March 2017

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Abstract

The purpose of this project was to design a grid connected solar micro inverter. Solar microinverters convert the power from a photovoltaic panel to power that can be injected into the grid. In this project, the solar micro inverter was designed using a DC-DC converter stage and a DC-AC inverter stage. Maximum power point tracking was used to maximize the power drawn from the photovoltaic panel in the DC-DC converter stage. Controllers were also designed for the DC-AC inverter stage. A simulation of the system was completed on Plexim. The simulation realized all design specifications. These specifications were a 200 V DC link voltage, a $120 \ V \text{rms} \pm 5\% \ output \ voltage \ and \ maximum \ power \ point \ tracking$. A prototyping stage was completed using perf board fabricated circuits. This stage was completed to validate the design of the physical system. The final project deliverables were a fully populated PCB and a complete set of microcontroller code. The DC link voltage was 200 Volts. The output AC voltage was 116 V rms, which was within the specification of $120 \ V \text{rms} \pm 5\%$. The efficiency of the DC-DC converter stage was 91%. The efficiency of the DC-AC inverter stage was 93%. The overall efficiency was 85%, which met the specification of efficiency greater than 80%.
Acknowledgements

We would like to thank our supervisor, Professor Carl Ho, for his guidance and assistance with the project. We would also like to thank several graduate students in the power systems group at the University of Manitoba, including Mandip Pokharel, Dong Li, Isuru Jayawardana, King Man Siu and Yang Zhou. We would also like to thank Professor Card for his technical assistance with the project. We would like to thank Erwin Dirks for allowing us to borrow several power circuit components. We also thank Glen Kolansky and all other lab technicians in ECE for their assistance in providing us with the required circuit components. Additionally, we would like to thank VITEC for providing us with the flyback transformer.
Contribution Page

The work was evenly shared amongst all team members. The project was divided into 5 design stages. Each design stage was assigned one primary lead and one secondary lead, to provide redundancy. The design leads were responsible for dividing work amongst themselves and assigning tasks to other team members. Each team member acted as primary lead for one design stage, and secondary lead for another design stage. The final implementation and testing stage required the expertise and background knowledge of all team members. Therefore, the work for this stage was divided equally amongst the team. The design stages are bolded. Individual tasks are specified under each design stage. The work completed by each team member is summarized below.

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Legend
X = Team Lead
O = Contributed
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<th>Description</th>
<th>Use</th>
</tr>
</thead>
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<tr>
<td>A</td>
<td>Amperes</td>
<td>Unit for current</td>
</tr>
<tr>
<td>V</td>
<td>Volts</td>
<td>Unit for voltage</td>
</tr>
<tr>
<td>rms</td>
<td>root mean square value</td>
<td>Used to describe AC voltages and currents</td>
</tr>
<tr>
<td>W</td>
<td>Watts</td>
<td>Unit for power</td>
</tr>
<tr>
<td>p-p</td>
<td>peak to peak</td>
<td>Used to describe AC voltages and currents</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
<td>A method used to find the maximum power point of a PV panel output voltage and current</td>
</tr>
<tr>
<td>D</td>
<td>Duty Cycle</td>
<td>The fraction of one period in which a signal or system is active</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
<td>A modulation technique to control the duty cycle of a square wave</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
<td>An electric current that reverses its direction with certain frequency</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
<td>An electric current that has fixed direction</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
<td>A board that electrically connects components</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
<td>A method for generating electric power by using solar energy</td>
</tr>
</tbody>
</table>
Chapter 1- Introduction

This section includes the project purpose, and an overview of the document. Background information about solar energy and microinverters is also discussed.

1.1 Project Purpose

The purpose of this project was to design and implement a grid connected solar micro-inverter. The project deliverables were divided into three subsections. The first deliverable was a simulation, completed using the Plecs design and simulation tool. The simulation included both the DC-DC converter, DC-AC converter and also the closed loop controls. The second deliverable was physical builds of the DC-DC and DC-AC converters, to verify the circuit topology and then PCB design and for the full power circuits. The third deliverable was microcontroller programming for closed loop control and maximum power point tracking. The input to the converter was a solar panel, modeled using a lab volt PV simulator. The output of the converter was connected to the grid (120 Vrms and 60 Hz). The purpose of the project was to design an inverter with an overall efficiency of over 80%.

1.2 Overview of Document

This document includes all major design goals, methodology and results for the design and implementation of a solar micro-inverter. Background information related to solar panels is presented. The design methodology and specifications are then stated. The simulation design process and results are discussed, followed by the physical build results, the design process for the PCB and the microcontroller programming methodology. The results of the subsystem integration are presented, and the overall success of the project is evaluated, as it relates to the design goals.

1.3 Background

This section includes background information regarding solar energy, micro-inverters, and the purpose and implementation of maximum power point tracking.

1.3.1 Overview of Solar Energy in Canada

The purpose of this project was to design and implement a single-phase grid connected solar micro-inverter. The design of a solar micro-inverter is relevant as renewable energy is becoming more popular due to an interest in replacing fossil fuels and in slowing the progression
of climate change. As of 2013, over 63% of Canada’s energy usage was considered renewable [1]. Hydro power alone accounts for approximately 60% of energy usage [1]. Solar energy currently comprises a small portion of energy production in Canada. However, solar energy usage in Canada has grown by 13.8% from 2004-2014 [2].

1.3.2 Advantages and Disadvantages of Solar Energy

Solar panels have several advantages. Solar energy is fully renewable. Additionally, the panels require little maintenance, in comparison to other forms of renewable energy such as wind energy, or hydro power [3].

One disadvantage of solar energy is the high initial cost. A large area is also required for the solar panels. One additional challenge is maintaining overall efficiency when coupling the system to the grid [3]. This project focused on addressing these challenges, by developing a low cost microinverter (with the budget specified in Appendix A). The microinverter also had a small size.

1.3.3 Micro-inverters versus Inverters

Solar micro-inverters are used to convert the electric energy from one photovoltaic panel to electric energy that can be injected to the grid [4][5]. In contrast, a conventional inverter connects to multiple solar panels. Microinverters are more resilient to small changes in cloud covering, or in sunlight [5]. The overall system efficiency is increased because each inverter panel can act on its own. Each solar panel has its own microinverter, and they are connected in parallel to the grid, as shown in figure 1-1.

![Figure 1-1: Parallel Connection of Micro-Inverters](image)

1.3.4 Function of Solar Micro-Inverters

Solar panels act as a DC current source with a parallel diode [7]. Therefore, the purpose of a solar micro-inverter is to convert this DC current to AC current. The output from the
micro-inverter can then be fed to the grid. This is commonly accomplished using two separate stages: a DC-DC converter and a DC-AC inverter.

### 1.3.5 Extracting Maximum Power from a Solar Micro-Inverter

A typical photovoltaic cell is a p-n junction diode with a cover that is optically transparent. When light falls onto the photovoltaic cell the light is converted to a photocurrent ($I_{PV}$). A simple circuit model for a photovoltaic cell is a current source equal to the photocurrent in parallel with the p-n junction diode with parasitic series and parallel resistances. Therefore, the photovoltaic cell cannot be simply modeled as either a current or a voltage source [7]. In order to produce maximum efficiency, a system is needed to couple the photovoltaic cell to the load with maximum power transfer. The system must have the ability to adjust the coupling to the load such that the power is extracted at the maximum power point. This type of DC-DC converter is called a maximum power point tracking converter, shown in figure 1-2 [8].

