Electrical Engineering Department

California Polytechnic State University

Senior Project Final Report

eWall Inverter

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Alexandro Lopez

Andrew Tsau

Professor Art MacCarley

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Abstract

The objective of this project is to demonstrate the capabilities of a Raspberry Pi when used as a grid-tied, bi-directional power inverter for renewable energy storage applications. Due to its economical nature, this system would play a large role in the growing solar industry by making solar energy more accessible, affordable, and easier to install. The inverter uses a single-phase H-Bridge to generate a sine wave from a proprietary wall mounted battery. To improve power quality, an enhanced low pass filter is added to provide a better drop off to reduce extraneous harmonics. The system synchronizes this synthetic sine wave output with the incoming grid frequency through a PID that controls a Phase Locked Loop (PLL). However, the Raspberry Pi proved incapable of this task due to being unable to power the drivers to run the switching circuit.

Chapter 1 Introduction

Harnessing the sun's power is not a new concept. Early civilizations have used it extensively- some even worshiping it for all the benefits it provided and for good reason too- it serves as the catalyst for almost every sort of organism here on earth. Today, it serves another purpose- to be a source of renewable electrical energy. Just through the last decade, Solar power has seen a meteoric rise - a new solar systems are installed every twenty seconds. However, one of the biggest flaws with solar is its inability to produce energy when there is no sunlight available. These include the unavoidable downtime of night as well as other more conditional factors such as cloudy days. Thus, having a 100% solar only economy is highly impractical. There must be other ways to supplement it. One of these solutions is to use a battery to store the charge provided by the sun and use it when the sun is not available. In the solar industry, this setup is called the grid assist system. During the day, the battery charges from the sun. It then uses the battery during peak usage hours on the grid in order to decrease the load on the grid [1], as well as save money by sending the excess energy back to the grid. This system is particularly useful in conserving the environment due to this battery factor. In addition to lower amounts of energy loss, through not needing to transfer the energy through long distances, the battery itself can be used for another key part of the renewable energy cause- powering an electric vehicle. Currently electric vehicles have one large environmental flaw. The generation of power that typically powers it (in the U.S. it is coal), generates much more pollution than what a standard gasoline car would. This makes this option even better when decreasing the footprint of renewable technologies as it would eliminate the coal factor that was used to generate that electrical energy in the first place. Thus, this is where our product comes in- to create an inverter that will take in power either from solar panels during the day, or the grid during the night, and allow it to charge a battery, which would then be used to charge an electric vehicle.

Chapter 2 Background

Currently, most standard grid tied inverters work in a single way- they convert the DC power from solar panels into an AC sine wave and then synchronize that with the grid [2]. However, with the rise of residential solar, the traditional setup of generation to load is no longer suitable as this would cause fluctuations on the grid due to overgeneration from these sources. This setup upgrades this current inverter system by making it bidirectional. A bidirectional inverter would accept AC and DC (either from the grid or solar panels) and output an AC voltage, which leads to a host of customizability options. Having an all in one system would mean that it would be easier to set up while giving the user the option for energy storage.

In addition to serving as an excellent backup power system, a battery allows for a more stable grid by reducing fluctuations especially if used in conjunction with smart grid technology as it provides a load for overgeneration issues. In our case, the main purpose of this battery is to charge an electric car and, in emergency scenarios, rerouted to critical loads within the house as shown in Figure 2-1.

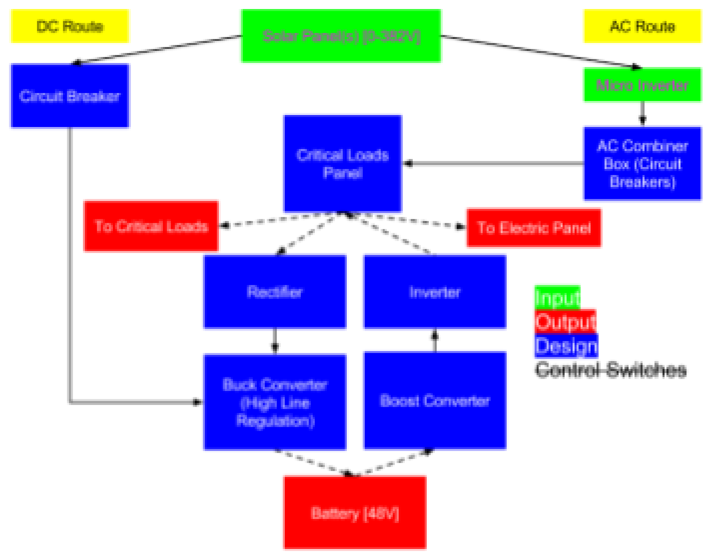

Figure 2-1: General Block Diagram

However, the biggest issue is that a standard residential inverter, nevermind bidirectional, is still quite expensive. By reducing this cost, we can allow the system to be more accessible to everyone. With this in mind, we decided to use a popular hobbyist microcontroller: the Raspberry Pi, which goes for around $35 to be the controller for our project. The Raspberry Pi is essentially a small computer which runs an entire operating system. Using this will allow us to control everything from switching signals, running the PID control, to creating a GUI for system monitoring, all within one device if it is successful. Our goal is to attempt to replicate this bidirectional inverter system using the Raspberry Pi.

Chapter 3 Design Requirements

The block diagram for our grid-tied power inverter is shown in Figure 3-1

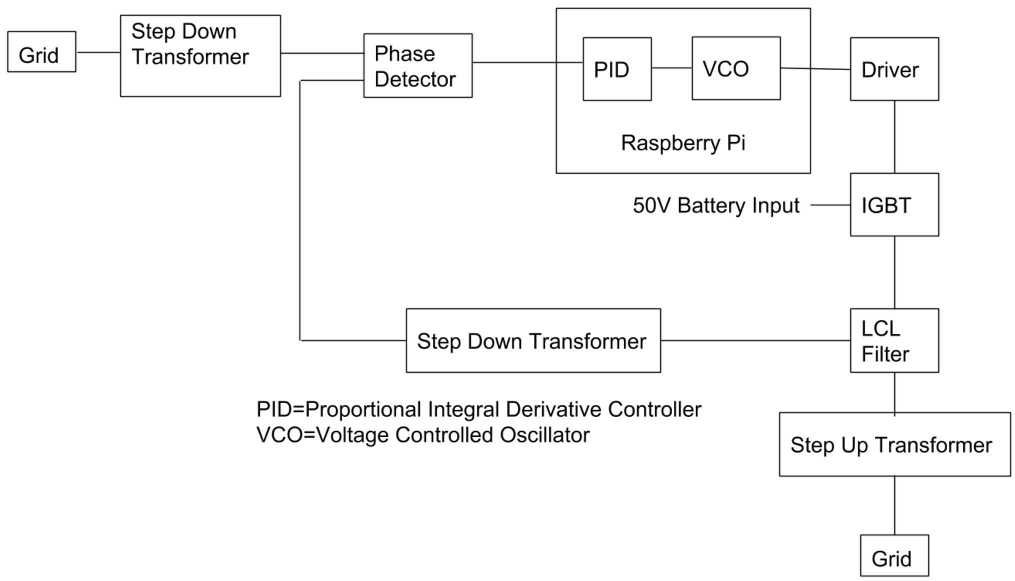

Figure 3-1: General Block Diagram of the Inverter System

In order to achieve grid synchronization, a phase locked loop is needed to measure the phase of the grid and correct our synthetic wave to match the incoming sine wave. The above figure is the general diagram of our phase locked loop composed of a phase detector, a voltage controlled oscillator (VCO), and a low pass (LCL) filter. According to the IEEE article on grid synchronization, a 1 degree phase lead is needed to ensure power flow from the inverter end to the grid, which is accounted for inside our controller [3]. This is also illustrated by the active Power Flow Equation

$$P = \frac{Vo*Vgrid}{X} sin(\theta_0 - \theta_{grid})$$

Vo= Inverter Output Voltage, Vgrid = Grid Output Voltage, X = Line Impedance, θ_0 = Angle of Inverter wave, θ_{grid} = Angle of the grid wave

