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Using Photovoltaic Generators as Active Power Filters

MAJOR QUALIFYING PROJECT (MQP)

AMBER DESJARDIN, SAMUEL FRANCOIS, MELISSA RODAS

ADVISOR: ALEXANDER E. EMANUEL

CO-ADVISOR: JOHN MCNEILL

SPONSOR: NECAMSID

Abstract

The ever-increasing reliance of electronic devices that utilize AC power has increased the amount of harmonics that pollute the distribution systems. Harmonic filters are an important tool for mitigation of harmonics. Therefore, there is a need for an inexpensive and reliable way to actively filter out harmonics from an AC power line. This project demonstrates that a photovoltaic generator can be used to provide reactive power and harmonic compensation. The simulated circuits were implemented using Multi-sim, PSPICE, and PSIM. Also, reduced scale circuits were built in order to confirm the feasibility of an active filter. The results of this project showed that a photovoltaic source can be used to actively filter harmonics by compensating for reactive power.

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1 Introduction

The focus of this project was to create a device that compensates harmonics and reactive power from an AC power line. The main component in this device was a Direct Current (DC) to Alternating Current (AC) inverter. A DC power source, like a solar panel, was inverted into a usable AC source. AC electricity is very common and more useful in many applications than DC electricity. A lot of items that are plugged into a wall get their energy from an AC source. A lot of alternative energy devices perform like a DC source, so inverters are very useful when it comes to those alternative energy applications. Without the inverter, energy from solar panels would be DC, and AC powered devices wouldn't be able to be used. Inverters are very common and used in many applications already. One example of the use of inverters are in cars. This type of inverter takes the 12V car battery voltage and inverts it to a usable AC voltage for charging electronics like cell phones and batteries. This can be especially useful for camping or when electrical outlets aren't available.

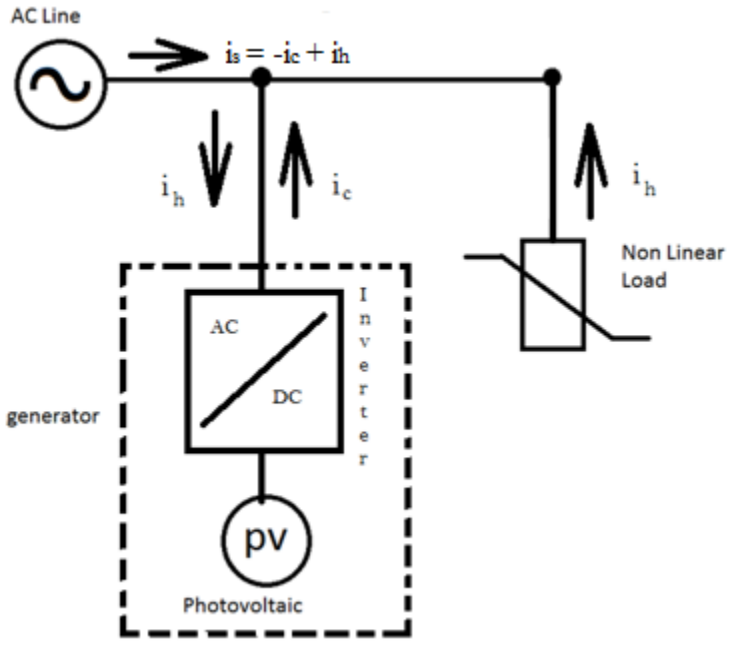

Figure 1: Photovoltaic generator with inverter that helps cancel current harmonics from non-linear load

The main idea of this project can be represented in Figure 1 above. This figure helps understand the application of the photovoltaic generator in this project. When a non-linear load was connected to the AC utility line, the current produced was out of phase or parasitic to the voltage which creates poor quality power. The photovoltaic generator produces active power, that carries energy to the load, and useful harmonics that are 180 degrees out of phase from the undesirable harmonics generated by the non-linear load. This technology enables the cancelation of the harmonic current, i_h, with the harmonics injected by the photovoltaic converter, i_C. In Figure 1, the current i_c contains the fundamental 60Hz current while the current i_h contains all the harmonics except the fundamental ones.

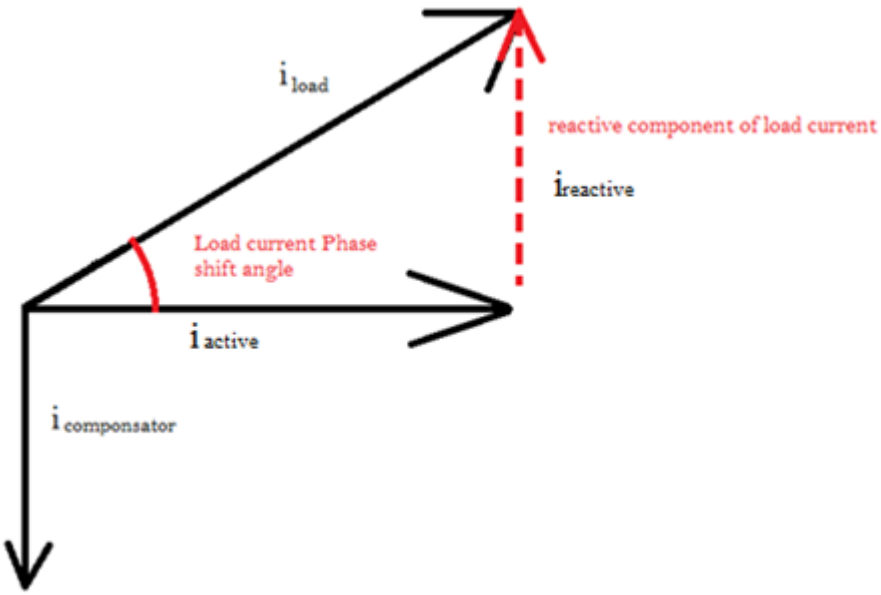

Figure 2: Phasor diagram of reactive power of the load current and current compensator

Figure 2 above shows the phasor diagram of a voltage source with a non-linear load. Since the load was non-linear, the current has an active (i_{active}) and reactive ($i_{reactive}$) component. The 'bad' current is the reactive component since it's not 'true' power. In order to get rid of the reactive component from the non-linear load, the compensating current, $i_{compensator}$, has to be in

the opposite direction and the same magnitude as to the reactive component of the load. This cancels out the reactive current and therefore would only have ‘true’ or good current, which basically gets rid of the harmonics. The proof of concept that this project demonstrates creates an opportunity for many future applications for photovoltaic generators.

2 Background

2.1 Project Inspiration

The concept behind this project was to use photovoltaic generators as a voltage source to filter out harmonics in a non-linear load and compensate for reactive power. A non-linear load would be when a resistance, an inductance, and a capacitance are not constant but instead are time varying. This is what causes the harmonics in the current. Ideally, the source from the Photovoltaic (PV) Generators would filter out the harmonics and convert the non-linear load into a linear load, thus creating a smooth sinusoidal current. Part of this idea comes from a previous research paper that used the power from a wind turbine as an active filter.

Dr. Todeschini was a PhD recipient from WPI [13]. She did a project similar to this, but used wind as her DC source instead of the Photovoltaic Generators that will be used in this project. Her project converted wind energy into electrical energy. It acted as an active filter and used injected harmonic currents, similar to this project. She concluded that her project is feasible and that it did in fact act as a power generator and harmonic compensator. By using her work as background, it was possible to point the project in the right direction.

Another useful paper was one from the IEEE website [9]. It was about using PV generators and active filtering, but with a reduced storage capacity. The goal was to create a three phase active power filter based on the concept of energy balance. This was useful in order to get an understanding of the end result of the project. In the paper, a circuit similar to the ideas of previous work was created and the end result was very similar to this project. This figure, shown below, was used in order to make sure the outcome was as expected in the end of the project.

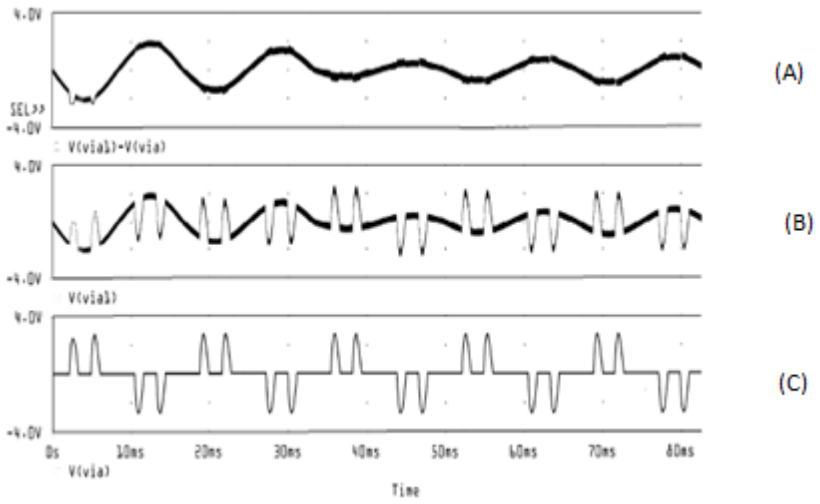

Figure 3: AC line with and without harmonics (A) Combined wave forms from B and C; (B) compensation current; (C) non-linear load current with harmonics

This gave a clear explanation of what the ending product should be, and helped guide the way to that point. In Figure 3, the top line was the line current, or the clean sine wave that should be seen coming out of the system after the harmonics are filtered. The second simulation in the figure was the compensation current, and the third was the non-linear load current. Ideally, the photovoltaic generator would create a current that looks similar to the Figure 3B. This was 180 degrees out of phase from the non-linear load current, Figure 3C. When these two currents are 'added' together, as in the compensated current was pushed to the AC line, the harmonics cancel each other out and the pure sine wave that was desired was produced.

There were also previous Major Qualifying Projects (MQPs) [6] that worked on DC to AC inverters, but most had a different goal. Those goals ranged from low power, to least expensive, to cleanest wave produced. All the projects were searched for similarities and the recommendations were read. The recommendations detailed what went well in each project and warned against certain techniques, but praised others. This was very helpful in the final decisions of the circuit design and the best procedure to follow. It allowed the team to pick the best traits and ideas from all of them in order to build the main circuit. This allowed more time to focus on

the end part of the project, which required more thinking and time in order to complete in the given time frame.

2.2 DC vs. AC

Direct Current and Alternating Current are the two forms of current used today. Direct Current is characterized by nearly constant voltage and current. Examples of this are solar panels and batteries, like that of a car. Alternating Current is quite the opposite, and it's characterized by the direction and amount of electricity that changes cyclically over time. This feature makes it possible to transmit electricity over long distances due to the ability to step the voltage up or down based on needs. This is a feature that a DC system cannot accomplish with ease.

2.2.1 DC to AC Inverter

DC to AC Inverters are commercially available. For the purpose of this project, it was decided that it was better if a DC to AC inverter was built rather than bought. To understand how the inverter works, Figure 4 shows a full schematic of an H-Bridge, DC to AC inverter with a resistor load.

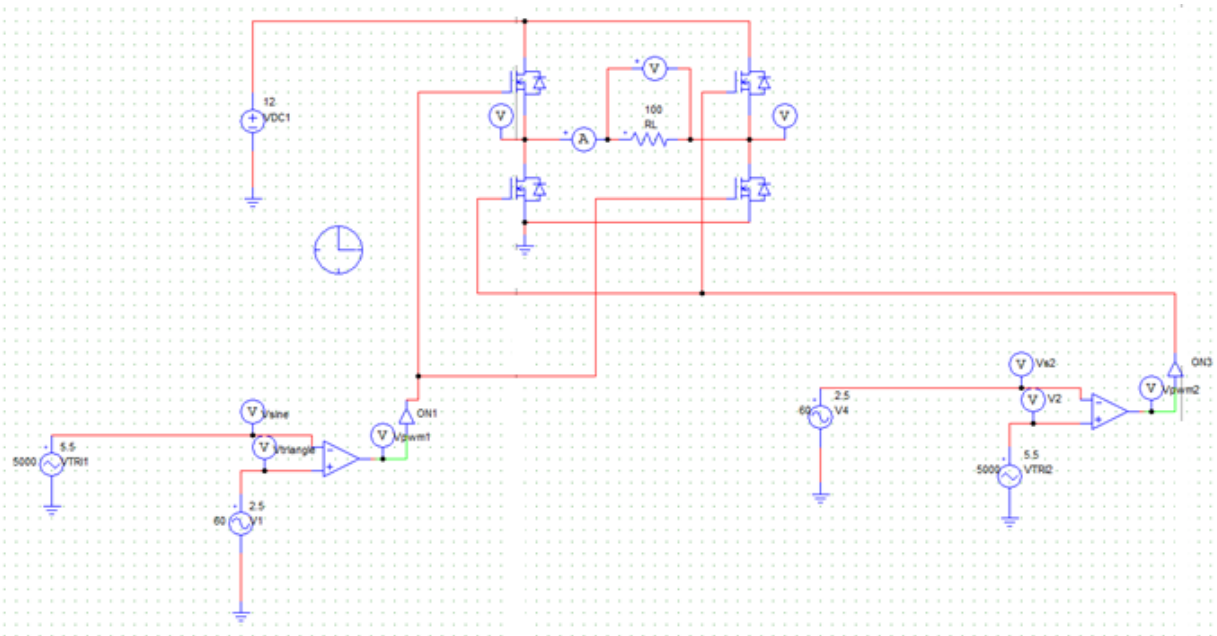

Figure 4: Full H-Bridge DC to AC Inverter

The main source that fed into the inverter is a DC source that for this case is a 12V photovoltaic source. The inversion process occurs because the current through a load is forced to switch directions when the gates transistors switch on and off. As can be seen in figure 4, there are two pulse width modulated (PWM) signals that control the MOSFET drivers. Even though it appears that there are two separate PWM, it is in fact the same PWM signal, only one is inverted. As is explained later in the report, the two MOSFETs from the same side of the H-bridge cannot be ON at the same time since it would create a short circuit. Therefore, in order to create the AC source, one PWM signal controls one high side MOSFET and the opposite low side MOSFET. This way, a current flows in one direction when one PWM signal is on, while the current flows in the opposite direction when the inverted PWM signal is on. This process is further explained later on in the report.