![Simple circuit model for a photovoltaic cell.](image)

Figure 1-2: Simple circuit model for a photovoltaic cell. [8]

Maximum power point tracking is employed in the DC-DC converter stage to maximize power extraction from the panel. The relationship between $I$ and $V$ for a solar panel is shown in figure 1.3. The grey line (indicated with a red arrow) represents the maximum power point for various irradiation (current) levels. As the light intensity changes, the $I_{PV}$ will change. Due to the nonlinear behavior of the system, the maximum power point tracking circuit has to adjust the coupling between the so that the power is extracted at the maximum power point [9].
Maximum power point tracking can be achieved by modifying the duty cycle of the DC-DC converter. This change in duty cycle modifies the impedance of the inverter, as seen by the solar panel [9]. As the $I_{pv}$ decreases, the voltage at which the power coupling is maximized will also decrease due to the diode behavior of the photovoltaic cell. In this work the photovoltaic cell is simulated using an electronic system that simulates the behavior of a photovoltaic cell.

Figure 1-3: IV curve for a solar panel [9]
Chapter 2- Purpose and Design

Methodology

The purpose and design methodology section includes the design specifications, and an overview of the design stages.

2.1 Design Specifications

The required design specifications are shown in table 2-1.

Table 2-1: Design Specifications

<table>
<thead>
<tr>
<th>Feature</th>
<th>Target Value</th>
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<tr>
<td>Maximum Power</td>
<td>100 W or more</td>
</tr>
<tr>
<td>Minimum Power</td>
<td>50 W or less</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-30°C to 50°C (operating temperature range for components)</td>
</tr>
<tr>
<td>Maximum Power Point Tracking</td>
<td>Extract maximum output power from the solar panel at different sunlight and temperature conditions</td>
</tr>
<tr>
<td>DC Voltage Controls</td>
<td>DC Voltage output to the microcontroller must not exceed 3.3 V</td>
</tr>
<tr>
<td>AC Voltage Controls</td>
<td>AC Voltage output to the microcontroller must not exceed 3.3 Vp-p</td>
</tr>
<tr>
<td>Voltage Requirements</td>
<td>DC link voltage</td>
</tr>
<tr>
<td></td>
<td>The nominal value of the voltage link the DC-DC and DC-AC stage must be 200 V</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>120 Vrms ±5% at 60Hz</td>
</tr>
<tr>
<td>Current Requirements</td>
<td>Output current must be sinusoidal and in phase with output voltage</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Average efficiency of &gt;80%</td>
</tr>
</tbody>
</table>

2.2 Design Methodology and Staging

The design and validation had five main stages. The subsequent chapters are reflective of these stages:

- Simulation on Plecs
- Physical testing of topology at low power
- PCB design
- Microcontroller programming
- Integration of subsystems

The first stage was completing a topology design and a simulation on Plecs. The purpose
of the simulation was to design and test the DC-DC converter stage and the DC-AC inverter stage topology. Plecs was also used to design the controllers for the DC-DC and DC-AC converter stages. The Plexim design was iterated until all design goals, specified in table 2-1, were met.

The second design stage was physical testing of the topology of the converters. In this stage, the DC-DC and DC-AC converters were built on perfboard. The two stages were tested separately using open loop controls with signal levels similar to the voltages available from the microcontrollers and digital signal processors used for the controls. During the second stage, control circuits were also designed to step down the DC link voltage, DC current, grid current and grid voltage so that the voltages were compatible with the voltage levels of the microcontrollers and digital signal processors used for the controls.

The third stage of the project was to complete a printed circuit board (PCB) design. The PCB design was completed in Altium Designer. The board housed all the power circuit components for both the DC-DC and DC-AC stages. The control voltage step-down circuits were also included on the PCB. A connector was also added for all outputs to the PCB.

The fourth stage of the project was development of the control algorithms for the microcontrollers and digital signal processors. Additional dead band circuitry was also developed. Microcontrollers and digital signal processor programs were developed for the maximum power point tracking, AC current control and DC link voltage control. In order to facilitate individual subunit testing, microcontroller programs were also developed for open loop controls of the DC-DC and DC-AC converter stages. These programs were designed using blocks in Simulink and were then compiled and exported to the microcontrollers and digital signal processors.

The fifth stage of the project was the integration of all the subunits. The first stage of integration was testing the DC-DC converter with the MPPT code. The next stage was testing the DC-AC inverter with close loop controls. Finally, the DC-DC converter and DC-AC converter were tested together, and the output of the system was connected to the grid.
Chapter 3- Topology

The solar micro-inverter design included two stages; the DC-DC converter stage and the DC-AC inverter stage. The DC-DC stage receives an input from the solar panels, and the DC-AC stage is output to the grid. The topology is shown in figure 3-1.

![Block diagram of grid connected solar micro-inverter](image)

Figure 3-1: Block diagram of grid connected solar micro-inverter [10]

3.1 DC-DC Converter

The DC-DC converter stage is a flyback converter, which converts the voltage at the solar panels to a stable 200V DC link voltage at the output the DC-DC converter. The fly-back DC-DC converter also provides isolation for the converter when it connects to the electric grid [8]. The voltage of the solar panel is normally in the range of 25~50V. The use of a flyback converter with a step up transformer serves two purposes. It provides isolation, while also reducing the current at the output of the DC-DC converter stage [11]. Consequently, this reduces the ripple current across the DC link capacitor. The schematic of the DC-DC converter stage is shown in figure 3-2.

![Fly-back DC-DC converter](image)

Figure 3-2. Fly-back DC-DC converter [11]
The fly-back circuit is able to produce output voltages that are greater than the input voltages. This is important as the photovoltaic panels produce voltages lower than that required for the DC-AC converter using a bridge topology, which produces no voltage gain. The operation of a flyback converter is shown in figure 3-3. With the switch on the current flows through the transformer and the load. In the off state the induced current flows through the diode to the capacitor and the load. This current continues to flow until the diode become reverse biased and shuts off the flow of current.

![Figure 3-3: Flyback DC to DC converter operation](image)

During the on state (top), the current flows through the transformer, the power flows to the load from the capacitor and the diode prevents power from flowing back through the transformer. In the off state (bottom), the induced current from the transformer forward biases the diode and current flows through the diode onto the capacitor and the load. This continues until the voltage on the capacitor falls to the point when the diode becomes reverse biased and shuts off the flow of current. This circuit can produce output voltages that exceed the input voltages by many times. If the losses in the circuit elements are minimized, the efficiency of the circuit can be very high [13].

The flyback converter consists of a panel side capacitor to stabilize the voltage from the panel. A MOSFET acts as a switch, and receives a PWM signal. The transformer of the flyback converter boosts the voltage and also provides isolation from the grid. Additionally, the diode is used to block the negative voltage cycle from the secondary side of the transformer. A DC link
capacitor is placed at the output of the flyback converter. Under a constant switching duty cycle, a flyback converter is similar a buck-boost converter with an additional transformer [13]. The output of the flyback converter follows the equation:

\[ V_{out} = -\frac{n_2}{n_1} \frac{D}{1-D} V_{in} \]

In this equation, \( V_{in} \) is the voltage on the panel side, \( \frac{n_2}{n_1} \) is the ratio of the transformer, and \( D \) is the duty cycle of the PWM signal going to the MOSFET gate [13]. The polarity of the voltage output depends on the direction of the diode connected after the secondary side of the transformer.

### 3.2 DC-AC Inverter

There are many ways to convert a DC voltage into an AC voltage. One commonly used method makes use of switches to periodically switch the direction of current flow from a DC source through a load, to produce an AC voltage across the load, as shown in figure 3-4. This is often referred to as an H-bridge or full bridge inverter [14]. The frequency of the output voltage can be controlled by the frequency of the switching and flow of power can be controlled using pulse width modulation of switching signals [14]. In this project the load is replaced by the grid. Pulse width modulation is used to control the flow of power into the grid.