The Raspberry Pi is the controller of the system serving as the Proportional Integral and Derivative Controller (PID) and a virtual VCO sine wave reference. The phase detector compares the grid and synthetic wave and outputs the serial data into the Raspberry Pi. The Raspberry Pi then reads the data and ,through a PID, is able to accurately measure the error signal and adjust the VCO pulse width modulation switching frequency to match the grid frequency.

The IGBT array is rated to handle a 50VDC battery input and the gate driving voltage is set to 12V for the required current level of 65A. To achieve the necessary 12V, the gpio pins on the Raspberry Pi output a voltage of 3.3V thus allowing for a boost step up DC-DC converter to obtain the needed gate voltage. The phase detector is required to read frequencies at around the 60 Hz in order to properly compare both sine waves.

Chapter 4 Design and Simulation Results

4.1 Raspberry Pi

The microcontroller we have decided to go with is the Raspberry Pi 3 model B due to its low cost and adaptability. The processor speed of the Raspberry Pi is at 1.2GHz which is more than enough speed to handle the PWM, PID, and the VCO controls [4]. We installed the Wiring Pi library to run the PWM signal for our switching. We chose Wiring Pi due to the large amount of documentation and reviews.

Figure 4-1: Raspberry Pi set up

We also used software to create a PID controller within an interrupt service routine (ISR). This interrupt would trigger every three microseconds and estimate what output frequency the Pi should produce given the phase difference from the grid. It then adjusts the internal sine wave reference through a predetermined 60 Hz reference sine wave table. This is done by “skipping” the next values in the table proportional to the phase difference. It will always skip the three microseconds worth of values within the table to account for differences in time between the ISRs. However, the precise number of values it skips would change based on how far off the grid frequency is. If it is slower than the 60 Hz, this “skip” would decrease, allowing more values to be expressed within the sine wave in each cycle. Thus this would decrease the frequency. The faster the frequency required, the larger this “skip”, allowing for a larger change in the sine wave values, thus increasing the frequency. Although doing this would decrease the resolution, our reference table already has a relatively high number of points (~2000). Any sort of reasonable “skips” would not affect this as much. When the frequency deviation is too high in either direction (or zero in the event of a blackout), we also have the advantage of shutting the connections to the grid down completely and using the unaltered internal sine wave table to continually power to the house.

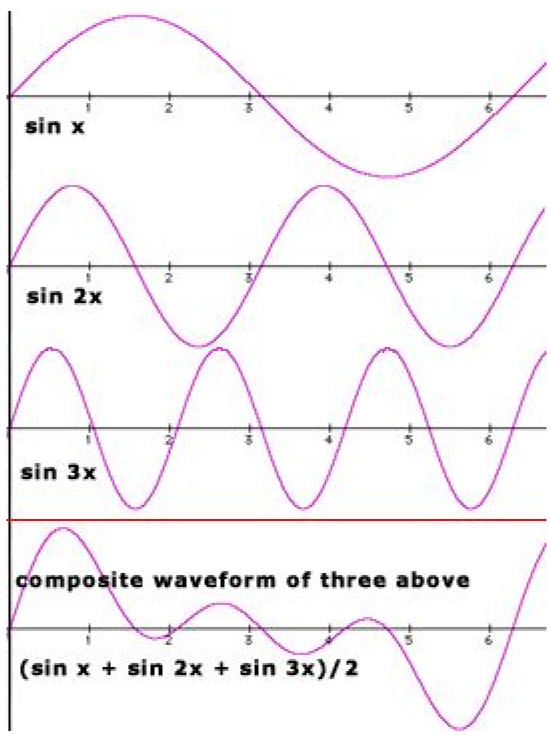

Figure 4-2: Varying Sine Wave Frequency Representation [5]

4.2 Boost Converter

This will boost up the output voltage of the 5V pin on the Raspberry Pi to around 12V which is enough to turn on IGBT to the required voltage level. The boost converter we have chosen is the LT1303 Step up DC-DC converter which uses a feedback pin that will allow us to adjust the output voltage simply through changing two resistors. We tested this boost converter using the following values as shown in Figure 4-3. The corresponding output voltage waveform is shown in Figure 4-4.