2.3 Pulse Width Modulation (PWM)

2.3.1 Fundamentals

In order to create the noiseless sinusoidal waves required, Pulse Width Modulation is the technique of choice. The duty cycle is modulated so that the oscillating DC signal looks like an AC signal across the load. PWM results in a square wave in which the pulse width is varied in such a way that the average voltage of the waveform is sinusoidal. Typical applications use a comparator in order to see the signals together, as shown in figure 3. The PWM signal is produced as the low-power reference sine wave is compared to the triangle wave. When a triangle wave and a sine wave are entered into a comparator circuit as seen below, the outcome is the PWM signal.

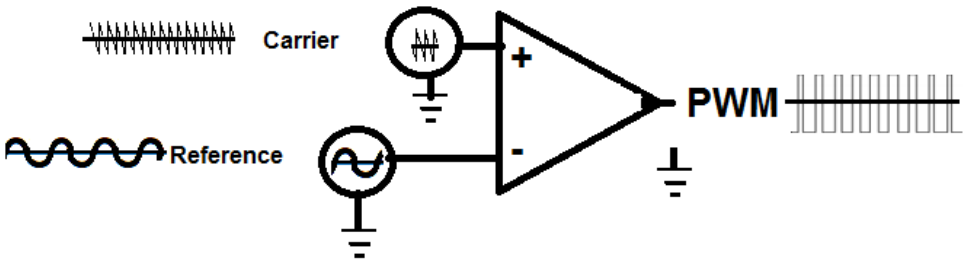

Figure 5: Comparator used to create PWM

2.3.1.1 Bi-Level PWM

This application of Bi-Level PWM simply compares a sine wave and a triangle wave. The result was a square wave that changes between the voltage values powering the rails of the comparator, as shown in figure 6b. When the carrier wave, v_{tri}, is lower than the reference wave, v_{sine}, the square wave goes high and hits the comparator rail if V_{dc}. When the carrier wave is higher than the reference, the square wave goes low and hits the comparator rail $-V_{dc}$.

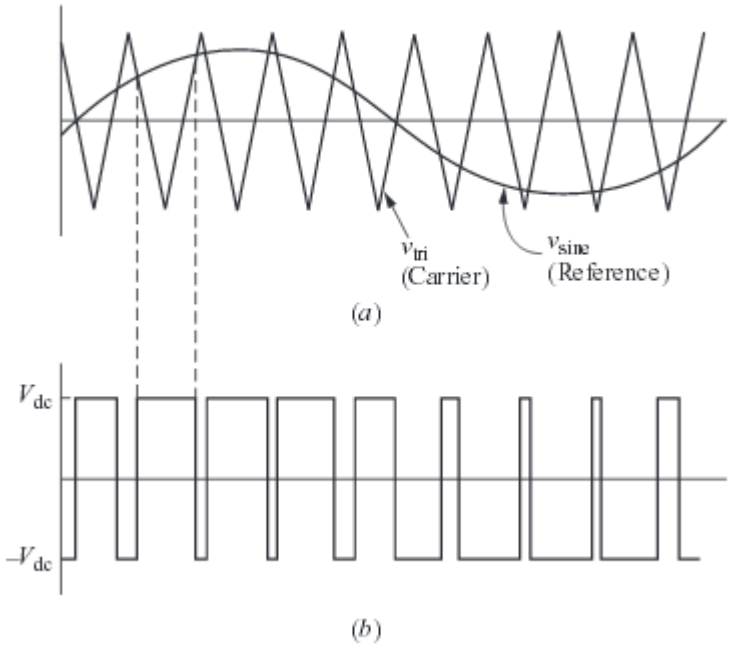

Figure 6: Bi - Level PWM Concepts [7]

Figure 6a shows the comparison of the carrier and reference waves. Figure 6b shows the resulting PWM. Notice the time alignment relationship between the comparison time and the square wave pulse width.

2.3.1.2 Tri-Level PWM

A tri-level PWM waveform is a much closer signal to a true sine wave since it is generated with high, low and zero values. As with a bi-level signal, a triangle wave is used but half its amplitude is summed with a square wave. This way one half of the reference sine wave is compared to the triangle wave at a time as can be seen in Figure 7.

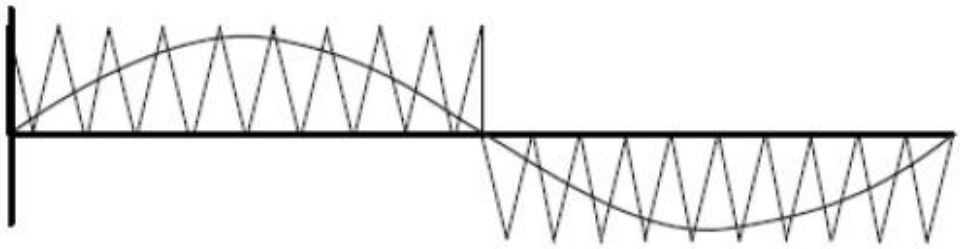

Figure 7: Triangle waves with a high, low and zero reference [12]

Figure 7 shows a sine and triangle wave that is both positive and negative. They are both positive at the same time, as well as negative at the same time. This waveform is in reference to a square wave.

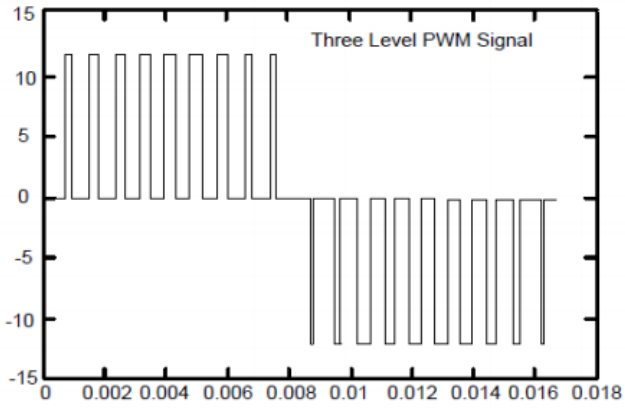

Figure 8: Tri-Level PWM signal [12]

*Figure 8: Tri-Level PWM signal [12]*Figure 8 shows when a sine wave is used as a comparator. It results in the square wave pulses that are shown above.

2.3.2 Inverting PWM Signals

There are two different PWM signals needed for the switching devices in the H-Bridge, as was shown earlier in the report, in Figure 4 . Ideally one PWM signal would be turning on while the other would be turninFigure *8*: Tri-Level PWM signal [12]g off. One way to possibly invert the PWM signals to achieve the alternating stages of the switching devices in the H-bridge is to use a CMOS inverter.

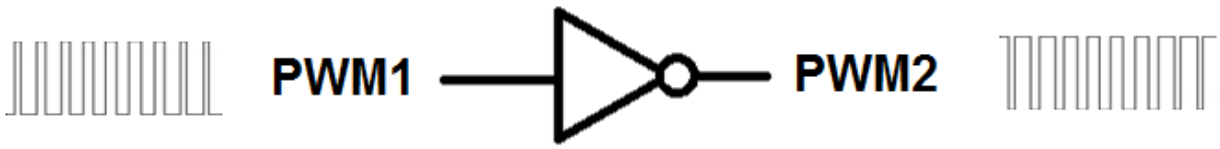

Figure 9: Using CMOS Inverter / Not Gate to create 2 PWM Signals

CMOS logic inverters or not gates simply change the value of the in voltage to the opposite voltage. This means if a voltage entered in at the positive rail it would exit the gate at the negative rail. This is shown above in Figure 9 . As can be seen, the waveform going in is the exact opposite of the waveform coming out.

Another potential solution would be switching the comparison calculation of the comparator used to create PWM. This would mean creating two separate PWM circuits:

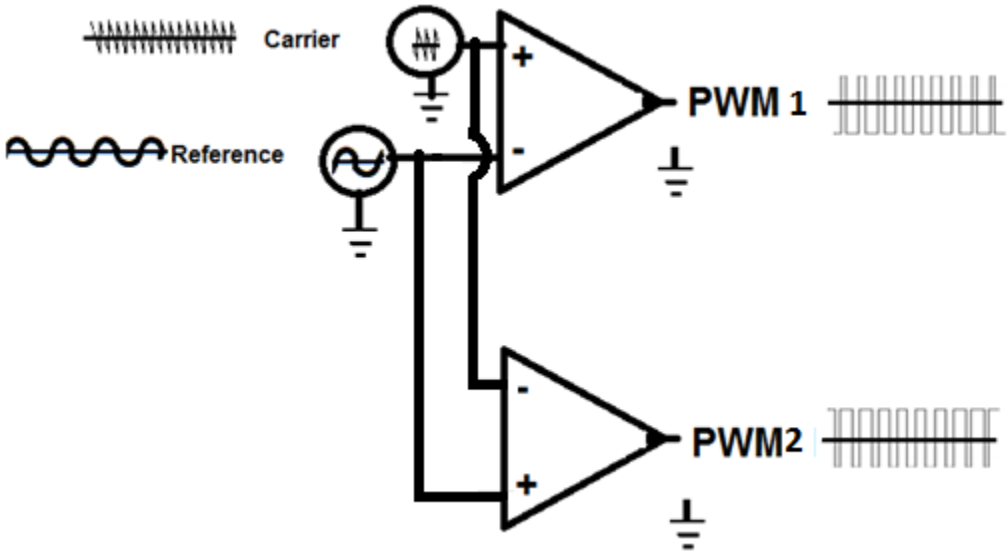

Figure 10: Using 2 comparators to create 2 PWM signals

Above, Figure 10 shows two separate circuits creating the PWN signal instead of a single inverter. This is also a very viable technique.

2.4 H-Bridge

The name H-bridge comes from the configuration of switching devices and their load being placed in a shape that resembles the Letter H. An H-bridge is an essential circuit configuration in both inverters and converters as mentioned in a previous section. To build an inverter an H-bridge of switching devices is required. There are several possible options for the devices placed in the configuration. H-bridges are commonly used in motor control applications. The switches are often controlled by square wave pulses, these pulses are quite often PWM signals. There are two major configurations: Half Bridge and Full Bridge configurations.

2.4.1 Half Bridge

In a half bridge configuration, there are two switching devices and two energy storage devices which are typically capacitors. The Half-bridge performs approximately the same as a full bridge. The Half-bridge requires less switching devices and therefore would also require less control signals to operate the switching.

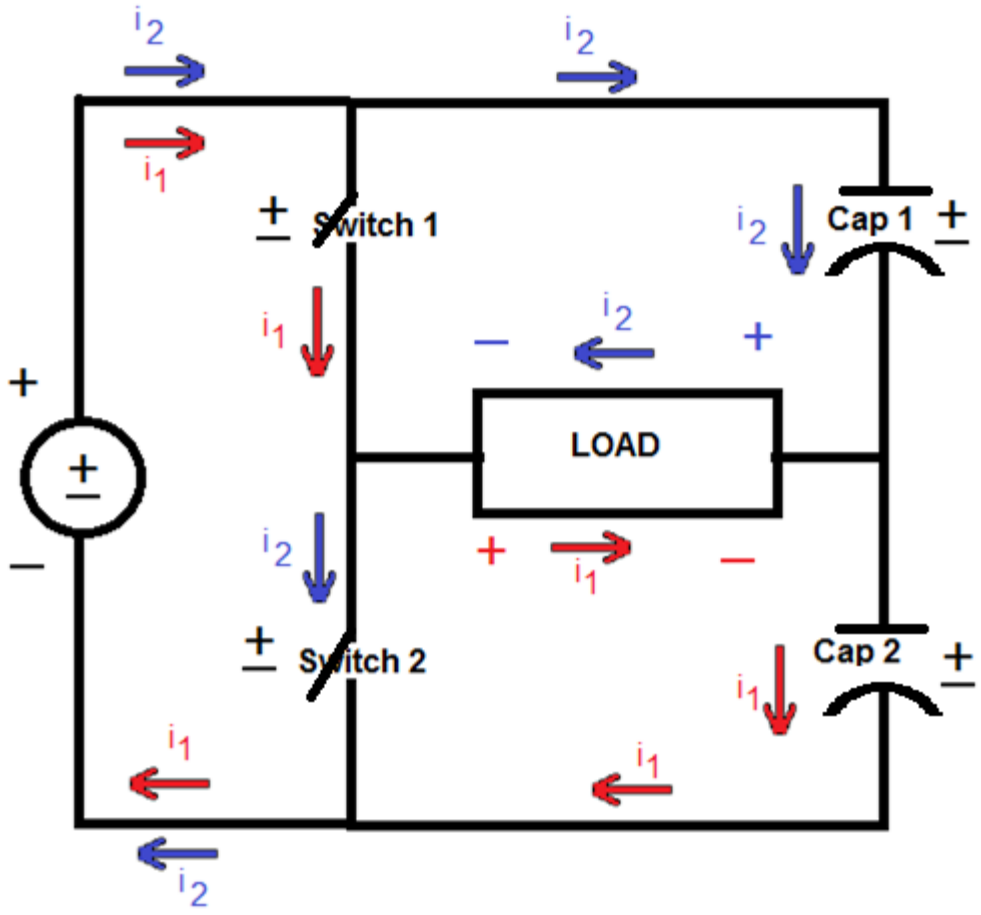

Figure 11 : Half-Bridge concept

In the configuration in Figure 11, the red current, i_1, passes through switch 1, the load and cap2; the blue current, i_2, passes through cap1, the load and switch 2. The direction of the current controls the value and sign of the voltage measured across the load. In a half bridge configuration, there are several possible combinations for Switch 1 and Switch 2: Switch 1 = P-Channel MOSFET, Switch 2 = N-Channel MOSFET; Switch 1 = N-Channel MOSFET, Switch 2

= N-Channel MOSFET; Switch 1 = PNP BJT, Switch 2 = NPN BJT, Switch 1 = NPN BJT, Switch 2 = NPN BJT; Switch 1 = Mechanical Switch, Switch 2 = Mechanical Switch. The switches need to be controlled by opposite PWM signals to ensure alternating.