![Figure 3-4: H bridge full inverter [14]](image)

In this project, the DC-AC inverter consisted of four IGBT’s, which acted as the switches. The input to the DC-AC inverter stage was a 200 V DC link voltage. The switching frequency for this project was 20 kHz and was provided by the Concerto F28M35X microcontroller. This switching frequency was selected to reduce the inductance required for the filter, as this inductor is one of the higher power and costlier components. Using higher frequencies allowed a lower inductance value to be used, thus reducing the cost of the inductor. Pulses were sent to the IGBT’s by the microcontroller. Gate drivers were used to drive the
IGBT’s. The gate driver circuit is shown in Fig 3-5 and ensures the low signal levels from the microcontroller can produce voltages large enough to turn the switches fully on and also electrically isolates the low voltage control signals from the high voltage IGBT’s. The low signal level from the microcontroller is used to turn on a transistor, which drives an LED. The LED optical output couples into a phototransistor and switches a higher voltage to the drive the gate of the IGBT. The optical separation provides electrical isolation between the two circuits.

![Gate driver circuit](image)

Figure 3-5: Gate driver circuit

The pulse to IGBT’s 1&4 is always opposite the pulse to IGBT’s 2&3. In practice, a dead band is required to ensure that the switches are never closed at the same time to avoid short circuiting. The circuit used to accomplish is described in section 7.3. A filter is used to connect the full bridge inverter to the grid. This filter consists of a coil powder inductor. The inductor filters out the higher order harmonics of the output signal, to produce a smooth sinusoidal wave.

The second stage of the solar micro inverter is a full bridge IGBT inverter, as shown in figure 3-6.

![Full bridge inverter](image)

Figure 3-6: Full bridge inverter
3.3 Filter Design

An inductor filter was designed and connected between the output of the full bridge IGBT inverter and the load/grid. The inductor was used to remove the higher order current harmonics caused by the IGBTs switching. The inductor also provided continuous current to the load or grid. The inductor and resistor can also perform as a low pass filter. The impedance of the resistive load can be estimated as:

\[ R = \frac{V_{\text{grid, rms}}^2}{P_{\text{rms}}} = \frac{(120V)^2}{250W} = 57.6\Omega. \]

The inductance of the low pass filter was calculated based on a chosen cut-off frequency of 2kHz at the output of the filter. The actual switching frequency of the IGBTs in the inverter was 10 times higher than 2kHz. Therefore, referring to the Fourier spectrum distribution of SPWM switching, the higher order current harmonic can be filtered out by an inductor with a value of:

\[ L = \frac{R}{2\pi f_{\text{cutoff}}} = 4.6mH \]

This means that the inductance should be at least 4.6mH to filter out the high order current harmonics under the maximum power condition. The inductance of the filter can be smaller when the output of the inverter is connected to the grid. This is because the output voltage of the inverter can be fixed to 120V rms by the grid voltage. Therefore, the output current delivered to the grid can be controlled by switching the gates. However, the actual value of the inductor cannot be precisely calculated, since it is affected by many conditions, such as control technique. Therefore, the actual inductance was designed in the simulation, and is discussed in the next chapter. A custom inductor was designed for the filter, and is discussed in appendix B.
Chapter 4- Simulation and Design

An initial design was completed on Plecs to validate the selected topology and to develop control algorithms. This section covers an overview of the Plecs design, and the simulation results from maximum power point tracking, AC current control and DC link voltage control.

4.1 Design and Validation on Plecs

The DC-DC and DC-AC converter were both designed using the Plecs simulation software. Plecs software was selected because it is designed specifically for power electronics simulation [15]. Plecs also allows for custom blocks to be designed using c code [15]. This feature was employed for developing the maximum power point tracking algorithm. The purpose of the simulation was to design each of the converter stages, as well as the required controls and maximum power point tracking. The complete simulation schematic is shown in figure 4-1.

In figure 5, the DC-DC converter includes the panel voltage, panel capacitor, transformer, diode and DC link capacitor. The DC-AC inverter contains 4 IGBT's. The filter is a 7.3 mH inductor was used for the simulation. Using a first order filter simplified the design process, while still sufficiently eliminating the harmonics. The first set of controllers (left most controllers), were used for the maximum power point tracking. A PI controller was used to change the duty cycle sent to the MOSFET. The second set of controllers (right most controllers) controlled the DC-AC inverter stage. The inner control loop employed a PI controller to control the current being injected to the grid. The outer loop ensured that the DC link voltage remained steady at 200 Volts. The PI controllers were tuned to provide optimum results. The final values of components for the DC-DC converter stage are shown in table 4-1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Capacitance</td>
<td>360 uF</td>
</tr>
<tr>
<td>DC Link Capacitance</td>
<td>360 uF</td>
</tr>
<tr>
<td>Transformer Step Up Ratio</td>
<td>1:5 step up ratio, lossless</td>
</tr>
<tr>
<td>MOSFET Characteristics</td>
<td>Ideal MOSFET</td>
</tr>
</tbody>
</table>
Figure 4-1: Complete simulation schematic
The final values of the components for the DC-AC inverter are shown in table 4-2.

Table 4-2: DC-AC Inverter Parameter Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET Characteristics</td>
<td>Ideal MOSFET</td>
</tr>
<tr>
<td>Filter Inductance</td>
<td>7.3 mH</td>
</tr>
</tbody>
</table>

4.2 Simulation Design Process

The simulation was successfully completed after performing 10 iterations of the design. The values of the capacitors were changed to achieve optimum results. The step up ratio of the transformer was also altered. Several different filters were tested. The initial design utilized a third order filter with two series inductors and a shunt capacitor. However, a similar result was achieved using a first order filter. Using the first order filter with one series inductance also helped to simplify the design and parameter calculation process, while also reducing overall cost.

Several design changes were made to the controls. Two different types of controls were tested for the DC-AC current and voltage controls. Hysteresis control was initially used. However, two PI controllers were ultimately selected due to the ability to tune the parameters to change the speed and steady state error of the system. Many iterations of the PI parameters were tested in order to optimize the results. The control design is described in further detail in chapter 7.

4.3 Maximum Power Point Tracking Results- Simulation

The simulation design was able to successfully identify the maximum power point for varying irradiance levels. The output of the maximum power point tracking is shown in figure 4-2.
In figure 4-2, the transition from the green circle to the red circle represents a change in irradiance from 50%-100% of maximum irradiance. To test the maximum power point, several solar panels were connected in parallel and series. The maximum voltage level was 90 Volts. The maximum power point is boxed in red. The maximum power was 240 Watts, and occurred when the voltage was 65 Volts, or approximately 72% of the maximum voltage.

4.4 DC Link Voltage Results- Simulation

The design goal was to produce a DC link voltage of 200 V nominal. This voltage level is sufficiently high to produce a 120 Vrms signal at the output of the DC-AC inverter. The DC link voltage in the plexim simulation was 200 V with a ripple of 4 V, as shown in figure 7. This result met the design specification for the DC link voltage. The DC link voltage starts at 0 volts, immediately climbs to 340 volts and then settles at 200 volts after approximately 0.1 seconds. The results in figure 4-3 were obtained for an input voltage of 65 Volts from the solar panel.
4.5 Output of DC-AC Inverter Stage- Simulation

The current output of the DC-AC inverter stage was sinusoidal, and in phase with the grid voltage, as shown in figure 4-4. The output was the grid voltage (120 Vrms). This matches the design criteria for the DC-AC inverter stage. The results in figure 4-4 were obtained for an input voltage of 65 Volts from the panel. The output current was sinusoidal and in phase with the output voltage, which matched the design specifications.
4.6 Summary of Simulation Results

The simulation was used to validate the DC-DC and DC-AC converter designs. The maximum power point tracking, DC link voltage and output voltage and current criteria were all met. Therefore, the simulation successfully validated the design of the converter stages and the controllers.
Chapter 5- Low Power Physical Testing

After successfully completing design and simulation, the DC-DC and DC-AC converter stages were tested by completing perf board builds. The purpose of these physical builds was to validate the design (and component selection) of each converter stage. The designs were initially tested at low power. The DC-DC and DC-AC converter stages were tested separately. Each stage was also tested with open loop microcontroller code. This section outlines the design process and results from this perf board testing. The testing of both stages was successful and the designs were validated.