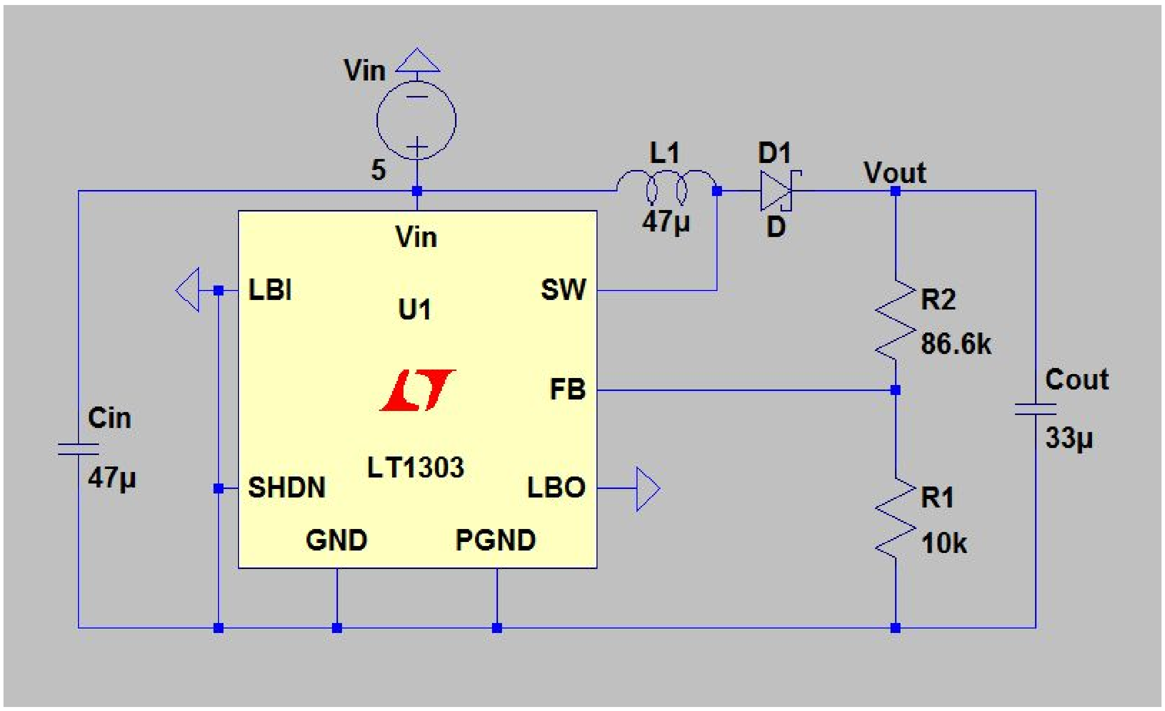

Figure 4-3: Boost Converter Schematic

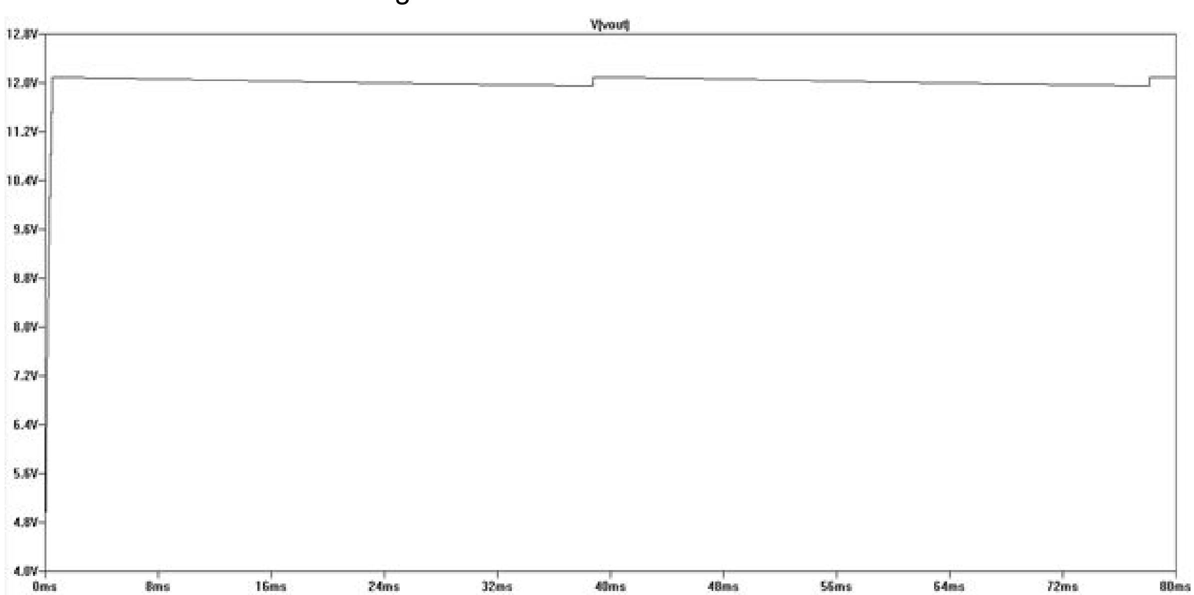

Figure 4-4: Boost Converter Output Waveform

4.3 Driver (IRS2186)

These will mirror the 3.3V PWM of the Raspberry Pi and run it at a higher 12V PWM voltage with very little propagation delay as shown in Figure 5-6. Each driver contains a high (HI) and low (LO) side driving circuit. These, when turned on, will maintain the required output voltage of 12V, provided by the boost converter, across the gate and source in each of the IGBTs in the array as shown in Figure 4-5. This is especially important for the HI side as the source voltage will change as the IGBT turns on. The gate to source voltage must maintain its 12V for proper operation. In our system, we tied the high (HIN) and low (LIN) low inputs together to synchronize the two outputs. This way, with a single control signal, we can control two opposing legs of the IGBTs at once as shown in Figure 4-6.