2.4.2 Full Bridge

In a full bridge configuration, there are four switching devices and no energy storage devices. The full bridge performs approximately the same as a half bridge but produces slightly better results because it is able to transfer the full load rather than a stored portion of the load. The full bridge requires more switching devices and therefore would also require more control signals to operate the switching.

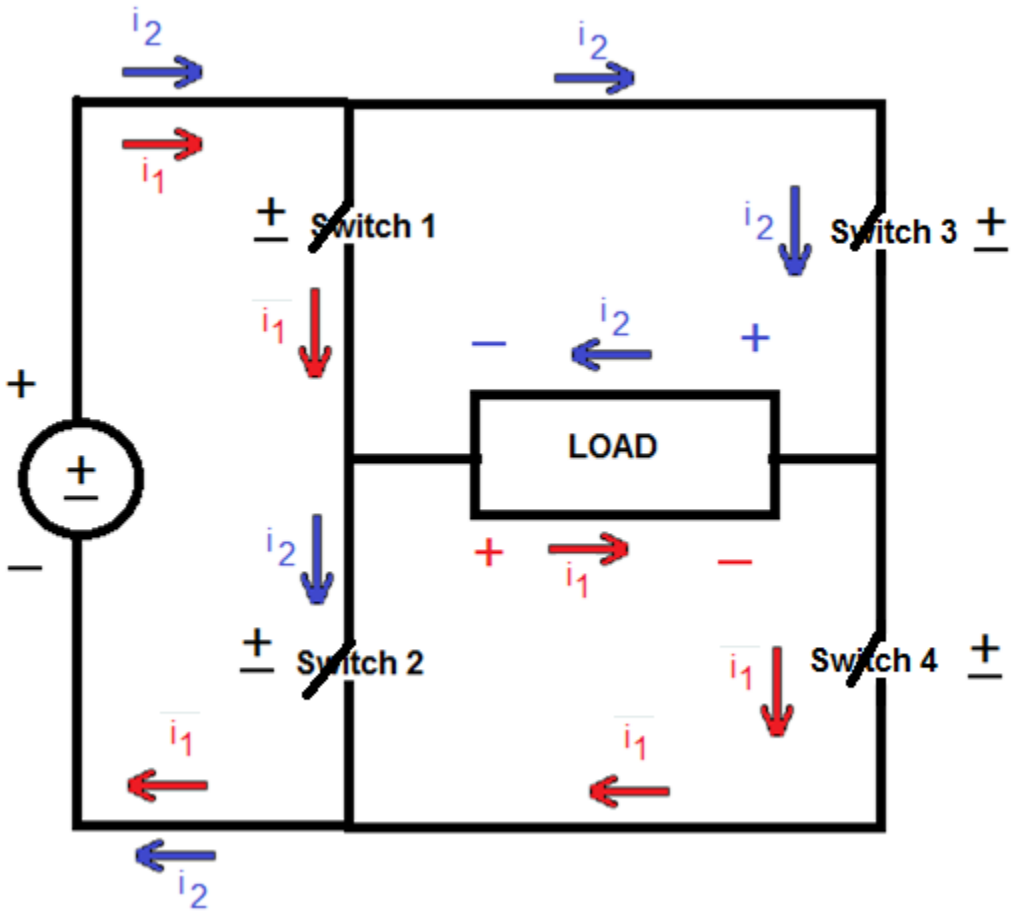

Figure 12: Full Bridge Concept

In the configuration in Figure 12, the red current, i_1, passes through switch 1, the load and switch 4; the blue current, i_2, passes through switch 3, the load and switch 2. The direction of the current controls the value and sign of the voltage measured across the load. In a full bridge configuration, there are several possible combinations for the switches. The important things to understand is that Switch 1 = Switch 3 and Switch 2 = Switch 4. This gives the same possible combinations as the options for a half bridge. Switch 1 and Switch 2: Switch 1 = P-Channel MOSFET, Switch 2 = N-Channel MOSFET; Switch 1 = N-Channel MOSFET, Switch 2 = N-Channel MOSFET; Switch 1 = PNP BJT, Switch 2 = NPN BJT, Switch 1 = NPN BJT, Switch 2 = NPN BJT; Switch 1 = Mechanical Switch, Switch 2 = Mechanical Switch. The switches need to be controlled by opposite PWM signals to ensure alternating.

2.5 Gate Drivers

H-bridges use switching devices and the switching devices receive PWM signals to operate. Depending on the device or the combination of devices the PWM signal may not be enough to power the on and off mechanism of the switching devices used in the H-bridge. There are devices or sub-circuits that can help provide a sufficient amount of power to control the switches. These devices or combinations of devices are called gate drivers.

2.5.1 Transistor Gate Driver circuits

Daniel Hart's Power Electronics [7] provided some sample circuits that are useful for controlling both the low and high sides of the switching components in an H bridge configuration.

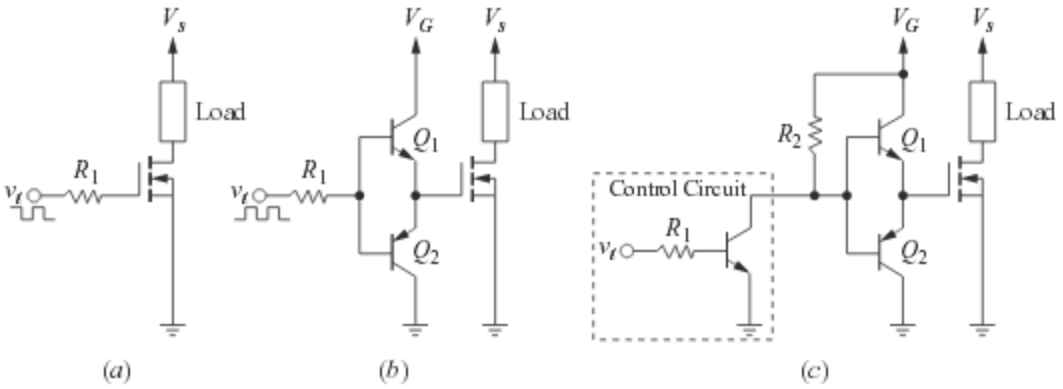

Figure 13: Example MOSFET drive circuits: (a) Elementary MOSFET drive Circuit; (b) Double emitter-follower drive circuit; (c) IC drive with double emitter-follower buffer [7]

Figure 13a, b and c are all different versions of gate drive circuits. These helped reduce the voltage but also helped provide a lot of current through the amplification of the BJT's emitter.

2.5.2 Isolated Gate Drivers

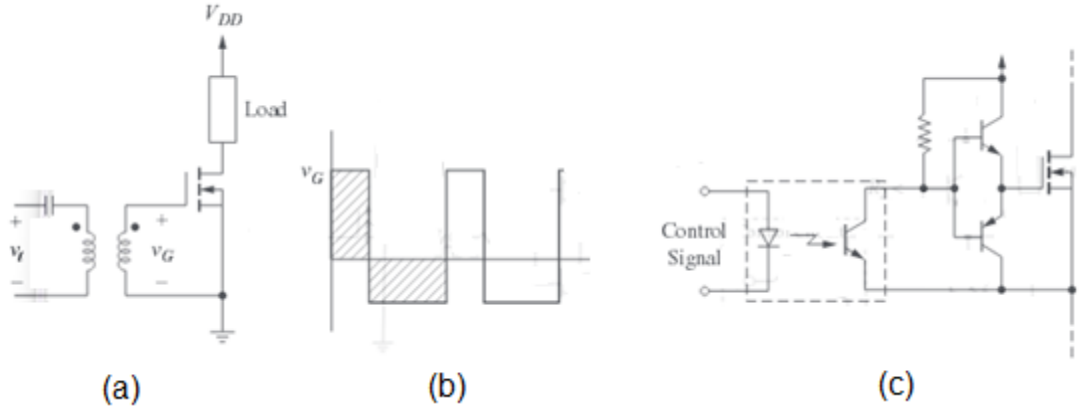

Figure 14: Isolated Drivers: (a) Electrical isolation of control and power circuits; (b) Transformer secondary voltage; (c) Optically isolated control and power circuits [7]

In some applications, it may be advantages to provide electrical or optical control to the gates that are completely isolated from the H-bridge. The results are still a control waveform of a user's choice but this prevented the circuit from having any unexpected shorts.

2.5.3 Integrated Circuit (IC) Gate Drivers

Some companies worked to create specialized ICs to control the gates. There are several examples but a popular specialized IC gate driver is the IR 2110. The functional block diagram for this gate driver can be seen in Figure 15.

2.5.3.1 IR2110

The IR2110 is an example of a gate driver that works really well for MOSFET devices. The IR2110 has several different configurations with supporting devices that makes the IR2110 a very flexible device. Several previous MQPs [6] and the Daniel Hart's Power Electronics book [7] reference and suggest using the IR2110. The IR2110's functionality can be understood through observing its internal workings, as can be seen in Figure 15.

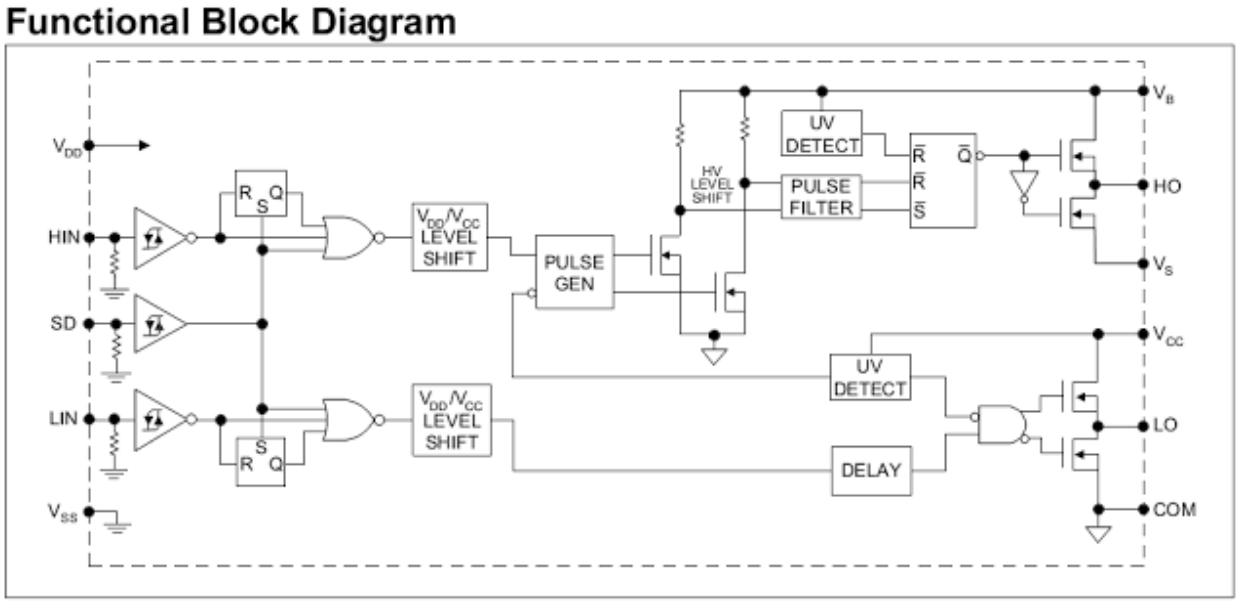

Figure 15: Block Diagram for the IR2110 [8]

The IR2110 also came with a user guide that has many equations that helped calculate supporting components such as a bootstrap capacitor:

$$C \geq \frac{2\left[2Q_g + \frac{I_{qbs(\max)}}{f} + Q_{ls} + \frac{I_{Cbs(leak)}}{f}\right]}{V_{cc} - V_f - V_{LS} - V_{Min}}$$

Where:

Qg = Gate charge of high-side FET (A)

f = frequency of operation (Hz)

ICbs (leak) = bootstrap capacitor leakage current (A)

Iqbs (max) = Maximum VBS quiescent current (A)

VCC = Logic section voltage source (V)

Vf = Forward voltage drop across the bootstrap diode (V)

VLS = Voltage drop across the low-side FET or load (V)

VMin = Minimum voltage between VB and VS. (V)

Qls = level shift charge required per cycle (typically 5 nC for 500 V/600 V MGDs and 20 nC for 1200 V MGDs)

This equation helped the team understand what capacitor values should be used for the bootstrapping capacitor. This was very important part of the H-bridge since if the value was too low for the capacitor then the high-side voltage of the H-bridge would be too small and it wouldn't work. A bigger value wouldn't necessary harm the circuit, but unless the value was calculated, it was not possible to know what the minimum value of the bootstrapping capacitor.

2.6 Reactive Power

The power triangle is presented in Figure 16.

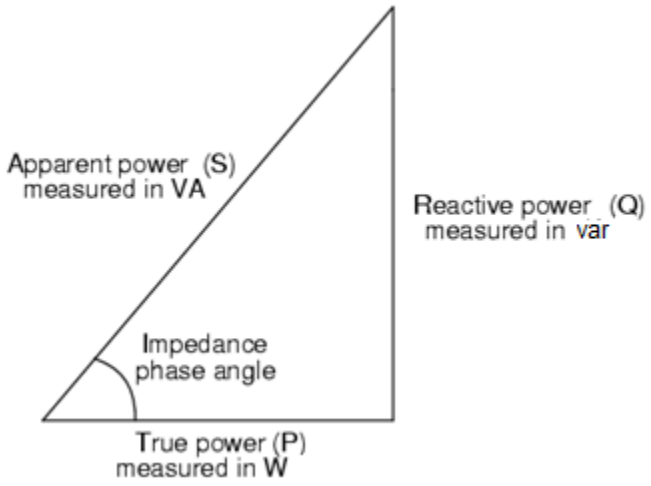

Figure 16: The Power Triangle

There are three sides of the triangle: the apparent power, the reactive power, and the true power. The power that is dissipated across the load is called true power and is symbolized by the letter P and units of Watts. The power that is merely absorbed and returned to the load due to its reactive properties is called reactive power. This is referred by the letter Q and units VAR (Volts-Amps-Reactive). The total power of the AC circuit is both the dissipated and absorbed power which is called apparent power. This is symbolized by the letter S and unit VA(Volts-Amps). Figure 16 shows that true, reactive and apparent power can be represented as the vectors of a triangle.