5.1 Physical Testing of DC-DC Converter Stage

The DC-DC converter stage was tested on perfboard using a low voltage DC input (5 volts). The low voltage DC input was used instead of the solar panel output, for testing purposes. The output of the DC-DC converter stage was connected to a 138 ohm load, in lieu of the DC-AC converter. The leads were kept as short as possible to minimize parasitic inductance. The schematic used for testing the DC-DC converter stage is shown in figure 5-1.

![Figure 5-1: DC-DC converter stage physical testing schematic](image)

For this stage of the testing, the parameter values for the capacitors and transformer were the same as listed in table 4-1. However, a transformer with a step up ratio of 4.75 was selected. This change was due to the fact that VITEC sponsored a transformer with a step up ratio of 4.75.

The complete setup of the DC-DC converter testing is shown in figure 5-2. This test was used to validate the overall topology. The selected transformer had a step up ratio of 4.75.
The perf board testing was initially completed by driving the MOSFET with a square wave output from a signal generator. Open loop microcontroller code was then used to drive the MOSFET with a constant pulse width modulation. The perf board test validated the design of the DC-DC converter. The 5 Volt DC input voltage produced a 15 Volt DC voltage at the output. The output of the DC-DC converter test is shown in figure 5-3.
The DC-DC converter test also served to validate the functionality of the MOSFETs at the appropriate switching frequency, as shown in figure 5-4.

![Figure 5-4: MOSFET switching signals](image)

### 5.2 Physical Testing of DC-AC Inverter Stage

The DC-AC converter was also tested using perf board, to validate the design, prior to PCB implementation. A DC voltage was connected to the input of the DC-AC converter. The DC voltage source was connected in order to simplify the testing process. The output of the DC-AC converter was measured across a load, in lieu of the grid. The complete setup of the DC-AC converter testing is shown in figure 5-5.

![Figure 5-5: Setup for testing DC-AC inverter stage](image)
The DC-AC converter stage was initially tested using a signal generator, and a NOT gate to drive the MOSFETs, rather than microcontroller programming. This test served to validate the DC-AC converter, prior to introducing the microcontroller programming. The output of the test using the NOT gate is shown in figure 5-6. The test was successful, producing a sinusoidal output of 2 Vp-p as shown in figure 5-6. The output waveform had a frequency of 60 Hz, as was expected.

![Figure 5-6: Output of DC-AC converter using signal generator and NOT Gate](image)

The signal generator and NOT gate were then replaced with the microcontroller controlled digital signals to provide pulse width modulation to the MOSFET’s. This test produced an output with peak to peak voltage of 3.44 Volts and frequency 60 Hz. The perf board test validated both the DC-AC converter design, and the microcontroller code for pulse width modulation. The output of the DC-AC converter is shown in figure 5-7.
5.3 Design of Step Down Circuits

The control blocks in the simulation took their inputs directly from the DC link voltage, panel voltage and grid voltage. However, for the physical design the control blocks were implemented using a microcontroller. The maximum input voltage the microcontroller can accept is 3.3 Volts. Due to this constraint, the microcontroller was unable to directly read in 200 V for the DC link voltage, 50 Volts for the panel voltage or 120 Vrms for the grid voltage. Therefore, step down circuits were implemented to step down these voltages to levels that are within the acceptable range of the microcontroller.

Control circuits were designed for the DC-DC and DC-AC converters to step down measured voltages to levels that are within the acceptable range of the microcontroller. Control circuits were used to step down the solar panel voltage (~50 volts), the DC link voltage (200 volts) and the grid voltage (120 Vrms). These voltages had to be stepped down to values within the range of 0 to 3.3 Volts. The measured currents were also detected using a current sensor.

For the DC voltage signals (panel voltage and DC link voltage), a resistive divider was used to step down the voltage levels to approximately 2 volts. The initial design only included the resistive divider. However, the signal ground (microcontroller ground), and power ground are separate. Therefore, an isolator was also used to provide isolation between the power ground (floating ground) and signal ground (earth ground). The schematic is shown in figure 5-8. Diode clamps were also used for safety, to ensure that the output voltage did not exceed the 3.3 Volts.
(the maximum voltage of the microcontroller).

Figure 5-8: DC voltage step down circuits

The AC voltage control circuit had to scale down, and provide a DC offset, to the AC grid voltage signal. Since the microcontroller was unable to read in negative voltage levels, the DC offset circuit was implemented. The voltage was stepped down from 170 Vp-p to 2.48 Vp-p using a resistive divider. Then, an amplifier was used to provide a 1.65 Volt DC offset to the voltage signal. The design is shown in figure 5-9. As in the DC step down circuits, an isolator (AD202JN) was used to separate the power ground and signal ground.

Figure 5-9: AC step down circuit
The output of testing the AC grid voltage control circuit is shown in figure 5-10.

![Figure 5-10: Output of AC control circuits](image)

As shown in figure 10, the output of the circuit was 2.48 Volts p-p. This is within the acceptable range of the microcontroller of 0-3.3 Volts. Therefore, the control circuits met the specified design criteria.

Step down circuits were also designed for the current controllers. Current sensors were used to detect the DC panel current and the AC grid current. The current sensor for the DC current converted 1 A into a 0.28 V. The AC current sensor converted 1 A rms into 0.64 V. For the AC current, the same DC offset circuit was used to ensure that the signal being sent to the microcontroller was always positive.

The control circuits met all necessary design criteria. The outputs for both the DC step down circuits and the AC step down circuits were within the acceptable range of the microcontroller.

### 5.4 Summary of Physical Builds

Physical builds of the DC-DC converter and DC-AC converter were successfully completed on perf board. These tests validated the design topology and the simulation at low power. Additionally, step down circuits were designed which met the design specifications. After successfully completing the physical tests, a PCB was designed to facilitate high power testing.
Chapter 6- Printed Circuit Board Design

After the design topology was successfully validated using the physical builds, a PCB was developed to facilitate the high power testing. This chapter provides an overview of the power and control circuits on the PCB as well as the design decisions that were made as part of the PCB development process.

The printed circuit board design was completed on Altium Designer [16]. The printed circuit board was used to house the components for both the DC-DC converter and DC-AC inverter. The PCB also included the components for the control step down circuits. A connector was added to provide outputs for the microcontroller. Prior to designing the board layout and traces, a schematic was developed on the Altium Designer software. The schematic was divided into three main sections: the power circuit, the control step down circuits and the output connector.

The power circuit included the DC-DC converter and the DC-AC converter. The DC-DC converter schematic is shown in figure 6-1. The DC link capacitor and the input capacitor values were both 360 µF. Two 180 µF capacitors were placed in parallel to produce 360 µF total. Banana cables were used for the input from the solar panel. A gate driver was used to drive the MOSFET. A custom footprint was developed for the transformer, which had a step up ratio of 4.75. A current sensor was included in the main power circuit, to measure the input panel current.

The DC-AC inverter is shown in figure 6-2. The DC-AC inverter includes four IGBT’s.
(for the full bridge inverter). These IBGT’s are driven by gate drivers and are placed directly next to heat sinks. A 33.7 mH inductor then acts as a filter. The output of the DC-AC converter is connected to banana cable outputs. In the final stage of testing, these banana cable outputs were connected to the grid. A current sensor is included to measure the output grid current. A step down control circuit was also used to step down the grid voltage.