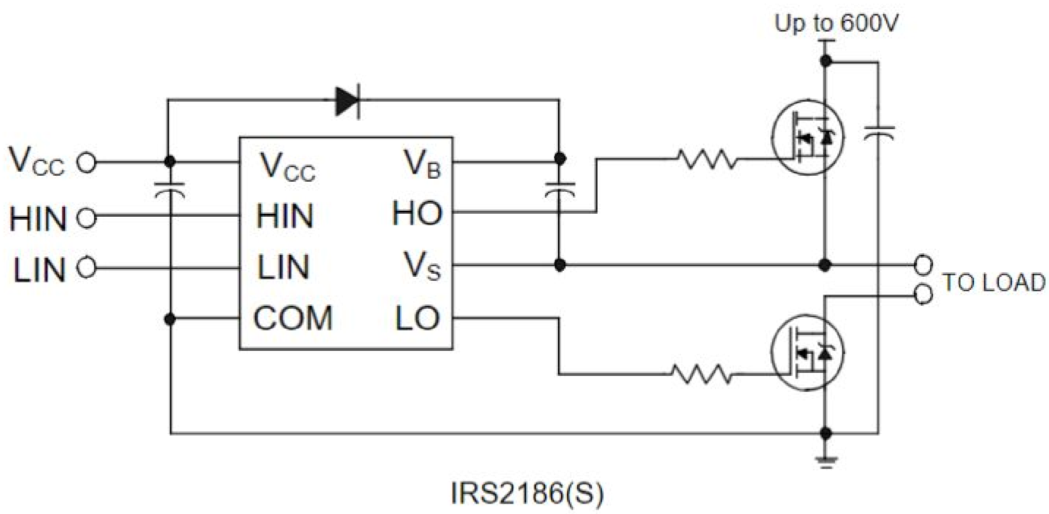

Figure 4-5: Driver Circuit connected to switches

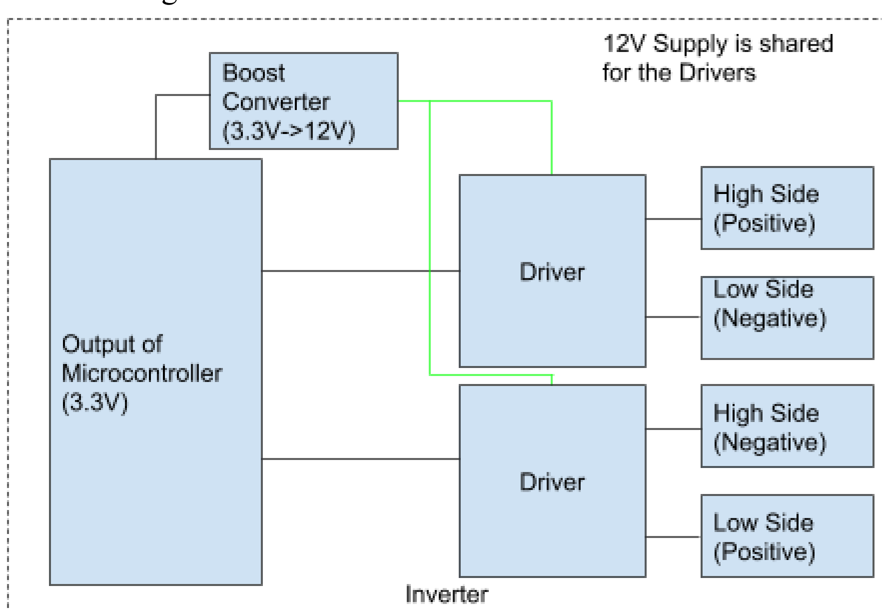

Figure 4-6: Block diagram of Microcontroller-Drivers-IGBT

4.4 IGBT

The switching array or more specifically, the Insulated Gate Bipolar Transistor (IGBT) array that we used is the Microsemi APTGT75H60T1G. IGBTs are the power devices that will be connected to the battery and actually generate the square wave in a unipolar switching topology as shown in Figure 4-8. We chose this topology because it provides a good balance between generating a decent sine wave and providing a lower cost due to less components required. The two drivers in section 4.3 will be connected to Q1/Q4, and Q3/Q2 respectively as shown in Figure 4-7. We intend on using a better output filter to attenuate the additional harmonics as result of using this topology.

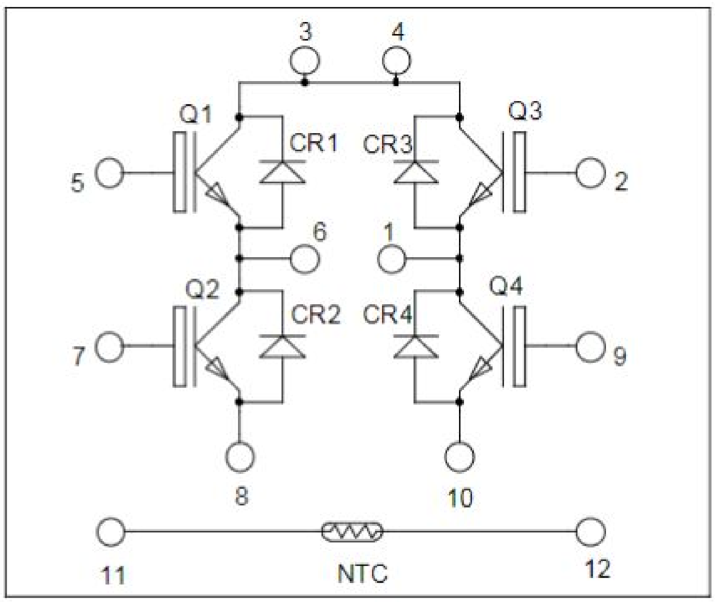

Figure 4-7: Internal diagram for the IGBT Array

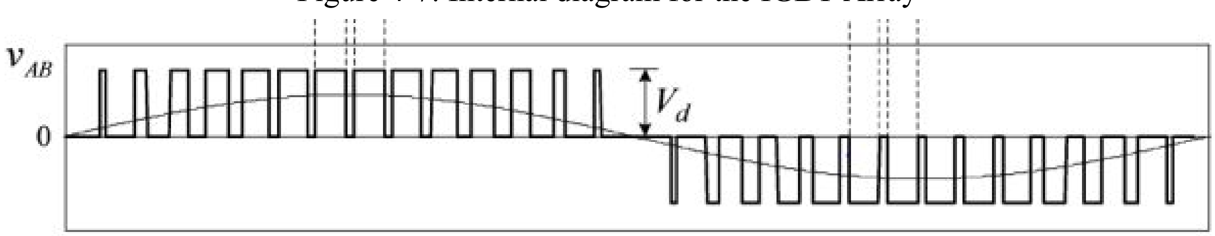

Figure 4-8: Unipolar Switching

4.5 LCL Filter

Lastly, we need a filter to filter out the higher frequency output of the Square Wave.
We decided to use an LCL low pass filter for this purpose due to the high attenuation (60db/dec) above its resonant frequency as shown in Figure 4-9 [6]. We also decided to double up the filter in order to maintain the same impedance on both the positive and negative cycle while providing better current ripple reduction as shown in Figure 4-10. The resistor on each of the bridges is used to dampen the filter and reduce the gain around the cutoff frequency.