The phase impedance angle is an important application since this relates to power factor. The power factor can represented by an equation as shown below.

$$Power\ factor\ = \frac{working\ power}{apparent\ power} = \frac{kW}{kVA}$$

In electric power applications, poor power factor, or low power factor, is usually caused by harmonics in the AC line. In order to further understand how to minimize harmonics,

understanding the power factor and specifically reactive power was an important part of the project.

2.7 Harmonics

There are two types of harmonics in an electrical power system, current and voltage harmonics, that distort current and voltage waves respectively. In AC power systems, where the current has the fundamental frequency of 60 Hz, non-linear loads can draw a current that is not quite sinusoidal. Since the current waveform is quite complex, it can be described through the Fourier series analysis. Through this analysis, it is possible to decompose it into a series of simple sinusoids which start at the fundamental frequency and then occur at integer multiples of the fundamental frequency. Voltage harmonics are usually caused by current harmonics. The current that is drawn from the AC line distorts the voltage due to source impedance. Therefore, if the impedance is small, this will only cause small voltage harmonics.

Harmonics are common in power applications and for the most part, the harmonics of the potential PWM systems are predictable. The parasitic components of the current and voltage can be calculated through the Total Harmonic Distortion equations presented in Daniel Hart's Power Electronics book.

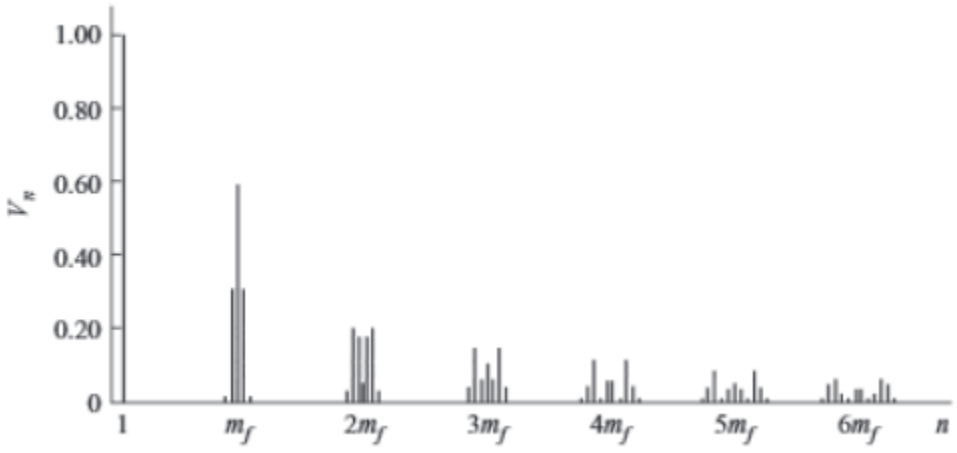

Figure 17: Normalized Harmonic Values for Bi-level PWM [7]

	m_a=1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
n=1	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10
$n=m_f$	0.60	0.71	0.82	0.92	1.01	1.08	1.15	1.20	1.24	1.27
$n=mf\pm2$	0.32	0.27	0.22	0.17	0.13	0.09	0.06	0.03	0.02	0.00

Figure 18: Normalized Coefficients for Bi-Level PWM [7]

Figure 17 shows the normalized harmonic values for a Bi-level PWM. As can be seen, as n increases, V decreases. In Figure 18, it can be seen that the normalized coefficients for Bi-level PWM signals in a convenient chart. The same deductions can also be made from this.

2.8 Active Power Filters

Active power filtering has a lot of advantages and benefits for homes attached to the grid. One goal was to reduce the harmonics generated from PWM DC to AC inversion. A secondary goal of was to research and try some approaches to proactively reduce and even eliminate other parasitic currents generated from additional loads.

3 Methodology

3.1 Work Summary

The first term of this project consisted of researching about previous MQP's and reading Dr. Todeschini paper [13]. This gave insight on what should be planned for the rest of the project. What became very much obvious is that certain parts of the project had been previously done. The DC to AC inverter is a concept that had been around for a long time and hasn't changed much. The team knew that an H-bridge with NMOS transistors and PWM signals would be needed. Each team previous also used a specialized IC to drive the MOSFETS. It is the easiest and most reliable way to drive the circuit, and let each team focus on the bigger scope of their project without getting tied up with the driver. By using this device, the team knew that the focus would be on the harmonics and active power filtering pieces of the project, which are the biggest goals. A fair amount of time was spent focusing on simulating the H-bridge so that the team knew how to proceed in actually putting the circuit together in the lab. It is very important to simulate the idea first, and then move onto the build. This ensured that the team knows what to expect, and that it would be checked first to make sure that the idea is feasible and would work right the first time. This is especially important when parts outside of the ECE Shop Kit needed to be purchased.

This next part consisted of building each section of the project and combining them together in order to see the output that is expected from the simulations in the beginning. The DC to AC Inverter, the pulse width modulation, and the full H bridge were all built in order to have a working prototype. After completing a small section of each piece, testing ensued on each part. Once each smaller piece was working, the team could successfully move onto another piece. That way, if something was wrong with the output, the failing part could be identified

quickly. Having completed the building steps of the project, the focus shifted to the harmonics part of the project. The harmonics was very time consuming and the part that the team hadn't had much experience before in previous classes. It took a lot of time to work out the fine details and finalize the build in order to have something working for the end of the project.

3.2 DC to AC Inverter Circuit

Understanding the DC to AC inverter was the first step to starting the project. This kind of inverter has been done for many years, so it was hard to decide exactly what steps to take in order to find one that worked for this project. Several MQP's and a graduate thesis have previously done similar projects at WPI. With this information, the team was able to design the high level block diagram from the combined use of this information along with other sources that was found useful. Early into the project, the inverter was completed and it worked to the specifications expected.

3.2.1 Full H-Bridge

As stated in the previous sections, a DC to AC inverter requires a bridge configuration. For this project the team decided to use a full bridge. The full bridge also used PWM signals generated by a bi-level PWM configuration. In order to make things simply, a bi-level PWM was used. Before the circuit was built, it was simulated using PSIM. As it was explained earlier, in order to create the PWM pulses, a sine wave and triangle wave were used as inputs to a comparator. To achieve the alternating signals, the inverted method using two separate comparators is used. One of the first problems the team came up with when simulating the circuit on PSIM was finding the correct amplitude of the sine and triangle wave. It was discovered that the amplitude for the waveforms could not be the same and that the triangle waveform had to be

slightly larger than the sine wave. This was required so that the sine and triangle waves always intersected.

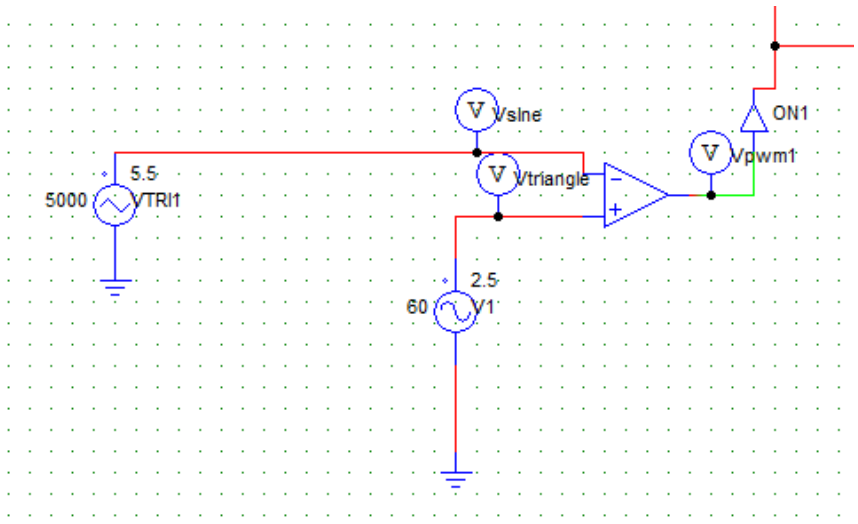

Figure 19: First PWM Circuit simulation schematic

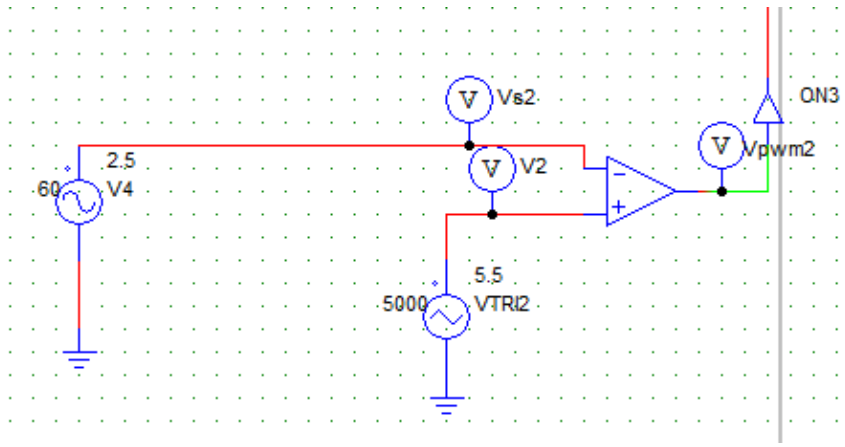

Figure 20: Second PWM Circuit simulation schematic

For the actual project the LM311N comparator and a function generator and Variable transformer (variac) were used to produce the appropriate reference and carrier waves. Figure 19 and Figure 20 correspond to the figures below in Figure 21. These figures will be explained in greater detail later when they become more relevant, but they are important to this part of the project. They show the outputs from the schematics of Figure 19 and Figure 20 when simulated.

The triangle and sine wave entering the circuit with an inverter outputs the opposite PWN signals.

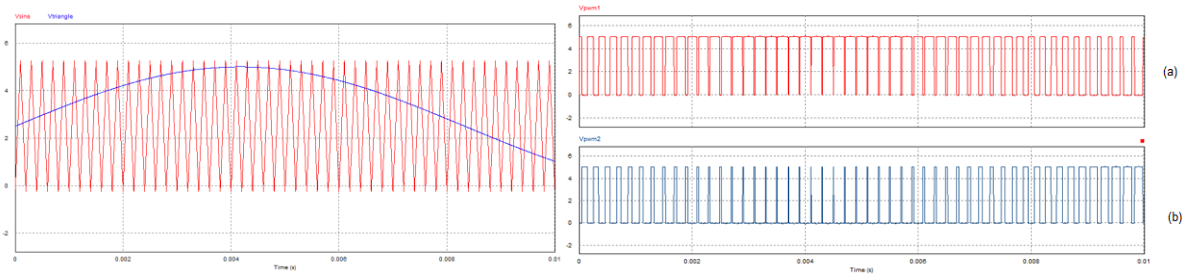

Figure 21: Output for Figure 19 and Figure 20

These figures were very important to this project as they display the very first necessary piece working.

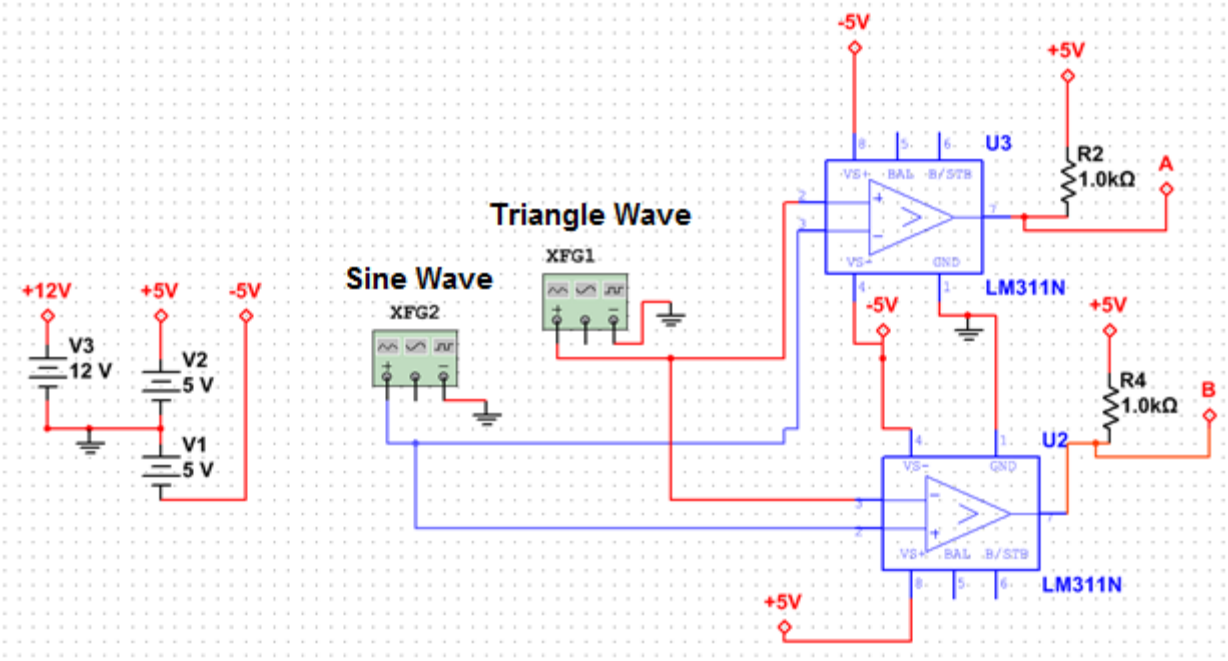

Figure 22: PWM circuits used to control the MOSFET drivers

Figure 22 shows the PWM generators for the H-bridge and MOSFET drivers. A sine wave and triangle wave are used as the inputs. The LM311N required pull up resistors. Also, the rails of the PWM are controlled by the rails of the LM311N. Although a LM311N can work off of a

single 5V supply it is essential to create and provide a ±5V to avoid any unexpected PWM results.

The H-Bridge in this project used all NMOS Transistors, IRF520Ns. This was due to the IRF 520N's built in freewheeling diode as well as the NMOS's ability to source more current at the semiconductor level.