![Figure 6-2: DC-AC PCB schematic](image)

The second main section in the PCB schematic was the control circuits. This includes DC step down circuits and AC step down circuits. The DC step down circuits were used to step down the panel voltage and the DC link voltage to a level under 3.3 volts (the maximum level of the microcontroller). The schematic for the DC step down circuit was the same for the panel voltage and the link voltage, although the resistor values differed. The schematic for the DC step down circuits is shown in figure 6-3. The DC step down circuit includes a resistive divider, followed by an isolator (to isolate the signal ground from the power ground). The isolator had a differential input, and was capable of providing an isolated 7.5 V supply to the circuit if necessary.
The AC step down circuit schematic for the PCB is shown in figure 7.4. The AC circuits served to step down the peak to peak voltage to under 3.3 volts and to provide a 1.65 V DC offset. This ensured that the final output voltage did not exceed the range of 0-3.3 Volts. The circuit includes three stages. The first stage was a resistive divider to reduce the peak to peak voltage. The second stage was an isolator, to separate the signal ground from the power ground. The final stage was a level shifter circuit, which added a DC offset to the signal. The level shifter circuit used an AD820AN amplifier. The offset provided by this circuit was equal to half of the voltage input to R14, as shown in figure 6-4.
The next section of the PCB was the output connector. The output connector is shown in figure 6-5. The output connector was used to receive and send signals to and from the microcontroller. The pulse width modulation pins on the microcontroller are coupled to the “gate” pins, shown in figure 6-5. The SGND pin is the signal (earth) ground. The AC_I, AC_VOL, DC_I, PAVEL_V and DC_LINK pins output the sensed voltage and current levels to the microcontroller.

Figure 6-5: Output connector PCB schematic

The completed PCB schematic is shown in figure 6-6.
6.1 Trace Width Design

The maximum expected current in the power circuit was 10 A. Therefore, the minimum acceptable trace width (accounting for a tolerance in current of 15%) for 1 oz copper with 20°C temperature rise was calculated to be 4.63 mm. To meet this minimum requirement for power circuit, polygons traces were used to supply power. This minimum was met for the core traces in the power circuit. For traces with 5 A of current, the minimum trace width was 1.79 mm. The control circuits carry significantly less current (due to the large values of the step down resistors). The calculations for the trace width are shown in Appendix C.

6.2 Selection of Component Style and Placement of Components

During the PCB design process, attention was paid to the selection of components, and their placement on the board. These design decisions are outlined in this section.

Through hole components were selected, as opposed to surface mount. Through hole components are significantly easier to desolder. This provided the freedom to remove and replace components such as resistors, capacitors and IGBT’s, which simplified the testing process. Custom footprints were designed for several components, including the IGBT’s, power capacitors, transformer, current sensor, isolators, heat sinks, gate drivers, and the inductor. These footprints are shown in appendix D.

Attention was paid to the placement of components relative to each other. The trace lengths were kept as short as possible to minimize the effects of parasitic inductances. Heat sinks were placed directly next to each IGBT/MOSFET to allow proper heat dissipation. Sufficient space was also provided between each IGBT/Heat Sink pair, as well as between the IGBT’s and gate drivers. This was done in an effort to prevent the IGBT’s and gate drivers from overheating.

Two planes of signal ground were placed in both layers to reduce the supplied gate signal noise. Capacitors were placed in parallel with low power inputs to maintain input power to devices. A 15 V supply was used to supply power to the board. Two voltage regulators were used to supply 3.3V and 5V.

Several additional pads were added to the PCB to allow for testing and debugging.

6.3 Selection of Number of Boards

All components and design stages were included on one PCB. One alternative considered was housing the power circuits on one PCB and the control circuits on a second PCB. However, this required transmitting high power signals from one board to another. The design with one PCB also provided a more compact design, with a lower cost.
6.4 Completed PCB

The completed PCB design is shown in figure 6-7.

![Completed PCB Design](image1.png)

**Figure 6-7: Completed PCB Design**

The fully populated PCB is shown in figure 6-8. The DC-DC converter is boxed in red. The DC-AC inverter is boxed in cyan. The DC link capacitor is boxed in green. The control circuits are boxed in pink. The input (panel) is boxed in purple. The output (grid) is boxed in black. The components not included in any of the boxes are the current sensors and the isolators (all blue components).

![Fully populated PCB](image2.png)

**Figure 6-8. Fully populated PCB**
Modifications were made to the PCB after it was received. The inductor value was modified after the PCB design was completed. Therefore the inductor was soldered to perf board, which was subsequently connected to the PCB. Additionally, two of the traces burnt out so external jumpers were added.
Chapter 7- Controls and Microcontroller Programming

Prior to testing the high power design on the PCB, microcontroller code had to be developed to implement the control algorithms. This sections describes the algorithms used to develop the microcontroller code. There were three firmware based controllers used for this project. The first controller was the maximum power point tracking. The second controller was for the DC-AC current control and the third controller was used to regulate the DC link voltage at 200 Volts. A physical circuit was also developed to add dead band time to the pulse edges for the pulse width modulation outputs. All the controller code was developed using blocks in Simulink. The code was then exported to the microcontroller.

7.1 Maximum Power Point Tracking

The irradiance on solar panels changes with the time of day and amount of cloud cover, among other factors. The microcontroller needs to be able to accommodate for these changes and keep the system operating at the maximum power point. Maximum power point tracking code was used to adjust the system parameters to the maximum power point out of the PV panel simulator, and keep the output panel voltage steady at that level. This was accomplished by the microcontroller reading in the panel voltage and current (PANEL_V and DC_I from the PCB connector). The panel power and the panel voltage were then compared to the respective values from the previous time point. The change in power over the change in voltage (dP/dV) was used to determine whether to increase or decrease the voltage. dP/dV was then integrated, which gave an updated voltage reference. The voltage reference was then fed to a PI controller, which output an updated duty cycle for the pulse width modulation. The final parameter set for the PI controller is shown in table 7-1.

Table 7-1: PI Parameters for MPPT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional Gain (Kp)</td>
<td>0.008</td>
</tr>
<tr>
<td>Integral Gain (Ki)</td>
<td>10</td>
</tr>
<tr>
<td>Derivative Gain (Kd)</td>
<td>0</td>
</tr>
</tbody>
</table>

The overall code for the maximum power point tracking is shown in figure 7-1.
Figure 7-1: DC-DC converter close loop code

The detailed MPPT controller block is shown in figure 7-2.

Figure 7-2: MPPT controller block

The detailed flyback gate controller block is shown in figure 7-3.

Figure 7-3: Flyback gate controller block

The above code was tested using the isolated DC-DC converter. The testing procedure is described in section 8.1.

7.2 DC-AC Current Control (inner loop)

The DC-AC converter required two different controllers; hysteresis current control, and link voltage control. This section describes the development of the inner loop hysteresis control. The DC link voltage control is discussed in section 7.4. Hysteresis control was used to regulate
the current sent to the grid, at the output of the DC-AC inverter stage. Hysteresis control, also known as bang-bang control, is a closed loop control method that switches between two limits [17]. Hysteresis control was selected, as opposed to PID control, in order to eliminate the need to tune the parameters of the PID controller. A sine wave acted as the current reference signal in the MCU internally, to compare the I_out and I_ref. The control program used for hysteresis control is shown in figure 7-4. The gate signal output is then sent to the deadband circuit described in section 7.3.

![Figure 7-4: Hysteresis control loop](image)

The hysteresis current control was tested using the DC-AC converter. The testing procedure is described in section 8.2.

### 7.3 Deadband Circuit

The current controller code for the DC-AC inverter required pulse width modulation signals (with varying duty cycles) to be sent to the four IGBT’s. Dead time had to be added to the pulses to ensure that the four IGBT’s were not on simultaneously. A circuit was used to produce the required dead band [18]. The circuit schematic is shown in figure 7-5.

![Figure 7-5: Deadband circuit [18]](image)

A 74LS14 was used for the inverter. The 74LS14 is a Schmitt trigger. The Schmitt trigger
produced sharp edges and was resistant to bouncing on the edges, which helped to produce smooth pulses. The resistor values were 820 Ω and 1 kΩ, and the capacitor values were both 2.7 nF. The different resistor values were required to produce even deadbands on both the rising and the falling edge. These values produced dead time of 1 us on each edge. The results can be seen in the scope trace in Fig 7-6.