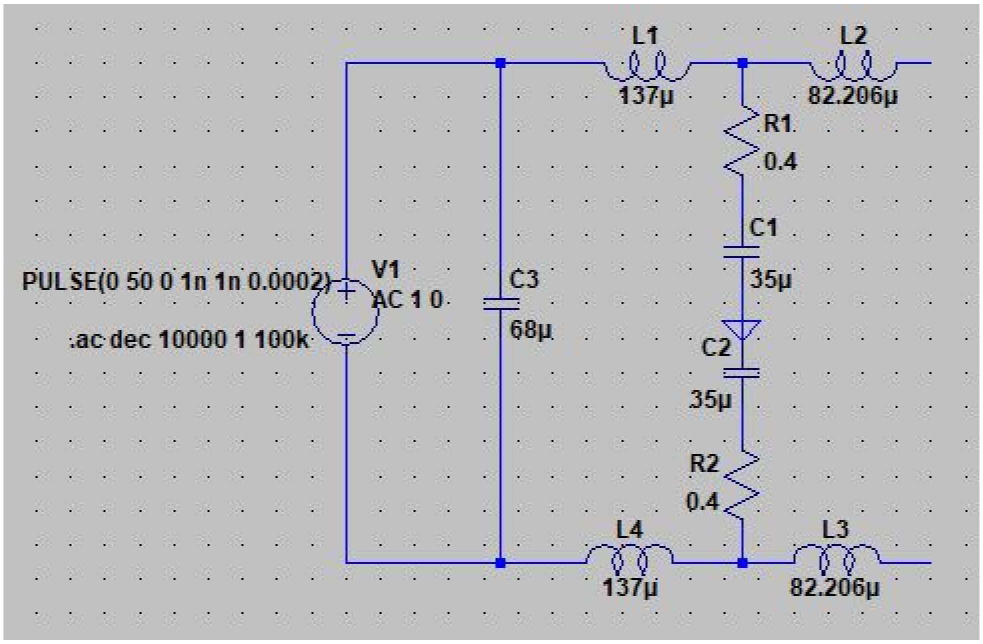

Figure 4-9: "Double Ended" LCL filter using LTSpice

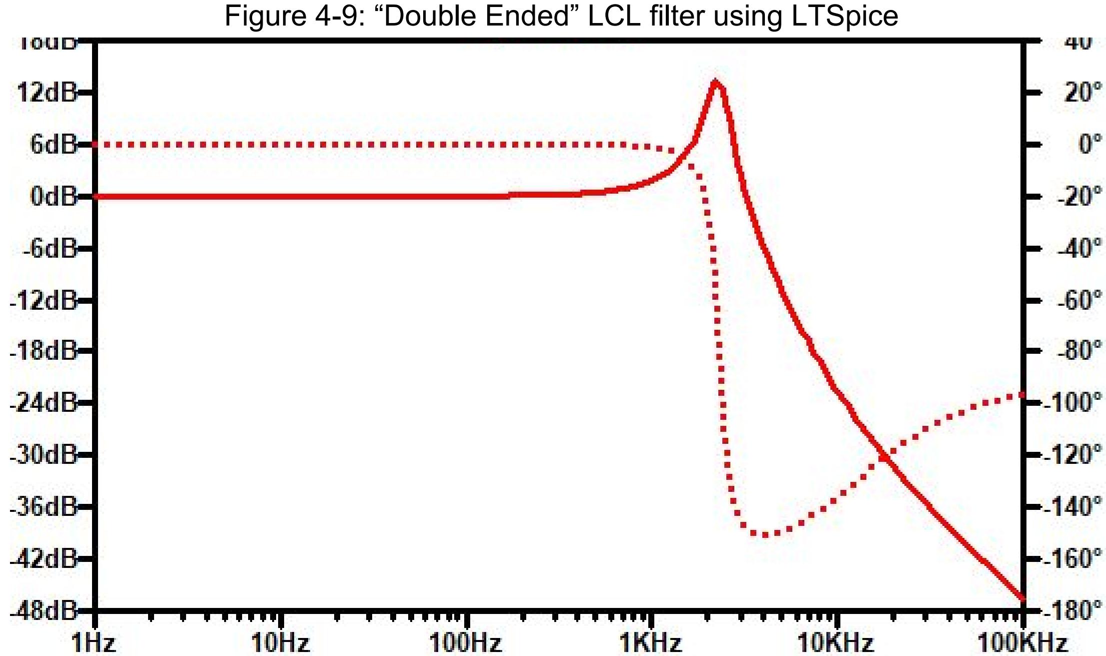

Figure 4-10: LCL filter Bode plot using LTSpice

Chapter 5 Hardware Test and Results

5.1 Phase Detector

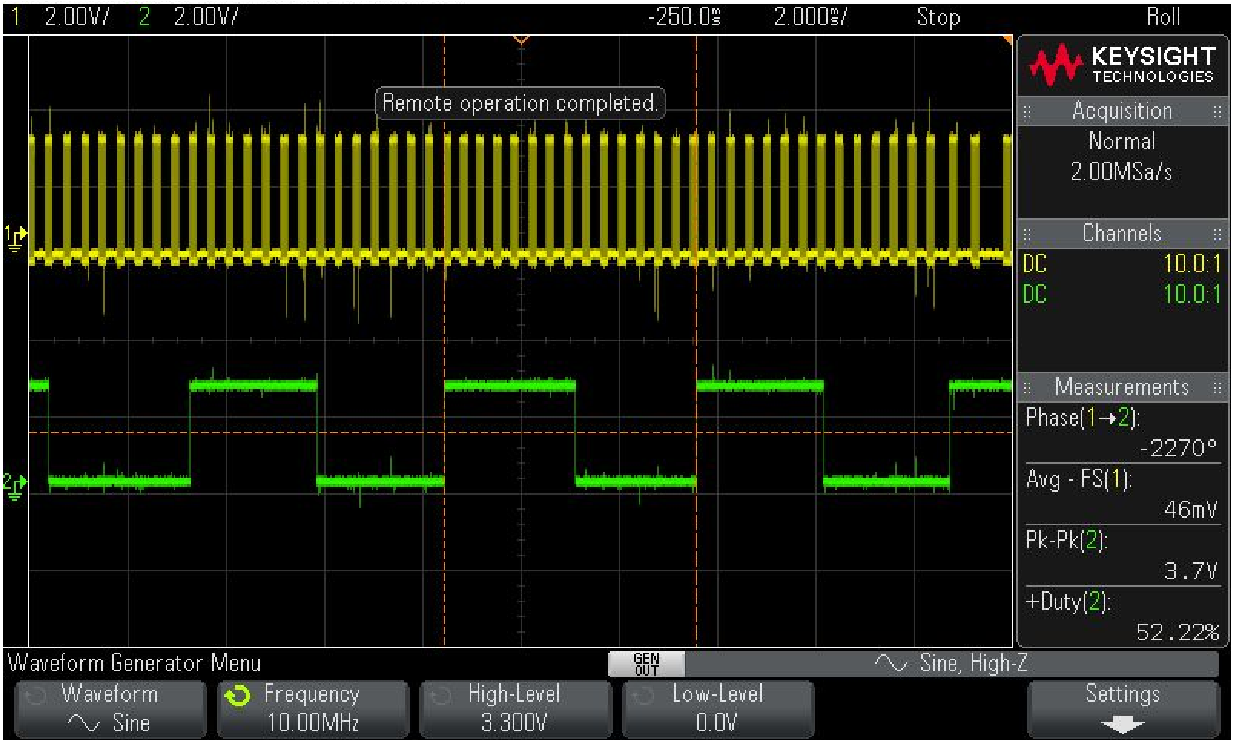

Figure 5-1: Phase Detector Lock Detect Output

The phase detector was successfully interfaced with the Raspberry Pi through a Serial Peripheral Interface (SPI) connection. The phase detector works in such a way so that when it achieves grid lock, it will output a certain frequency. When the frequency of the inputs was approximately 10 Mhz, we were able to achieve a viable output as shown in the figure 5-1. However, when the inputs are a 60 Hz signal as representative of the grid frequency, the outputs will no longer be able to produce a consistent frequency this is probably because the frequency is too low for the Phase Detector. Although there was no lower limit stated for the frequency input of the Phase Detector, it was still recommended to run at around 10Mhz. This, in addition to the extraneous 60Hz noise inside the lab, made it difficult to achieve a consistent frequency output.

5.2 Raspberry Pi

The Raspberry Pi uses the PigPiod library which directly control the registers to generate a PWM signal. We used this instead of the original WiringPi library because although WiringPi generated the required PWM, it did so inconsistently- having intermittent "crashes" where the signal would inexplicably go to zero for several cycles. By using PigPiod, this problem would no longer occur. The below Figure 5-2, is our microcontroller output where the green wave represents the control for the positive cycle of the sine wave and the orange wave represents the negative cycle of the sine wave. These two signals would each be connected to the two tied drivers.