The MOSFET required a special driver to turn it on and off without creating a short circuit. Also, since NMOS transistors are being used, the voltage on the high side of the H-Bridge had to be a lot higher than the low side. This was fixed with a bootstrapping capacitor. The team had to test the circuit in various configurations to see what worked best. In order to get the high side of the driver to work, a correct bootstrapping capacitor had to be picked. The capacitor value was picked by using the supporting equations in the user's guide of the IR2110. Using these equations and the MOSFET data sheets, it was calculated that the driver needed at least a 26.86 nF capacitor. However, when the team tried using this value in the circuit, the team found that the high side of the driver was not working. The team talked to professors on campus who had worked with MQP groups that used this chip in the past, and tried to get advice from them. Since there isn't much data on the IR2110, there were a couple of weeks where the team had to do a lot more research on the chip to figure out why it isn't working.

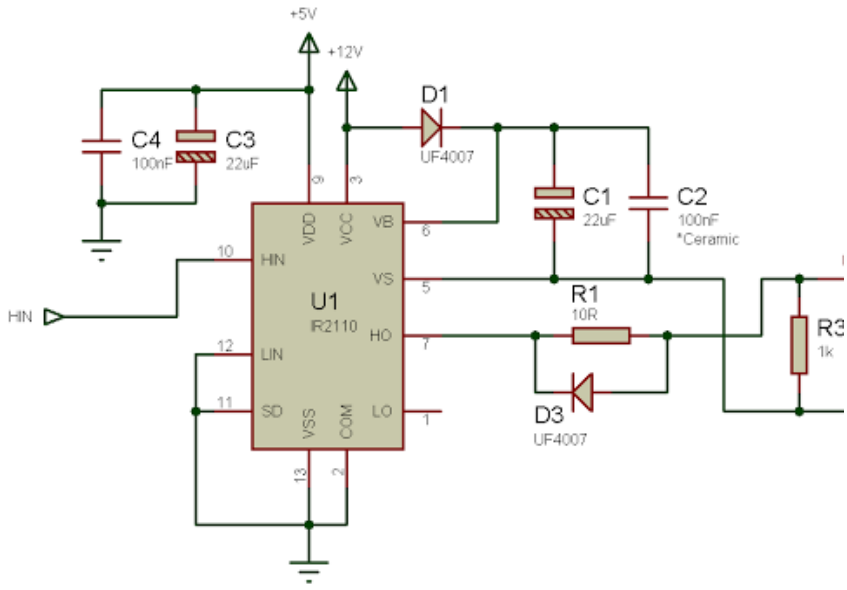

Figure 23: High Side Test Circuit [11]

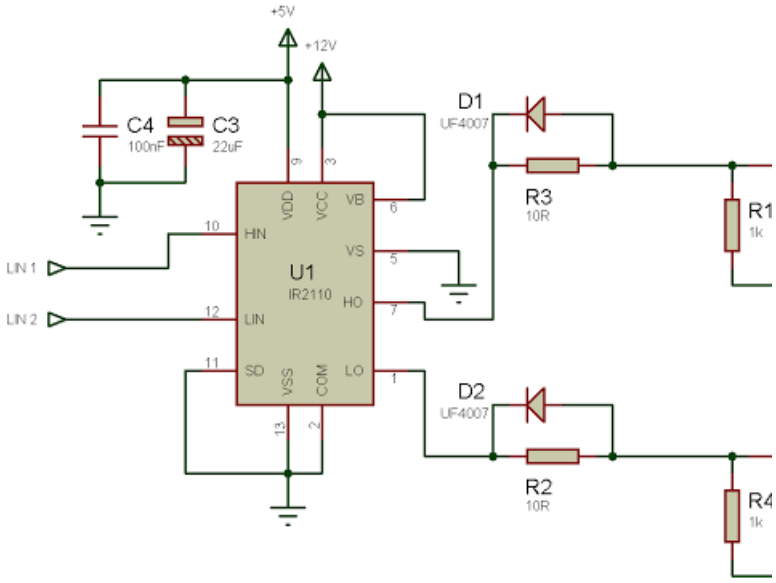

Figure 24: IR2110 used as a double low side driver [11]

During one of the searches, a high side test circuit shown in Figure 24 was found. Since the low side is working correctly, the only problem seemed to be with the high side since it

would not give a pulse like it is supposed to. Before the high side was tested on its own, it was tested as a low side to see that the driver was functioning correctly. This was done using the circuit shown on Figure 23. It was found that the driver was working correctly and that the high side and low side each worked on its own. The team had to raise the bootstrapping capacitor to 2uF before the high side started working. Also, the two grounds were necessary in the design. The team decided that this was acceptable and could move on to further implementation of the project.

By building an H-Bridge, the team was able to control the load. The H-Bridge allows the load to go over it in either direction. Before building the Full Bridge, a smaller much simpler circuit was simulated first. A Half H-Bridge, as shown in Figure 25 was simulated first to see how the voltage across a simple load would be affected. It can be seen in the circuit that the circuit uses two capacitors on the other side of the H-Bridge. Again, this was just testing the NMOS to make sure that it was behaving properly. By testing, a lot of time was saved because things are seen before it was put into the overall picture. The team could also tell when there was going to be a problem and fix it early in the process. This was also a way to familiarize the team to the IR2110 since these drivers were what controlled the NMOS. It was a safe way to get the drivers to work since if the entire full bridge was set up first, there would’ve been a higher chance of a short circuit.

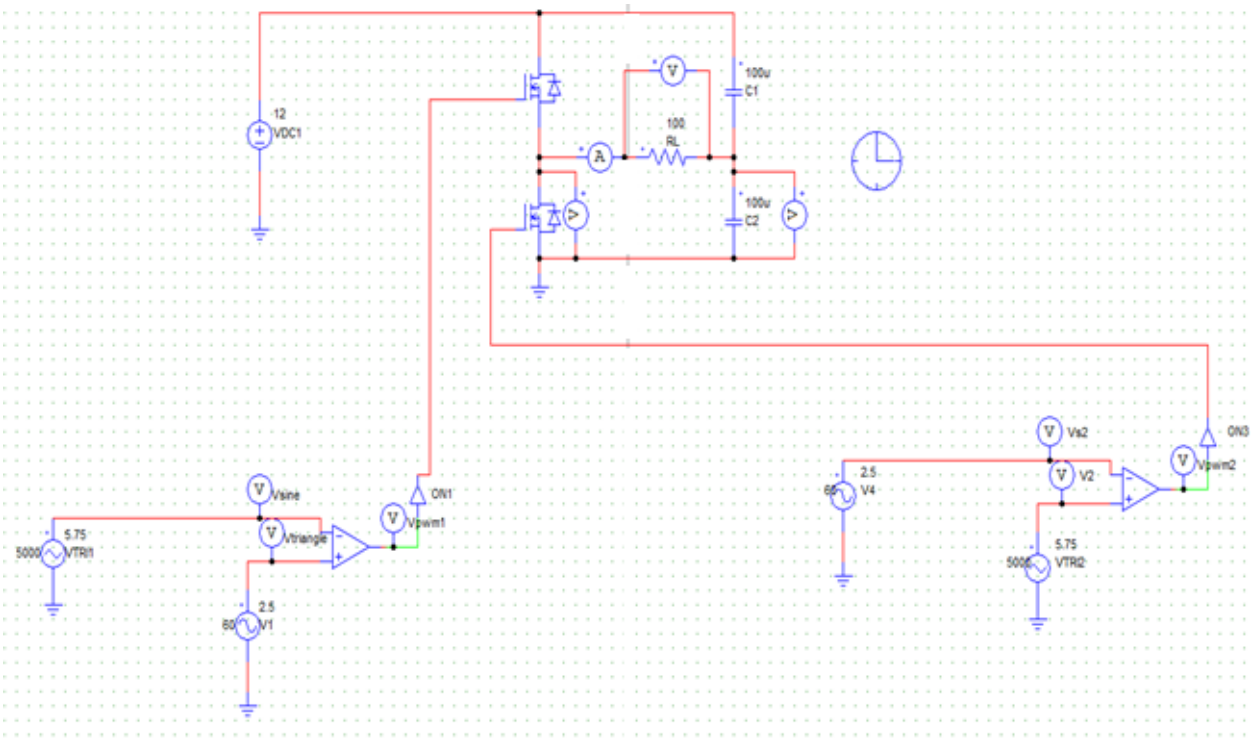

Figure 25: Half H-Bridge

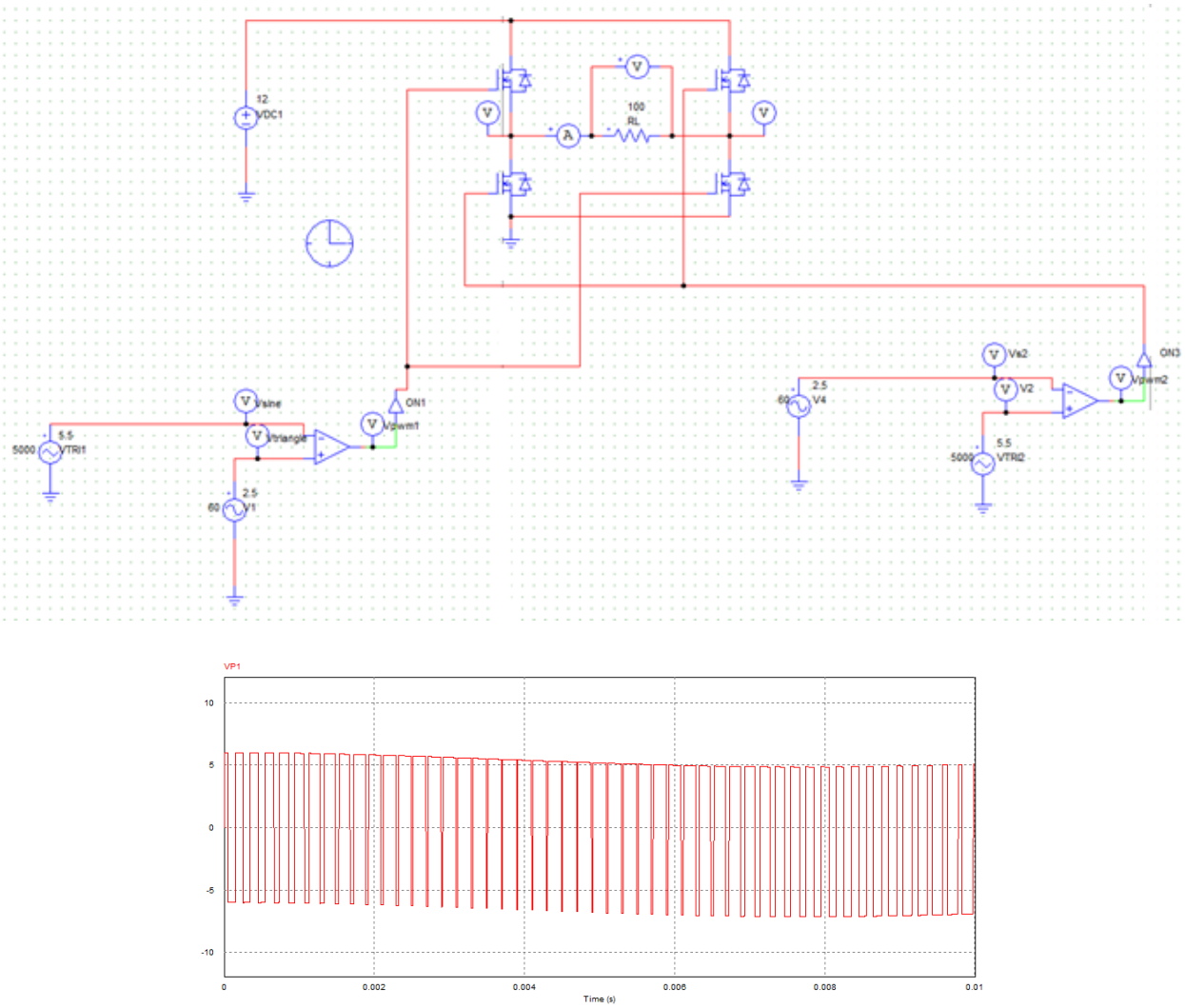

Figure 26: Full H-Bridge Simulation Circuit

This circuit was built in order to simulate how a full H-Bridge would work after the team tried the half bridge. It was essential to build these in two pieces so that the team knew what was being looked at. Once one side was done successfully, then it was just a matter of copying the work that was done onto the opposite side. The figures above, Figure 25 and Figure 26, are just a simulation and not how the actual circuit could be built in a lab setting. Figure 26 also shows the output on an oscilloscope for the schematic. The final DC/AC inverter schematic resulting from these decisions and tests is displayed in Figure 27. This is a circuit that can be built.