![Scope Trace](image)

Figure 7-6. Output of dead time circuit yellow is V1 and the green is V2

In Figure 7-5, Vin was the output from the microcontroller. V1 and V2 were the two output signals, which have dead time between them. V2 is the inverse of V1. This difference is due to the fact that two inverters were used at the output of V1, while only one inverter was used at the output of V2. V1 was then sent to two of the IGBT’s, and V2 were sent to the other two IGBT’s.

7.4 DC Link Voltage Control (outer loop)

A PID controller was used for the DC link voltage control. The DC link voltage was read into the microcontroller, after being stepped down by the circuit described in section 5.3. This voltage level was then compared to the scaled reference level of 200 V. The difference was fed into a PID controller. The schematic is shown in figure 7-7.
The PI parameters are shown in table 7-2.

Table 7-2: Parameters for PI controller in outer loop DC link voltage control

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional Gain</td>
<td>0.35</td>
</tr>
<tr>
<td>Integral Gain</td>
<td>1</td>
</tr>
</tbody>
</table>

This code was tested using the procedure outlined in section 8.4.
Chapter 8- Integration of Subsystems

This chapter discusses the procedures that were used to test the PCB (described in chapter 6) in conjunction with the microcontroller code (described in chapter 7). The integration of subsystems was broken down into four main stages: testing the DC-DC converter with maximum power point tracking, testing the DC-AC converter with open loop controls, testing the DC-AC converter with current control, and testing the DC-AC converter with DC link control. These tests are described in this chapter.

8.1 DC-DC Converter with Maximum Power Point Tracking

For this test, the DC-DC converter was tested with the maximum power point tracking microcontroller code. The DC-DC converter components (including the input capacitor, transformer, MOSFET, diode and link capacitor) were soldered to the PCB. In order to test the DC-DC converter in isolation from the DC-AC inverter, a 200 ohm load was connected in parallel with the DC link capacitors. A PV simulator was connected to the input of the DC-DC converter. This testing setup is shown in the block diagram in figure 8-1.

Figure 8-1: Block diagram for DC-DC converter test with MPPT

The complete system setup is shown in figure 8-2. The load is boxed in green. The DC-DC converter is boxed in pink. The PV simulator is boxed in blue and the DC link voltage is boxed in yellow.
The final set of parameters used for the PI controller are shown in table 5. The D controller was not used.

Table 8-1: PI parameters in Simulink for maximum power point tracking

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional Gain</td>
<td>0.08</td>
</tr>
<tr>
<td>Integral Gain</td>
<td>10</td>
</tr>
</tbody>
</table>

The maximum power point tracking was tested for irradiance levels ranging from 50%-100% of maximum irradiance. The output plots of the maximum power point tracking is shown in figure 8-3. The three data points represent irradiance levels of 50%, 75% and 100% of maximum irradiance. The maximum voltage in this case was 28 Volts. The voltage at the maximum power point was approximately 75% of the maximum voltage, which is consistent with the expected voltage level at the maximum power point.

Figure 8-2: Setup for DC-DC converter test with maximum power point tracking
This testing stage verified that the design requirement for maximum power point tracking was successfully met. This test was also used to calculate the efficiency of the DC-DC converter stage, which was 91%.

A simulation was completed in Matlab which utilized the diode equation to model the solar panel emulator. The parameters in the diode equation were estimated based on the characteristics measured from the PV emulator. The Matlab code is shown in Appendix E. The simulated PV curves for irradiance levels of 100%, 75% and 50% are shown in figure 8-4.
The measured and simulated maximum powers (and their accompanying voltage level) for each irradiance level are summarized in table 8-2. The average percent difference between the measured and simulated maximum powers was 3.4%. The average percent difference between the voltage levels at the maximum powers was 7.6%. Some sources of discrepancies are likely due to limitations of the model that was used to represent the solar panel, and as well as the measurement equipment.

Table 8-2: Differences in measured and simulated maximum power

<table>
<thead>
<tr>
<th>Irradiance Level (%)</th>
<th>Measured Maximum Power (W)</th>
<th>Simulated Maximum Power (W)</th>
<th>Percent Difference (Power)</th>
<th>Measured Voltage at Max Power (V)</th>
<th>Simulated Voltage at Max Power (V)</th>
<th>Percent Difference (Voltage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>21.61</td>
<td>21.90</td>
<td>1.33%</td>
<td>24.00</td>
<td>23.61</td>
<td>1.64%</td>
</tr>
<tr>
<td>75</td>
<td>15.10</td>
<td>16.4</td>
<td>8.25%</td>
<td>22.50</td>
<td>23.04</td>
<td>2.37%</td>
</tr>
<tr>
<td>50</td>
<td>8.50</td>
<td>8.54</td>
<td>0.47%</td>
<td>18.19</td>
<td>22.00</td>
<td>18.95%</td>
</tr>
</tbody>
</table>

The close match between the measured maximum power points and the simulated PV curves indicates that the maximum power point tracking algorithm was successful.

8.2 DC-AC Converter with Open Loop Controls

After completing testing of the DC-DC converter with closed loop controls (for maximum power point tracking), the DC-AC inverter was tested with open loop controls. The open loop code provided a sinusoidal pulse width modulated signal to the four MOSFET’s in the full bridge inverter. This test served two functions. The first purpose was to verify functionality of the DC-AC converter at high power. The second function was to test the filter. For this test the diode connecting the DC-DC converter to the DC-AC inverter was removed (to isolate the DC-AC stage). The input (DC link voltage) to the DC-AC inverter was 200 Volts, and the output was connected to a 230 ohm load. This testing setup is shown in figure 8-4.
The initial test with MOSFET’s resulted in the MOSFET’s overheating. Therefore, the MOSFET’s were replaced with IGBT’s, which have a reverse diode. The IGBT’s had the same pin out as the MOSFET’s and could be driven using the same gate drivers. This simplified the replacement process. The filter was also changed to a third order filter, instead of a first order filter. The third order filter used two series inductors and a shunt capacitor. The final parameters for the filter are shown in table 8-3.

Table 8-3: Output filter parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Series Inductor</td>
<td>1 mH</td>
</tr>
<tr>
<td>Shunt Capacitor</td>
<td>2.2 uF</td>
</tr>
<tr>
<td>Second Series Inductor</td>
<td>1 mH</td>
</tr>
</tbody>
</table>

With a 200 Volt DC input, the output voltage (measured across the 230 ohm load) was 330 volts peak-peak, as shown in figure 20. 330 volts peak to peak is equivalent to 116 volts rms, as shown in figure 8-6. This falls within the acceptable range of 120 Vrms ± 5% (the range is 112 Vrms – 126 Vrms). The output voltage specification was met.
The output current was sinusoidal, as shown in figure 8-7. The spikes in the figure are most likely due to the current sensor that was used to acquire the measurement, and not due to the actual current value.

This test successfully met two design specifications: output voltage level, and sinusoidal output current. Additionally, the frequency is 62 Hz. This matches the required output frequency of approximately 60 Hz.

This test was also used to test the maximum power and the efficiency of the DC-AC inverter stage. For the efficiency test, the input voltage and current are shown in figure 8-8. The input power was 178.4 Watts.
The output voltage and current are shown in figure 8-9.

As seen from figure 8-9 the output voltage was 114 Vrms, and the output current was 1.46 A rms (note that the probe had 10x magnification). Therefore, the output power was 166.44 Watts. This measurement met the design specification for maximum power over 100 W. The efficiency was 93%. Combined with the DC-DC efficiency of 91%, this resulted in an overall efficiency of 93%. Combined with the DC-DC efficiency of 91%, this resulted in an overall...
efficiency of 85% which met the design specification of efficiency over 80%.