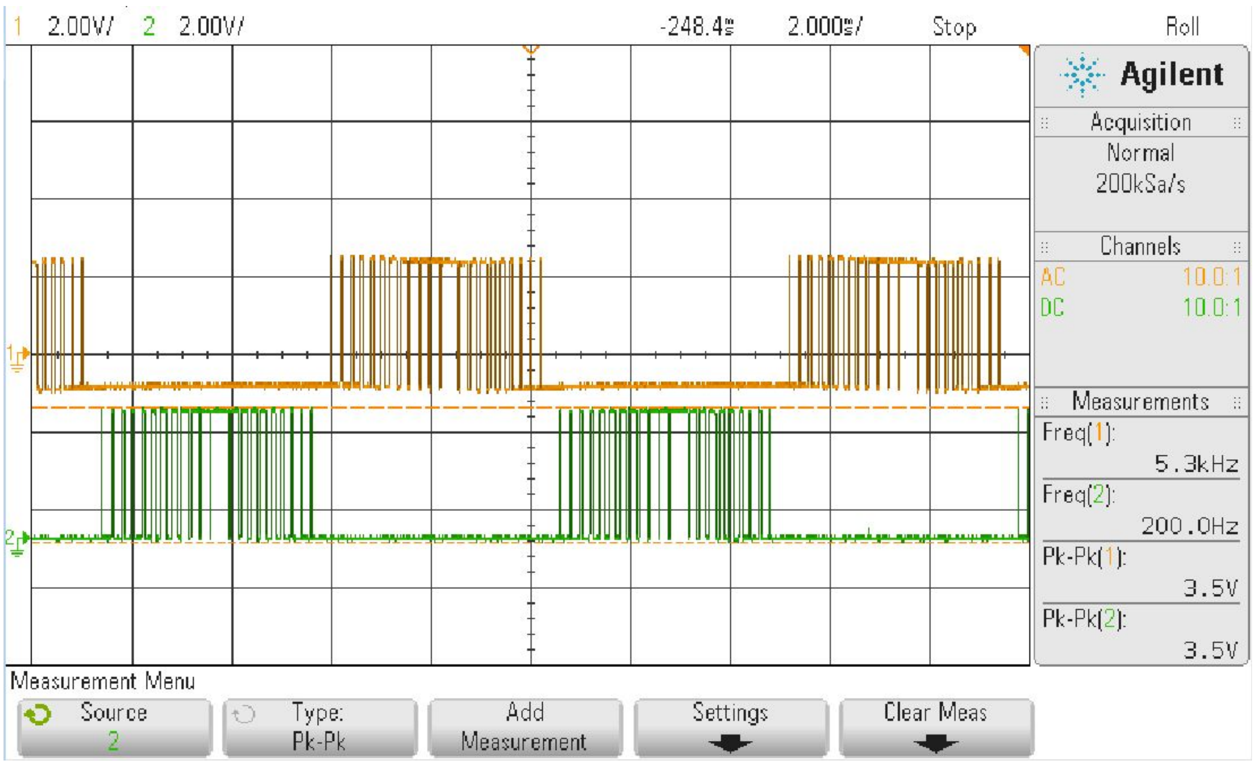

Figure 5-2: Raspberry Pi Unipolar Switching PWM Output

5.3 Boost Converter

The boost converter worked as intended, boosting up the voltage from the 5V pin to a higher 12V for the driver.

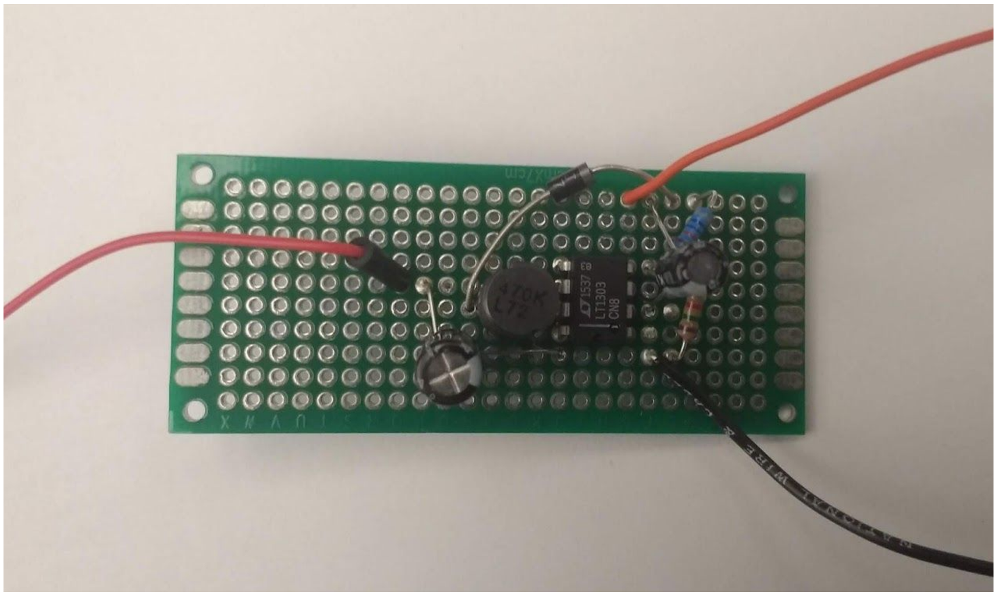

Figure 5-3: Boost Converter Circuit

5.4 Driver

After testing the drivers in its recommended setup to a protoboard as shown in Figure 5-4, we discovered that the HI side driver output (from HO to Vs) would not drive the 3.3V Raspberry PI PWM signal to the required 12V output, however the LO side works as intended. This is unusual because when using a function generator to generate a 5 khz square wave, the driver will output correctly on both the HI as shown in Figure 5-5, and LO side, with a low propagation delay as shown in Figure 5-6, albeit with no PWM. This is not due to the Pi's ability to output current either as the current draw out of the GPIO pins (0.1mA) is well within the limits of a GPIO pin. There are no loading issues either, because voltage remains at a 3.3V PWM when connecting the Raspberry Pi output to the driver. In fact, we were even able to test a voltage loading situation with the function generator and found that the driver still worked fine even with a 2.2V, 5 khz square wave. We eventually attempted to unsuccessfully try several other drivers, including a single high side driver but ended up with the same issue.

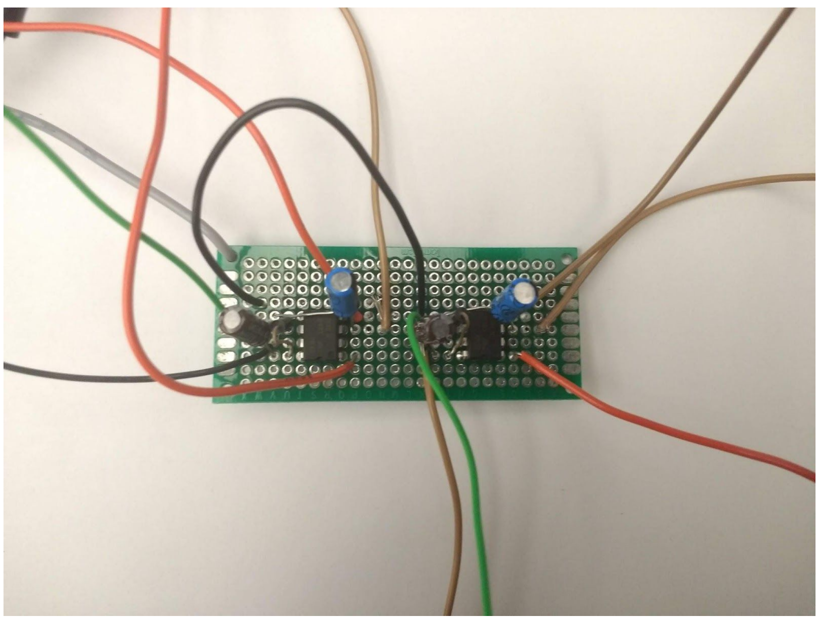

Figure 5-4: Driver Circuit

Figure 5-5: HI side Driver test with Function Generator
Function Generator Input (Yellow) and Driver HI Output (Green)