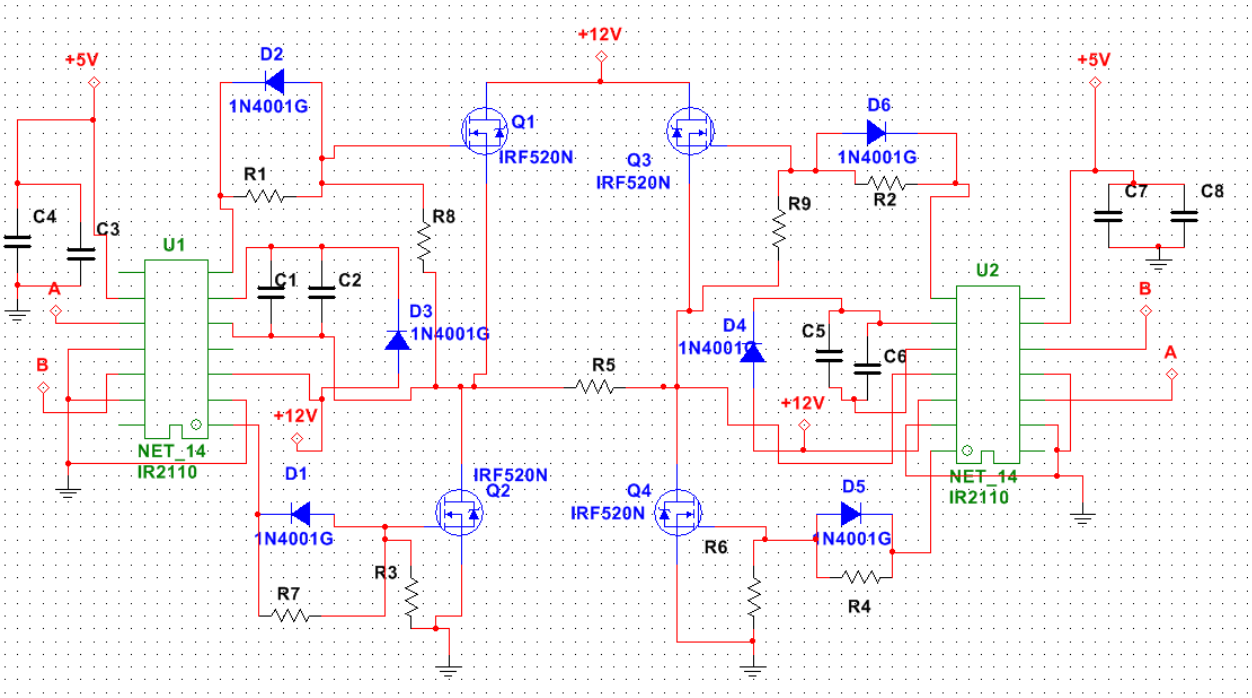

Figure 27: Full H-Bridge Schematic

Figure 27 shows the most detailed H-Bridge, using the specialized IR2110 ICs, IRF520Ns. Nodes A and B are referring to the PWM circuits in Figure 22. This is what the team built on breadboards in order to show a working full H-Bridge.

As should be noted, the IRF2110 is not a part of Multi-sim which was why the part on the schematic does not have labeled pins. Even so, the IRF2110 was very important to the circuit since it provided the necessary voltage to turn the high side MOSFETs on. Each MOSFET was turned on by the PWM signal that was created by the comparator earlier in the circuit.

3.3 Reactive Power Compensation circuit solution

In order to complete the project, it was decided that compensating for the Reactive Power would be the best method for completion. The team wanted to compensate for the reactive power in order to improve the power quality to loads attached to utility line. In theory,

demonstrating the ability to use the H-bridge configuration to compensate for reactive power also improves the ability to compensate for any type of harmful current including harmonics.

In order to demonstrate the ability to compensate for reactive power the current and voltage of the system needed to be identified. A voltage source in series with an RL load produced a lagging current that was approximately 90^{o} out of phase with the voltage.

As this sample circuit shows:

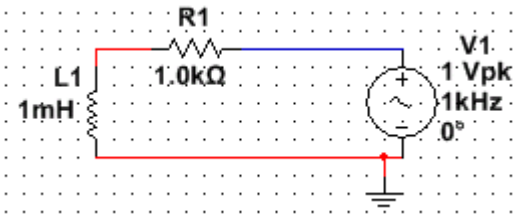

Figure 28: Sample Circuit AC voltage with RL Load

To properly observe the V-I characteristics the sample circuit from Figure 28 was modeled on PSPICE. The following is PSPICE code in order to create the circuit.

Sample Circuit AC Voltage with RL Load.CIR

VSine 1 0 SIN(0 1 1000)

R1 1 2 1000

L1 2 0 1m IC=0

.OPTIONS ABSTOL=1n RELTOL=0.01

.Probe

.Tran 105m 105m 100m 80u UIC

.End

This phase shift causes power quality problems. The H bridge circuit needed to produce a current through a coupled inductor that was 180 degrees out of phase with the leading current through

the inductor and approximately the same magnitude. The result of these combined currents should be a current that was completely in phase with the voltage.

To test this, the final configuration of the entire system which included both the sample circuit and the Bridge compensator was simplified and modeled as:

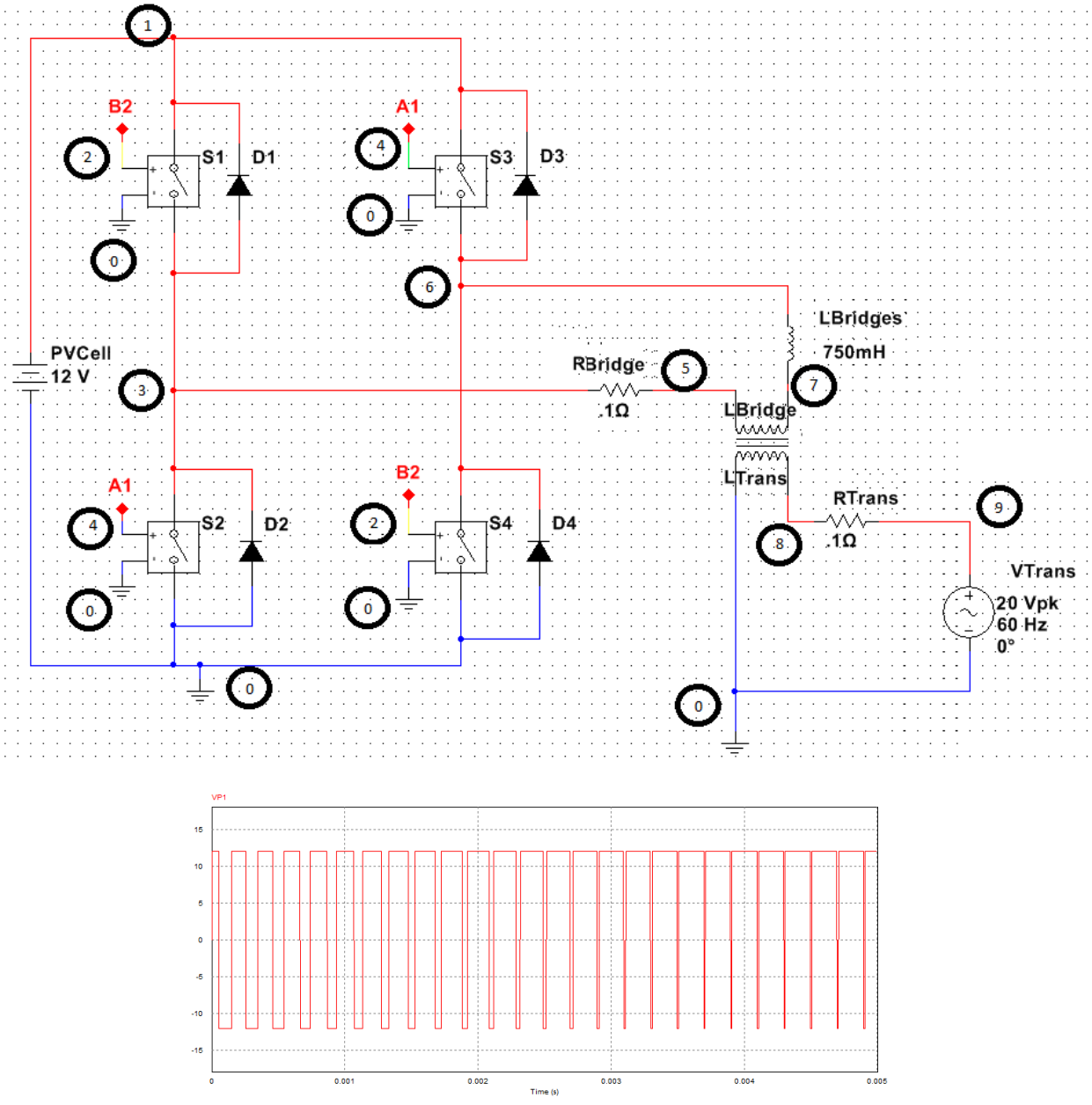

Figure 29: Simplified Schematic model of entire system

The PSPICE representing this circuit is:

PSICE MQP.CIR

***H bridge set up**

VPVCell 1 0 DC 12

S1 1 3 2 0 Zwick

D1 3 1 dix

S2 3 0 4 0 Zwick

D2 0 3 dix

S3 1 6 4 0 Zwick

D3 6 1 dix

S4 6 0 2 0 Zwick

D4 0 6 dix

***mechanical switch + diode is similar to MOSFET**

.model Zwick VSWitch(Ron=2m Roff=10MEG Von=1 Voff=0)

.model dix D(Rs=1m BV=200)

RBridge 3 5 .1

LBridge 5 7 5 IC=40m

LBridges 7 6 750m IC=32m

***IC required due to DC offset from outside of steady state**

***PWM Creation**

EB2 2 0 TABLE {V(P,N)}= -10,-5 -0.001,-5 0.001,5 10,5

EA1 4 0 TABLE {V(N,P)}= -10,-5 -0.001,-5 0.001,5 10,5

RIN P N 1MEG

VSine P 0 SIN(0 1 60)

VTri N 0 PULSE(-1.2 1.2 0 125u 125u .25u 250.5u)

***in actual circuit rather than dependant sources comparator outputs are used**

***AC LINE set up**

Ltrans 8 0 5 IC=-51m

***IC required due to DC offset from outside of steady state**

Rtrans 8 9 .1

Vtrans 9 0 SIN(0 20 60)

K LBridge Ltrans .995

***Coupling constant near perfect**

.OPTIONS ABSTOL=1n RELTOL=0.01

.Probe

.Tran 350m 350m 300m 80u UIC

.End

Above the PSPICE modeling for it, Figure 29 shows the circuitry used as well as the oscillogram. It was very important to note what the voltage across the load looks like.

After testing the concept tested in Figure 29, one more step had to be implemented. The sine wave signal controlling the PWM needed to be the same exact signal that was used in the sample circuit side of the system. This was achieved through using the variac and producing a smaller amplitude component of the utily line in a voltage divider.

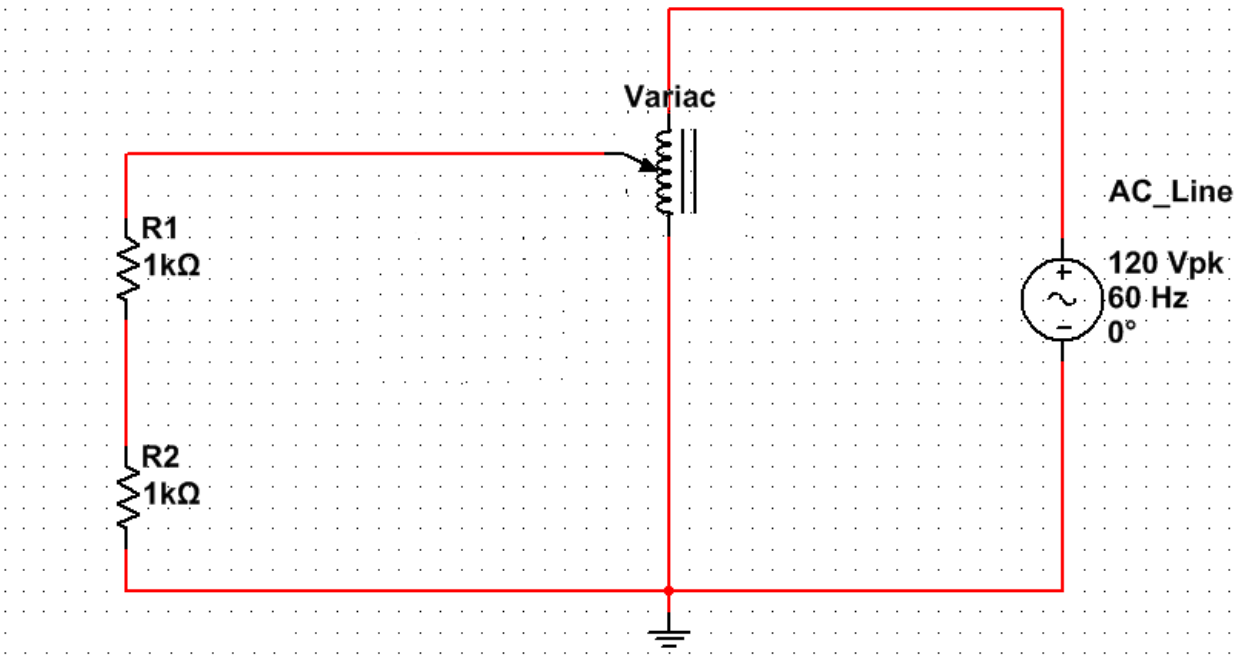

Figure 30: Voltage divider on variac

The circuit was behaving as expected and remains fixed and always componensates for the same amount of reactive power. To achieve full control of the amount of reactive power componensation, rather than using a regular voltage divider to reduce the sine wave used in the PWM reference, a voltage divider between a high value capacitor and adjustable resistor/ potentimeter needed to be used.

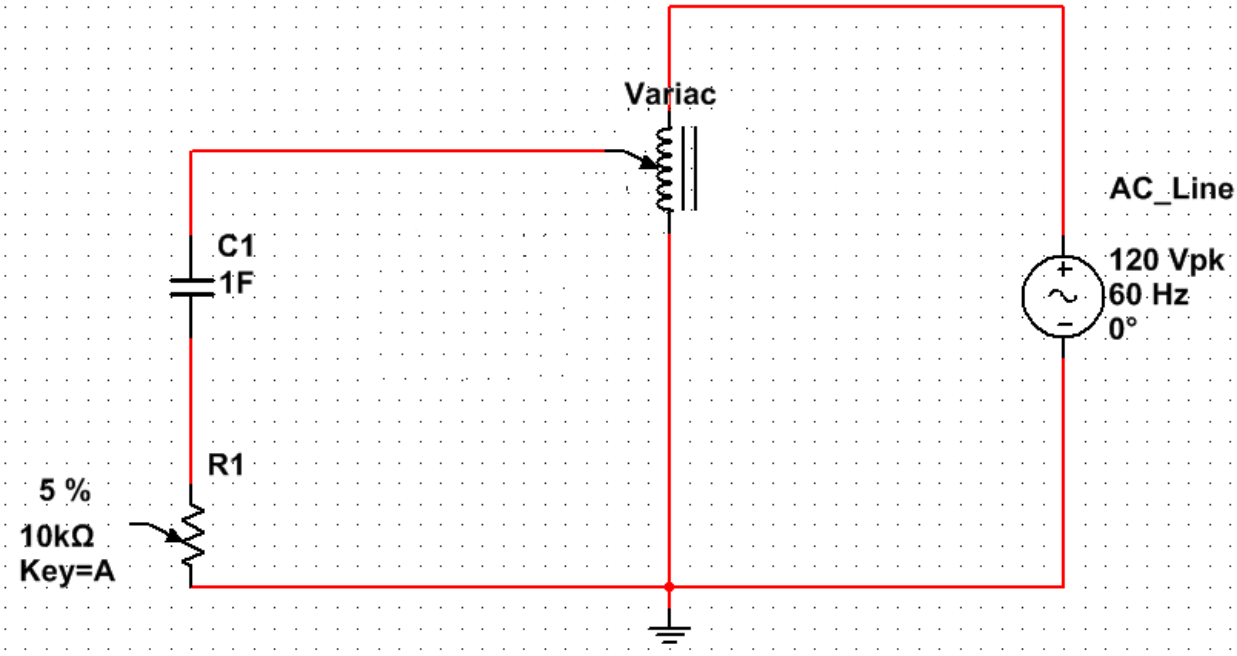

Figure 31: Capacitor and Potentiometer divider on the variac

The final resulting system can be modeled and simulated on multisim.