8.3 DC-AC Converter with Closed Loop Current Control

After testing the DC-AC Inverter with open loop controls, it was tested with closed loop hysteresis controls. The goal of the hysteresis control loop was to ensure that the current injected to the grid was sinusoidal. The hysteresis control loop was tested by connecting a 200 V DC source to the input of the DC-AC converter. A 200 ohm resistor was connected to the output of the load, rather than the grid. In this stage, the Hysteresis control for the DC-AC inverter stage was implemented and tested. The setup is shown in figure 8-10.

![Diagram of DC-AC Converter with Closed Loop Current Control](image)

Figure 8-10: AC current control testing setup

An external 1.65V DC was provided to bias the output current signal from the AC current sensor (the current sensor output a voltage sine wave). Therefore, the output signal was always in the range of 0-3.3V. In order to ensure that the output current was always the same as the reference signal, the output of the relay was the gate signals being sent to the IGBTs. The system was tested with a range of input voltages from 20 Volts to 200 Volts. The system produces a sinusoidal output current for input voltages ranging from 60 Volts- 200 Volts. This is due to the fact that the delta I is fixed, and if the current is not big enough, the control was not accurate. However the target value for the DC link voltage was 200 Volts, so this test met all necessary design specifications. The output current was measured using a current sensor, for input DC link voltages ranging from 60 Volts to 200 Volts. The output current for a DC link voltage of 120 Volts is shown in figure 8-11. The output current is shown in blue, and was 2.1 A peak-peak. The output voltage is shown in green and was 104.7 V peak-peak. As is seen in the image, the output current is a regulated sinusoid. This test indicated that the current controller was functioning properly. The goal of the controller was to produce a sinusoidal current, that is in phase with the
output voltage. Both of these criteria are met. Therefore, this test successfully met the output current control design requirement.

Figure 8-11: Output for testing grid current control

### 8.4 DC Link Voltage Regulation and Grid Connection

The final stage of testing was regulating the DC link voltage. For this stage of testing, a 200 ohm load was applied to the input of the DC-AC converter (the DC link voltage was then measured across the load). The grid was connected to the output of the DC-AC inverter. The current control code and the DC link voltage control code were then applied to the DC-AC converter. The purpose of this test was to ensure that the outer loop DC-AC controls successfully regulated the DC link voltage. The complete setup for this test is shown in figure 8-12. The load is boxed in purple, the DC-AC converter is boxed in blue and the grid voltage is boxed in green. The microcontroller is not shown in the photo.
The DC link voltage controller was able to regulate the voltage at 15 Volts. The output from this test is shown in figure 8-13. In this figure, the green waveform is the DC link voltage which is stable at 15 V nominal.

This test validated the algorithm used for testing the DC link voltage control at low voltage levels. This test also demonstrated that the microinverter can be successfully connected to the grid. The integrated control system was not tested. However, all design requirements were met through the subsystem tests.
# Chapter 9- Summary of Results and Conclusions

## 9.1 Summary of Design Specifications

The final design results are shown in table 9-1.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Target Value</th>
<th>Actual Results</th>
<th>Specification Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>100 W or more</td>
<td>166 W</td>
<td>Yes (exceeded)</td>
</tr>
<tr>
<td>Minimum Power</td>
<td>50 W or less</td>
<td>18 W</td>
<td>Yes (exceeded)</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-30°C to 50°C (operating temperature range for components)</td>
<td>All components have operating temperatures in range of -40°C to 85°C (Appendix F)</td>
<td>Yes (exceeded)</td>
</tr>
<tr>
<td>Maximum Power Point Tracking</td>
<td>Extract maximum output power from the solar panel at different sunlight and temperature conditions</td>
<td>Implemented using microcontroller</td>
<td>Yes</td>
</tr>
<tr>
<td>DC Voltage Step Down</td>
<td>Output Voltage&lt; 3.3 V</td>
<td>Max output voltage of 2 V</td>
<td>Yes</td>
</tr>
<tr>
<td>AC Voltage Step Down</td>
<td>Output Voltage &lt; 3.3 Vp-p</td>
<td>Max output voltage of 2.4 V p-p</td>
<td>Yes</td>
</tr>
<tr>
<td>Voltage Requirements</td>
<td>DC link voltage</td>
<td>The nominal value of the voltage link the DC-DC and DC-AC stage will be 200 V</td>
<td>200 V with open loop controls</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>120 Vrms +/-5% at 60Hz</td>
<td>116 Vrms (120 Vrms – 3.3%)</td>
<td>Yes (exceeded)</td>
</tr>
<tr>
<td>Current Control</td>
<td>Grid current must be sinusoidal and in phase with grid voltage</td>
<td>Sinusoidal and in phase with grid voltage</td>
<td>Yes (exceeded)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Average efficiency of &gt;80%</td>
<td>DC-DC efficiency= 91% DC-AC efficiency = 93% Overall efficiency= 85%</td>
<td>Yes (exceeded)</td>
</tr>
</tbody>
</table>
9.2 Added Value Features

This project had several added value features not included in the original design specifications. The original design required two PCB’s: one for the power circuit and one for the control circuit. The final design used only one PCB, which housed both the power and control circuits. This added feature reduced the size of the microcontroller, while also decreasing the production cost. Another value added feature was testing the complete design with a PV simulator. The original plan was to use an input DC voltage source. In addition to designing the main power circuit (DC-DC converter, DC-AC inverter) and the controls circuits, a circuit for adding dead time was also designed, which can be applied to future projects.

9.3 Future Work

Several possible expansions for the projects were identified. Testing of the microinverter was completed by connecting a PV simulator to the input of the DC-DC converter. The complete microinverter design could also be tested using a physical solar panel. Several potential improvements were also identified for the overall system. Additionally, a protective case could be designed for the microinverter. This would be useful if the inverter was being used outside, where it would be exposed to elements such as snow, rain and extreme temperatures.

9.4 Conclusion

All design specifications, except for efficiency, were successfully achieved in both simulation, and physical testing with a PCB and microcontroller code. The maximum and minimum power were within the acceptable ranges, the maximum power point tracking was successful, and the output voltage and current requirements were met. Additionally, all core components had operating temperatures within the acceptable range. Several added value features were also included in the design. The final project deliverables were a complete set of microcontroller code and a fully populated PCB.
Bibliography

Appendix A- Complete Team Budget

The completed team budget is shown in table A-1.

Table A-1: Final budget

<table>
<thead>
<tr>
<th>Hardware</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Items Name</td>
<td>Parts Number</td>
<td>Supplier</td>
<td>Sponsor</td>
<td>Number of Unit</td>
<td>Cost per Unit</td>
<td>Amount</td>
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<td>Op-Amps</td>
<td>AD820ANZ-ND</td>
<td>Digikey</td>
<td>ECE</td>
<td>2</td>
<td>7.51</td>
<td>15.02</td>
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<tr>
<td>Diode Arrays</td>
<td>568-1614-1-ND</td>
<td>Digikey</td>
<td>ECE</td>
<td>17</td>
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<td>4.42</td>
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<td>Heat Sink</td>
<td>HS403-ND</td>
<td>Digikey</td>
<td>ECE</td>
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<tr>
<td>Pin Connector</td>
<td>56106-ND</td>
<td>Digikey</td>
<td>ECE</td>
<td>3</td>
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<td>6.66</td>
</tr>
<tr>
<td>DC/DC Converter</td>
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<td>Digikey</td>
<td>ECE</td>
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<td>10.94</td>
<td>32.82</td>
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<td>Prototyping board</td>
<td>V1021-ND</td>
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<td>DC Capacitor</td>
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<td>Current Sensor</td>
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<td>G10</td>
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<td>Dr. Ho</td>
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<tr>
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<td>TLP350F-ND</td>
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<td>Microcontroller</td>
<td>Concerto F28M35x</td>
<td>TI</td>
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<td>N/A</td>
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<td>Magnetic Core</td>
<td>AMCC 10</td>
<td>N/A</td>
<td>Dr. Ho</td>
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<td>N/A</td>
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<td>Flyback Transformers</td>
<td>58PR6962</td>
<td>VITEC</td>
<td>VITEC</td>
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<td>Other Small Components</td>
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<table>
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<td>460.40</td>
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<td>Budget Spent Before Taxes</td>
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<td>GST (5%)</td>
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<td>PST (8%)</td>
<td>28.32</td>
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<td>Total Team Budget</td>
<td>399.95</td>
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</table>

Note:

1. The microcontroller and magnetic core were borrowed from Dr. Carl Ho. They will be returned after the project presentation.
2. The Flyback transformer (58PR6962) was sponsored by VITEC Electronics Corporation.
3. Other small components, such as wires, connectors, and low power passive components were provided by the tech shop.
Appendix B- Inductor Design

It was difficult to find an inductor with the specifications required for this inverter. Therefore, an inductor was custom made. The design procedure is included in this appendix.