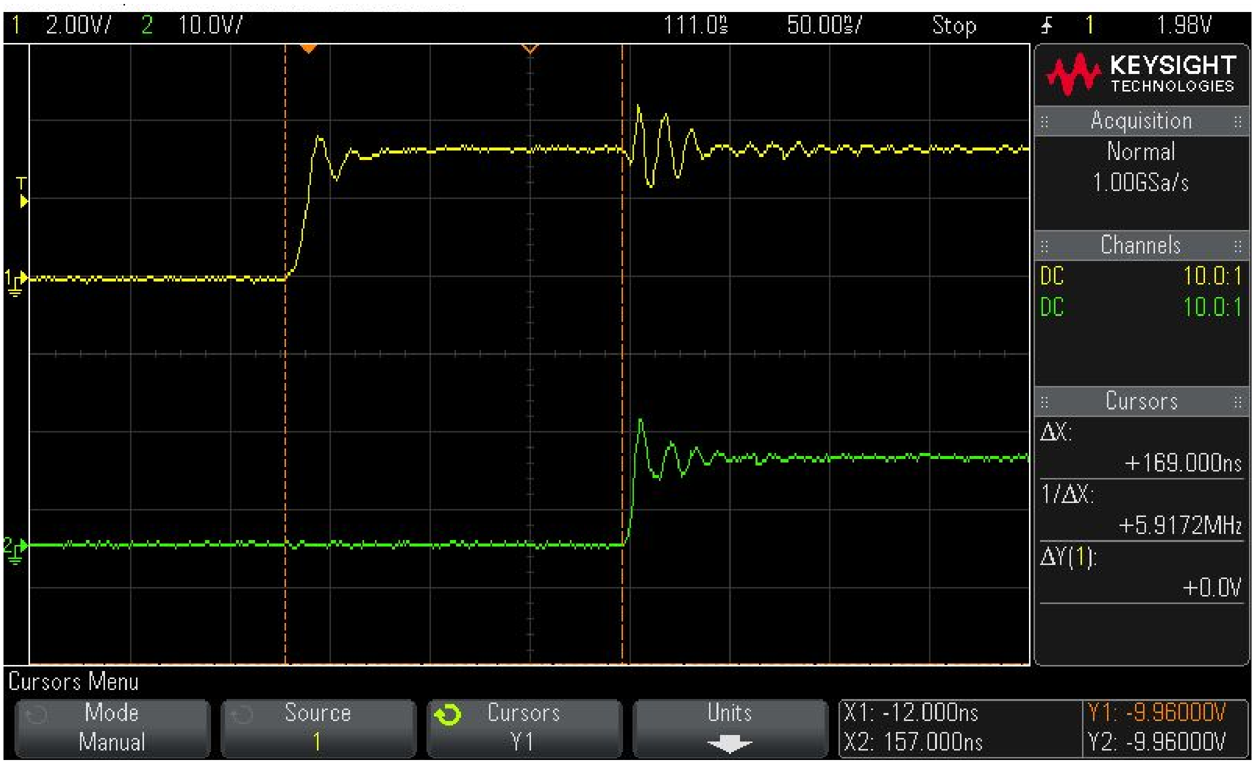

Figure 5-6: Propagation Delay Measurement
Function Generator Input (Yellow) and Driver HI Output (Green)

5.5 LCL Filter

The LCL filter we designed mostly matched what we expected from our simulation and tests with a function generator showed almost none of the extraneous switching frequency components.

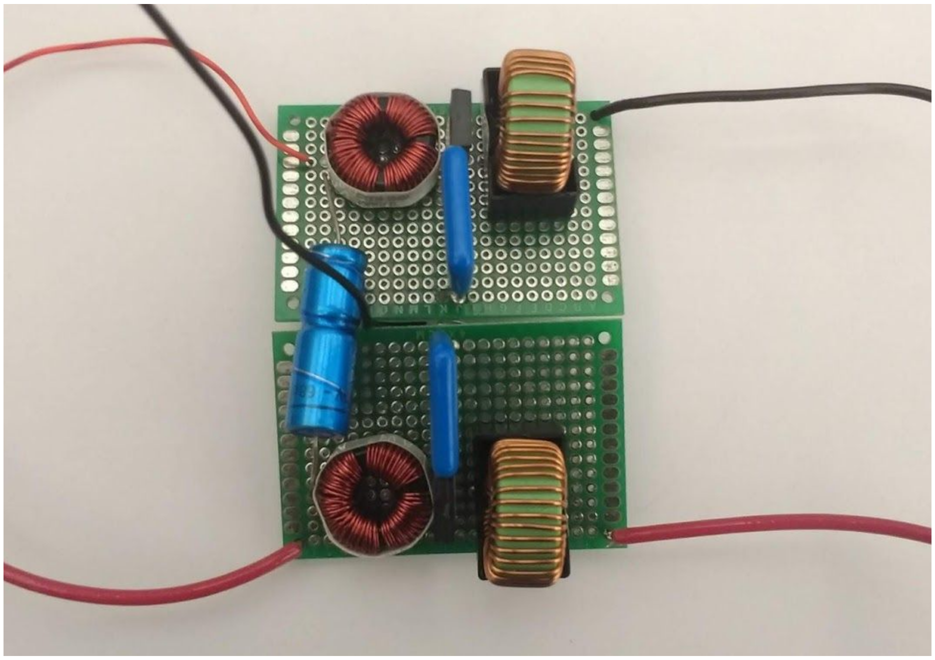

Figure 5-7: LCL filter

Figure 5-8: Spectrum Analyzer of our LCL filter

Chapter 6 Conclusion

The objective of this project is to demonstrate the capabilities of a Raspberry Pi when used as a grid-tied, bi-directional power inverter for renewable energy storage applications. The inverter system is designed to streamline the power inverters in the solar industry allowing for an economical product for customers. Most standard grid tied inverters in the market work in a single way called net metering- they convert the DC power from solar panels into an AC sine wave and then synchronize that with the grid. Transferring surplus power to the grid and allowing customers to reduce their energy bill. Our project provides the solution of a bi-directional power inverter that is able to charge a battery and also use the battery as the DC source to convert into the needed 120VAC sinusoidal wave at 60 Hz. Our system allows for the charged battery to be installed onto electrical vehicles providing customers with a renewable energy storage application. The system promotes renewable energy by making solar energy further accessible and economically viable for customers.

Through extensive testing and analysis, we were not able to fully complete our project. The Raspberry Pi as the controller for the inverter showed that it could possibly function if the components being used to interface with it would fully operate such as the drivers. With the same signal being given through the function generator and the Raspberry Pi, both sides on the driver would output correctly following the function generator signal. As for the Raspberry Pi, the driver would only work halfway. The LO side would follow the Raspberry Pi signal while the HI side would not output at all. Given the fact that the drivers are partially working gives promise that the Raspberry Pi is capable of operating the drivers and being able to successfully obtain a sine wave.