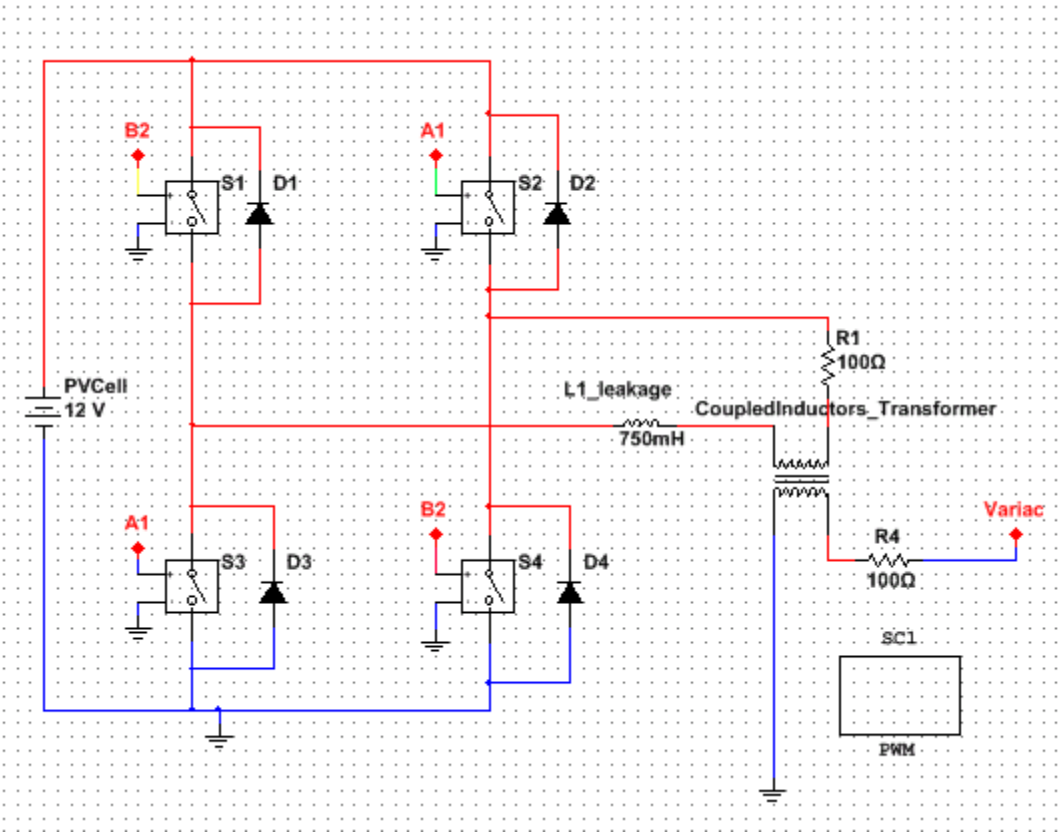

Figure 32: Simplest circuit Model

With a PWM input from:

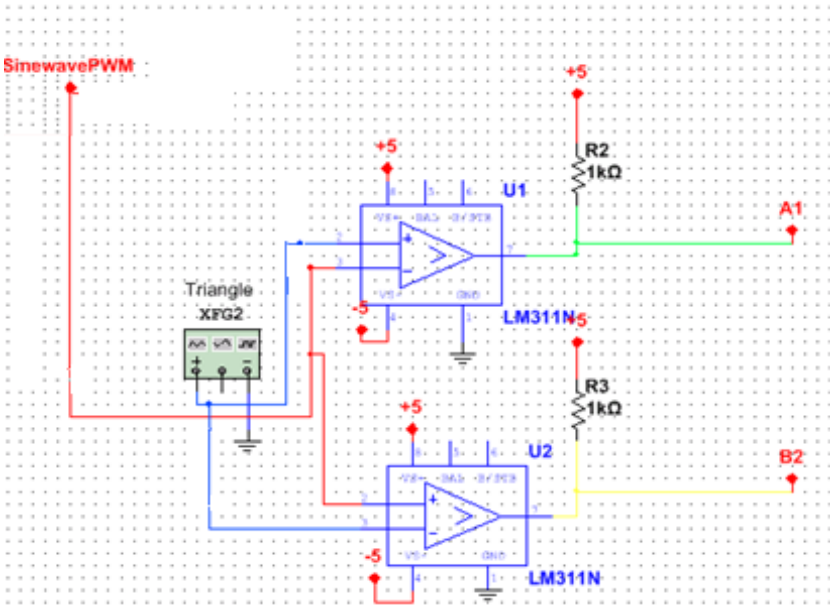

Figure 33: Sub-circuit 1 (SC1 PWM)

Only the triangle wave came from the function generator. The sine wave used the potentiometer and capacitor voltage divider. The 12V supply was from a lab power supply however in a real application this 12V supply would be a solar panel.

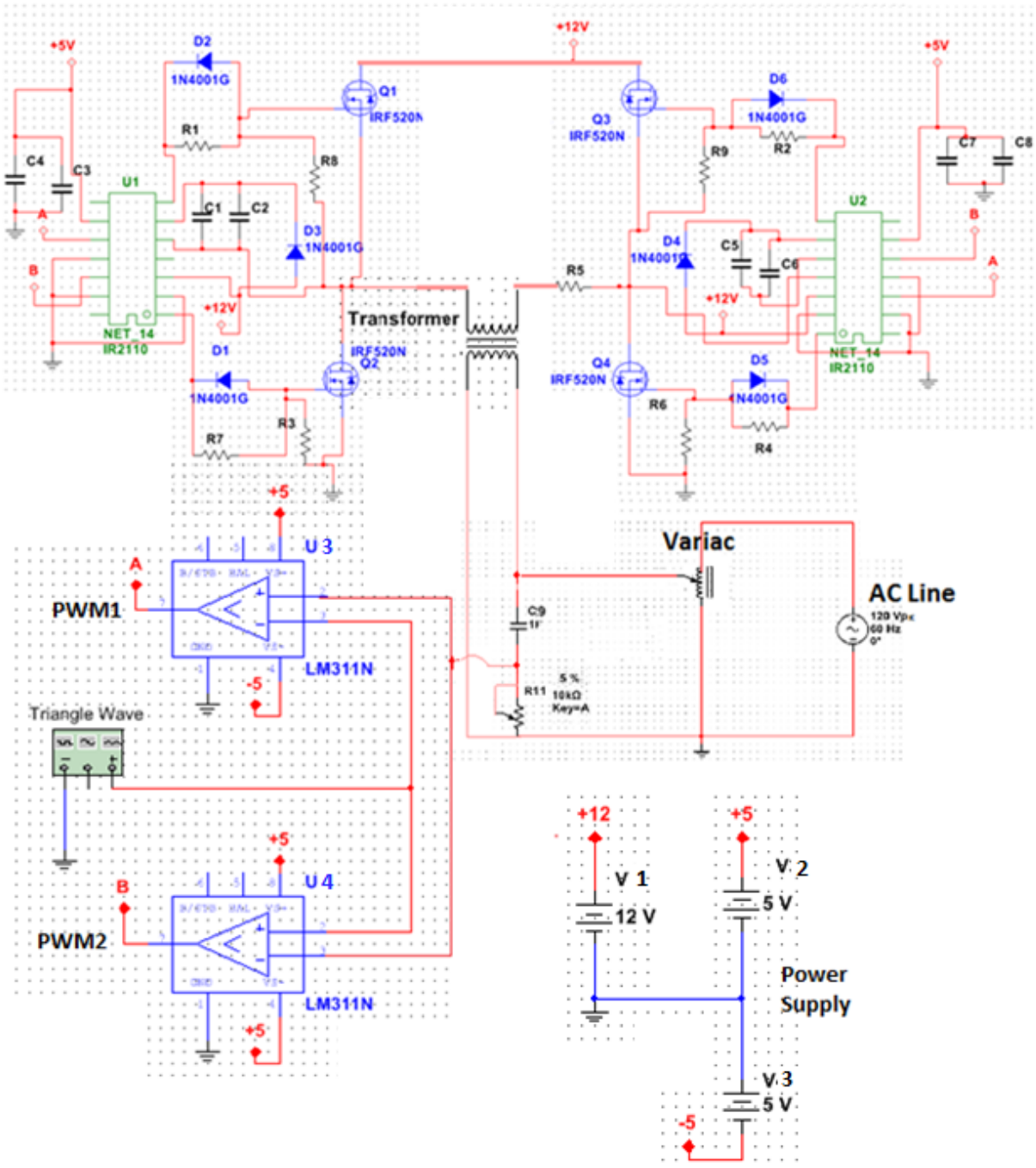

Figure 34: Final Schematic

Figure 34 shows the final schematic with all of the pieces of the circuit. This was a very important milestone in the project. The 5V and 12V supply was from the power supply. In a real world setting, these voltages would come from a solar panel and a voltage regulator would be needed to adjust to the necessary values.

4 Analysis

4.1 PWM Oscillosgrams and Observations

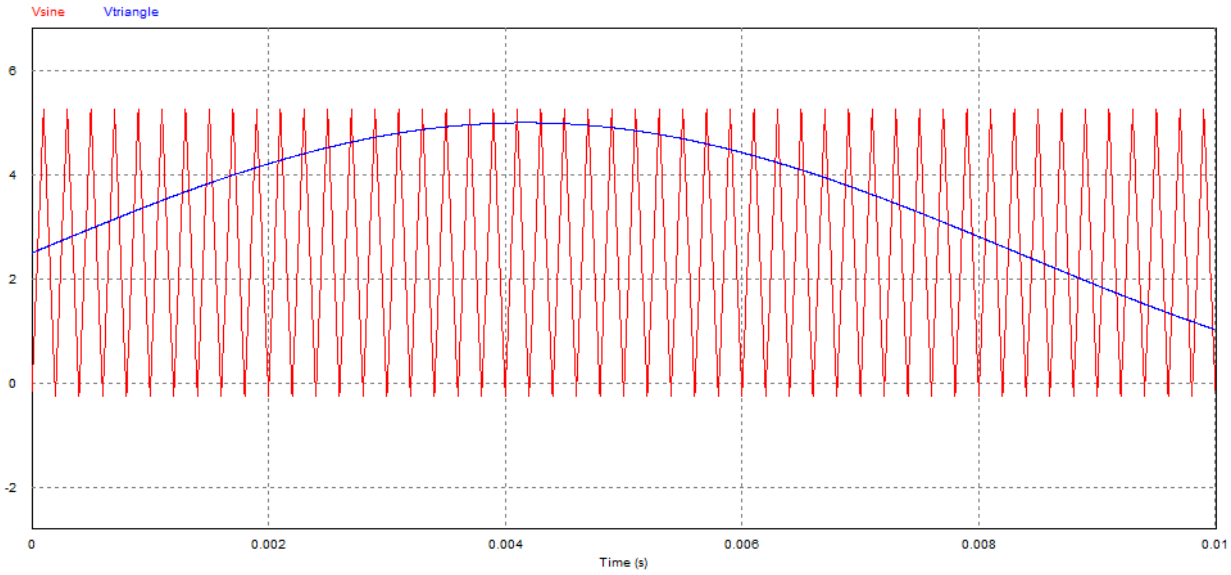

Figure 35: Triangle carrier wave and reference Sine Wave

The 5000HZ carrier triangle wave and 60Hz reference sine wave in Figure 35 were the result of one of the PSIM PWM circuit simulations from Figure 19 and Figure 20.

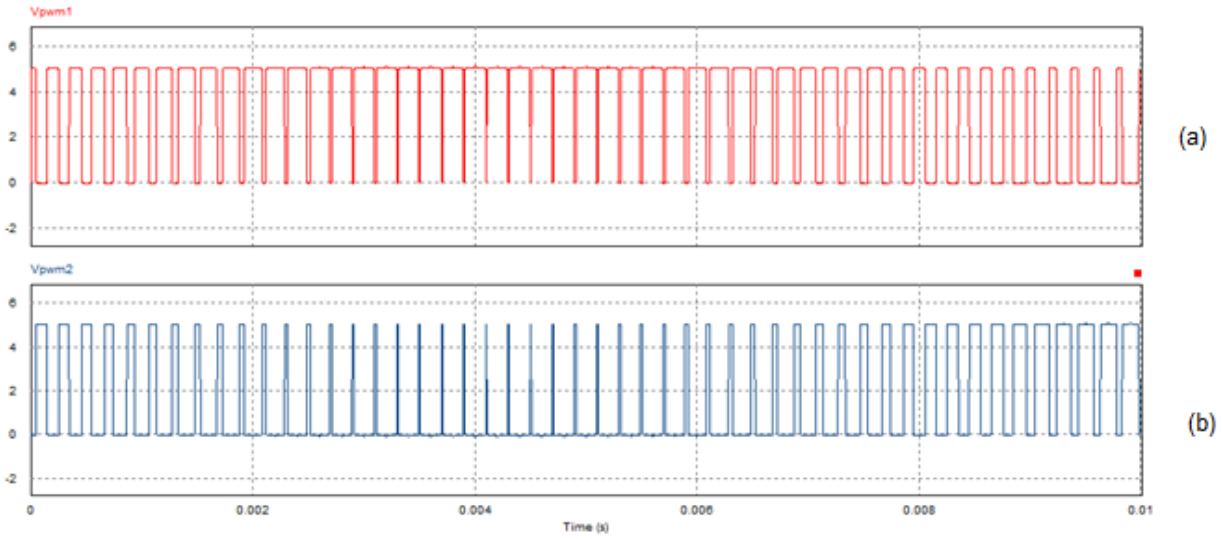

Figure 36: PWM output; (a) PWM from circuit in Figure 19 (b) PWM from circuit in Figure 20

As can be seen from Figure 36, when one square pulse was logic high, the other was logic low. They were constantly switching in turn with each other. The team had 2 NMOS always on, on opposite sides of each other, and 2 off constantly. They were switching, so that one set would be on, then one would be off. This was the result of the having 2 LM311N comparators. The important take away was that the triangle wave needed to be slightly greater in amplitude than the sine wave.