The selected magnetic core was AMCC 10, which has a high current saturation limit and a relatively small size. The wire type was AWG 16. This wire was selected because of its’ high current carrying ability and small cross section area. The data sheet for AMCC10 is shown in figure B-1.

![Figure B-1: Data sheet of AMCC10](image)

The specifications for AWG 16 are shown in table B-1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>1.291mm</td>
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<tr>
<td>Cross Section Area</td>
<td>1.31 mm²</td>
</tr>
<tr>
<td>Resistance per length</td>
<td>13.17 mΩ per meter</td>
</tr>
</tbody>
</table>

The required design specifications are shown in table B-2.
**Table B-2: Required inductor design specifications**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>4mH</td>
</tr>
<tr>
<td>Frequency</td>
<td>20kHz</td>
</tr>
<tr>
<td>Designed Current</td>
<td>2A</td>
</tr>
<tr>
<td>Current Ripple</td>
<td>25%</td>
</tr>
<tr>
<td>Turns</td>
<td>Less than 150 turns</td>
</tr>
<tr>
<td>Filling Factor</td>
<td>Slightly less than 0.4</td>
</tr>
<tr>
<td>Loss</td>
<td>Under 5W under maximum current condition</td>
</tr>
</tbody>
</table>

The calculations used to determine the inductor parameters are shown below.

*Mean Turn Length* = \(2 \times (a + d + 2b) = 0.114\ m\) \[1\]

\[\Delta I = \sqrt{2} \times I_{max} \times \text{Current Ripple} = 0.707\ A\] \[2\]

Choose the length of airgap being 1mm, the number of turns, N, can be calculated as:

\[N = \frac{\text{Airgap Length} \times L}{4\pi \times 10^{-7} \times a \times d} = 120\ \text{turns}\] \[3\]

The filling factor

\[K_{cu} = \frac{N}{\text{Cross Section Area of the Wire} \times W_a} = 0.303\] \[4\]

The flux density is given by:

\[B_{ac} = \frac{4\pi \times 10^{-7} \times N \times \Delta I}{\text{Airgap Length}}\] \[5\]

The maximum core loss is:

\[P_{core} = 6.5 \times f^{1.51} \times B_{ac}^{1.74} \times \text{Weight of the Core} = 2.448 W\] \[6\]

The maximum copper loss is:

\[P_{cu} = f^2 \times MTL \times N \times \text{Resistance per Meter} = 0.722 W\] \[7\]

Maximum power loss is:

\[P_{loss} = P_{core} + P_{cu} = 3.17 W\] \[8\]
The actual inductance produced was 3.7 mH, the power loss of the inductor was 3.17W under the worst condition, and the filling factor is about 0.303 which is close to the standard value of 0.4.
Appendix C- Calculation of Trace Width

The calculations for the trace width are shown in figure C-1.

Figure C-1: Trace width calculation [18]
Appendix D- Custom PCB Footprints

Several components used in the design did not have available footprints and schematics in the Altium library. Several of the custom component footprints and schematics are shown in this appendix.

The current sensor used in the design was 398-1007-ND. It had nine pins with 0.7mm pin width. The component had dimensions of 14.93x33.2. The current sensor footprint design and schematic design are shown in figure D-1.

![Figure D-1 : Current sensor footprint and schematic](image1)

The flyback transformer used in the design had 3.57mm diameter pins on the low voltage side. As a result, larger holes with pads were selected for the design of the footprint. The transformer footprint and schematic are shown in figure D-3.

![Figure D-3 : Flyback transformer footprint](image2)

The flyback transformer used in the design had 3.57mm diameter pins on the low voltage side. As a result, larger holes with pads were selected for the design of the footprint. The transformer footprint and schematic are shown in figure D-3.

The flyback transformer used in the design had 3.57mm diameter pins on the low voltage side. As a result, larger holes with pads were selected for the design of the footprint. The transformer footprint and schematic are shown in figure D-3.
The gate drivers in the design were custom built gate drivers. Measurements were taken with a ruler to measure pin diameters and the space between them. The gate drivers were mounted vertically. The gate driver schematic and footprint are shown in figure D-4.

Two different isolators were used in the design. Both of them had different pin maps and footprints. As a result, two sets of Altium footprints and schematics were designed. The isolator footprints and schematics are shown in figure D-5.
Five heat sinks were used in the design. The heat sink footprint was designed in Altium. The size of the heat sinks were selected to fit around the IGBT footprint. The heat sinks were selected to match the outer dimensions of the IGBT. The heat sink footprint is shown in figure D-6.
Appendix E- Simulated PV Curves

The code used to simulate PV curves are shown in figure E-1.

```matlab
close all
clear all
clc

r = 1.3;
Iphoto = 1;
Io=(2e-9);
%W = 24.54;
n = 55;
vt = 0.026;

I = 0:0.00001:0.999999
V = (n+vt*log((Iphoto-I)/(Io))) - (I*r)
plot (V,I)

r = 1.3;
Iphoto = 0.75;
Io=(2e-9);
%W = 24.54;
n = 55;
vt = 0.026;
hold on
I2 = 0:0.00001:0.7499999
V2 = (n+vt*log((Iphoto-I2)/(Io))) - (I2*r)
plot (V2,I2)

r = 1.3;
Iphoto = 0.4;
Io=(2e-9);
%W = 24.54;
n = 55;
vt = 0.026;
hold on
I3 = 0:0.00001:0.39999999999
V3 = (n+vt*log((Iphoto-I3)/(Io))) - (I3*r)
plot (V3,I3)

figure (2)
P = I.*V
plot (V,P)
hold on
P2 = I2.*V2
plot (V2,P2)
hold on
P3 = I3.*V3
plot (V3,P3)
axis([0 30 0 25])
xlabel('Voltage(V)')
ylabel('Power(W)')
```

Figure E-1: Code to simulate PV curves at varying irradiance levels
Appendix F- Operating Temperatures of Components

The design specification was to have an operating temperature range for the core components in the main power circuit of -30 degrees Celsius to 50 degrees Celsius. Table F-1 summarizes the operating temperature ranges for each component in the main power circuit. All components have an operating range of at least -40 to 80 degrees Celsius.

Table F-1: Operating range of core components

<table>
<thead>
<tr>
<th>Component</th>
<th>Minimum Temperature (degrees Celsius)</th>
<th>Maximum Temperature (degrees Celsius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>-40</td>
<td>125</td>
</tr>
<tr>
<td>DC Link Capacitor</td>
<td>-40</td>
<td>85</td>
</tr>
<tr>
<td>Diode</td>
<td>Not specified</td>
<td>225</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Not specified</td>
<td>260</td>
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<tr>
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<td>-55</td>
<td>150</td>
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