For the phase detector, we could not find one that was specifically designed for 60 Hz operation. Our phase detector operated up to the megahertz range but at low frequencies the signal became too noisy due it being around the 60 Hz range. A phase detector for special operation at 60 Hz, as well as a shield for it to properly remove other 60 Hz noise will help in being able to properly interface with the Raspberry Pi.

A possible solution is to switch the Raspberry Pi with another controller such as with a Digital Signal Processor (DSP). There is documentation of DSP's being used for inverters as opposed to a Raspberry Pi. For example, an inverter design using a Texas Instruments chip (TMS320LF2407A) has a switching frequency of 20 KHz, PWM output signals, PID software control, and a digital Phase Lock Loop. Eliminating components and reducing the size of the overall system[7]. For future continuation of this project, further analysis into the components being used with the Raspberry Pi as well as an explanation for their behavior could possibly lead to a functioning power inverter system with the Raspberry Pi as the controller.

References

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[6]Kahlane, A.E.W.H., et al. “LCL Filter Design for Photovoltaic Grid Connected Systems.” *LCL Filter Design for Photovoltaic Grid Connected Systems*, pp. 1–6.

[7]Tao, Huanqi. “Design and Implementation of Digital Control of Photovoltaic Power Inverter.”*Egyptian Journal of Medical Human Genetics*, Elsevier, 8 Jan. 2012, www.sciencedirect.com/science/article/pii/S1878029611008474.

Appendix A: Bill of Materials

Part Description	Part Number	Vendor	Cost	Num	Total
Raspberry Pi 3 Model B	3055	Adafruit	35	1	35
Touch Screen Monitor for Pi	SC7B-1US	Amazon	43.99	1	43.99
Keyboard and Mouse for Pi	KU-0833 +MSU0939	Amazon	14.99	1	14.99
Case for Raspberry Pi	VZ00102	Amazon	15.99	1	15.99
Raspberry Pi Starter Kit	LYSB01C6Q2GSY-ELECTF	Amazon	69.99	1	69.99
IC Adapters	n/a	Amazon	9.07	1	9.07
SMT IC Adapters	a14062100ux0254	Amazon	4.19	3	12.57
IGBT Array	APTGT75H60T1G-ND	Digikey	44.47	1	44.37
Drivers	IRS2186PBF-ND	Digikey	3.9	5	19.5
Protoboard for SMT .65mm	3360BCA-ND	Digikey	2.64	2	5.28
Phase Detector	ADF4002BRUZ-ND	Digikey	4.43	4	17.72
Boost Circuit					
IC Reg Boost Converter	LT1303CN8#PBF-ND	Digikey	4.87	1	4.87
86.6kohm Resistor 1%	86.6KXBK-ND	Digikey	0.1	1	0.1
10kohm Resistor 1%	RNF14FTD10K0CT-ND	Digikey	0.1	1	0.1
Capacitor 37uF	493-15354-ND	Digikey	0.41	1	0.41
Capacitor 47uF	493-16225-ND	Digikey	0.43	1	0.43
Schottky Diode	1N5817-TPCT-ND	Digikey	0.41	1	0.41
Inductor 47uH	308-2106-ND	Digikey	0.67	1	0.67
LCL Filter					
Inductor 140uH	513-1658-ND	Digikey	10.1	2	20.2
Inductor 80.75uH	237-1198-ND	Digikey	4.27	2	8.54
Capacitor 33uF	565-4653-ND	Digikey	20.16	2	40.32
Resistor 0.4 ohm 1%	MP930-0.40F-ND	Digikey	5.46	2	10.92
Total Price					375.44$

Appendix B: Senior Project Analysis

Advisor: Art McCarley

1. Summary of Functional Requirements: The project is to construct an all in one grid assisted photovoltaic system inverter. Our system will take in an DC or AC input from the solar panels and charge the battery and output an AC voltage into the home for full power.
2. Primary Constraints: Main constraint are the switches that will be used as research has shown that our system is limited in available switches to use due to our current, voltage ratings and our bidirectional current need for them. Along with this is another constraint in the microcontroller that will be our control signals and the PWM to generate a true sine wave. Implementation of the control circuit can potentially take longer and further push back our schedule and fall behind.
3. Economic: To construct our project, a rather medium-large investment by our sponsor is needed for the completion of our system. The switches alone will cost around 1200$, and the purchase of the buck/boost/ and rectifier modules will add-on more to that including the microcontroller that is relative low cost at potentially less than 50$ depending on which one works best for our system. A potential total cost of around 2000$ will be needed to complete the project. Testing of smaller scale prototypes can be done at the lab benches at school with the final field testing provided by our sponsor. Main people that will benefit from our product is the customer and our sponsor. Customers will be able to purchase a product that is at the lower end of the market in terms of price and reap the benefits of having renewable energy. With the predicted success of the system along with the solar industry market going down and becoming more accessible to others, our sponsor will be able to thrive in solar inverter market and challenge the top companies.
4. If Manufactured on a Commercial Basis: With our product being targeted at a price of around 2000$ and with components totalling up to around that price, then total manufacturing cost can be around 2000$. Estimated number of devices sold in the first year can be estimated in the hundreds.

5. Environmental: The system is environmentally friendly as it is directly related to solar renewable energy. The push for a cleaner eco-friendly environment can be helped with this inverter system entering the market to help appeal homeowners to go green and reduce their footprint on the world. Not only does our system power a home through solar energy, it will also charge batteries that can be used for electric vehicles thus giving customers a reason to have electric vehicles and efficiently be able to power them with their charged batteries.
6. Manufacturability: In terms of issues with manufacturing what we are seeing is an issue of components being available and arriving on time for construction of the product. In a large scale wise, products will be ordered bulk to arrive at the same time and planned ahead for ordering.
7. Sustainability: Future upgrades to our system could be the use of different switches along with the buck/boost/rectifier modules used to improve efficiency and possibly compress our system. The system is designed to last for a large time such as 10 years and if any component fails, safety signals are implemented to ensure the safety of the homeowner and repair as needed.
8. Ethics: Making engineering decisions based on the safety, health, and welfare of the public. Multiple safety measures are installed in our project to ensure the wellbeing of the customer as safety is our number one priority. To increase accessibility for solar energy and to reduce our footprint and improve our global environment. With our project, customers will be able to use the charged battery for their electric vehicles. Allowing for a cleaner environment and future generations will benefit from this movement towards a healthier environment.
9. Health and Safety: For safety, if one line fails the control circuit will turn off the inverter system and have power delivered to the home via the critical loads panel that is tied to the grid. Also safety measures will be put to ensure the system is not live when repairing to prevent any damage to the system and the person as this system deals with high voltage.
10. Social and Political: The project has a direct impact in the renewable energy field as the solar industry market goes down allowing more homeowners accessibility to solar.

California is a state that is currently pushing for complete renewable energy and with this product, solar energy could be more appealing to customers due to its capabilities. With society and the political landscape seeing the potential of solar and the need to use renewable energy for an eco-friendly world, the project can be a large push in the right direction to reduce carbon emissions.

11. Development; Independently we have learned to fully design an inverter and all the necessary components needed to produce the desired output. A new tool we will learn is the PWM to produce the sine wave of our output and implementing a microcontroller to control our circuit.