4.2 DC to AC Inverter Oscillograms and Observations

The results provided from the PWM controlled half bridge simulations were useful but not the most effective.

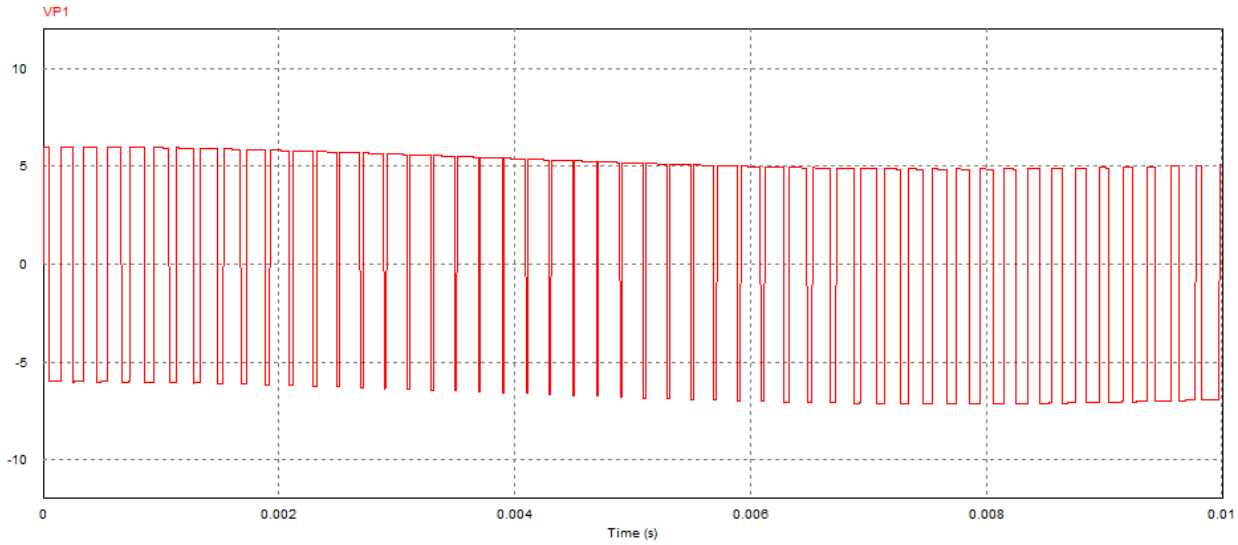

Figure 37: Voltage across the load for Figure 25

The simulation showed that the voltage across the resistor pulses between -5V and 5V. This made sense because when the low side is ON, there was negative current running across the resistor. When the high side was ON, there was a positive current path. The capacitors cause there to be a small ripple which causes the pulse to fluctuate from -7 to 5V and -5V to 7V.

The DC to AC inverter using a resistive load was simulated, debugged, built, and fully functional. The next steps included changing one device at a time and adding the inductive components to the load and observing the changes.

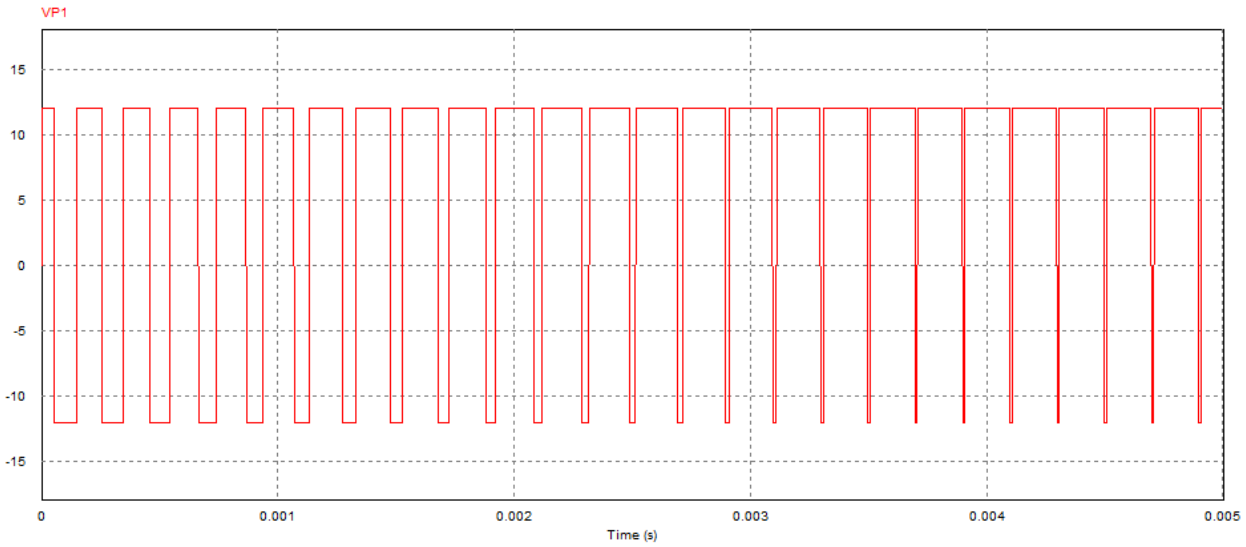

Figure 38: Voltage across the Load for Figure 26

This showed the output from the H-Bridge in terms of the voltage going across the load. It was very similar to the pictures seen earlier through research and what was expected to be seen as the output.

The goal for the H-bridge was to pulse between +12V and -12V as shown through the simulations. Before the team could see if the H-bridge would provide capacitive current to the load, it was necessary to see how it reacted to other loads. First, a purely resistive load was used. The expected results for the current and voltage are shown in the PSIM simulations below.

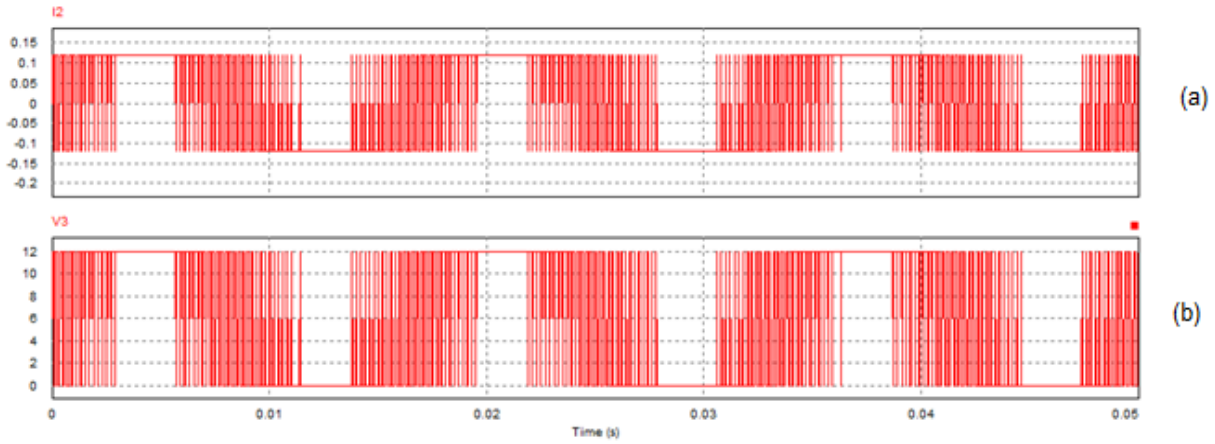

Figure 39: H-Bridge with Resistor Load (a) current through the resistor; (b) voltage across the resistor

As seen above in Figure 39, the current and voltage are both in phase across the resistor. As seen below in Figure 40, the H-bridge circuit reflects the expected results and was in phase with the voltage. This verified that the circuit worked like planned.

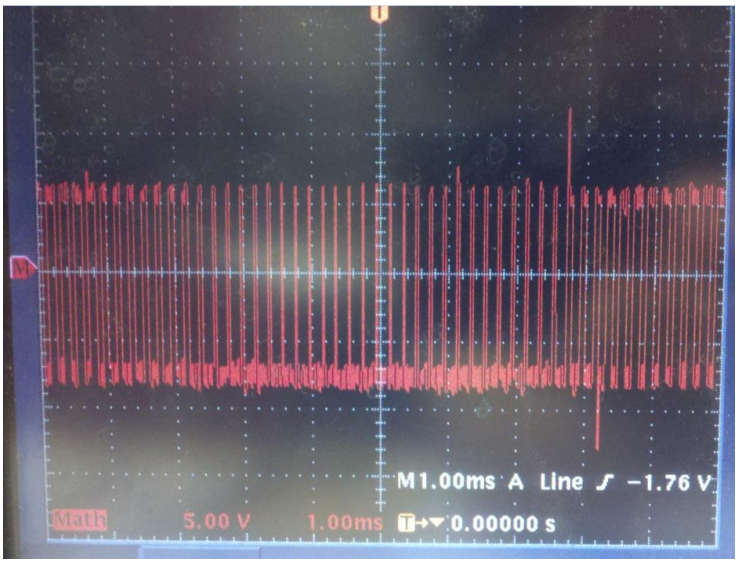

Figure 40: H-Bridge Voltage with a resistive load

Since the oscilloscope that was used only has two probes, it was not possible to see the current and voltage on the same screen. Since both were in phase, the voltage and current looked very similar.

Next, the resistive load was replaced by an inductor and resistor in series. The same resistor was used and a low inductance of 53mH was used. The simulations showed the following effect on the inductance.

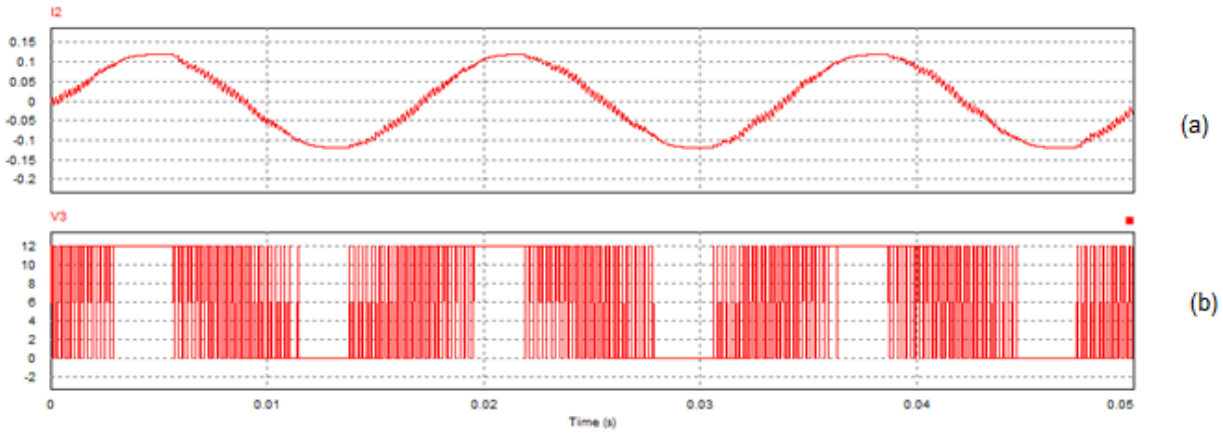

Figure 41: Oscillograms from H-Bridge with 53mH Inductor Load simulation (a) current through inductor; (b) voltage across inductor

The current and voltage can be seen above. The actual current has a very close similarity to the one that was simulated as seen below. It was seen that the current was much higher than expected. This was probably due to the voltage that could be producing a higher current than expected.

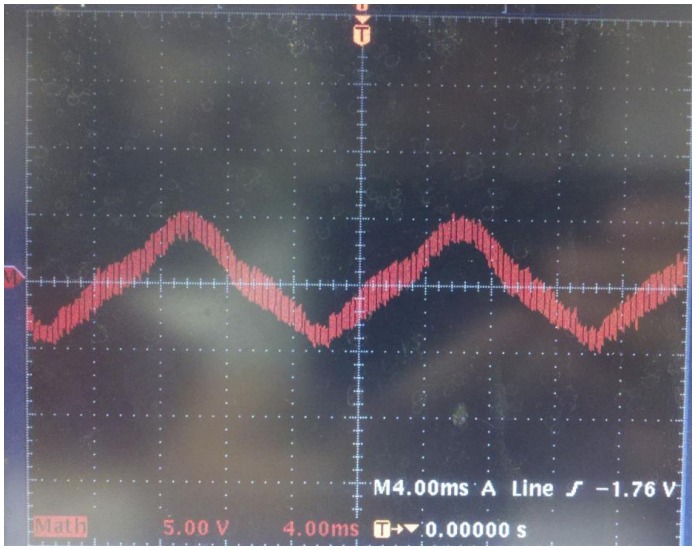

Figure 42: H-bridge Current with 53mH inductor load breadboard result

This inconsistency was due to several problems. The inductor used was nonlinear and poorly coupled to another inductor which could be coupling in some noise. Also the real application verse simulation was bound to produce differences naturally due to other non-idealities in components. The main reason for the lack of a cleaner sine wave was the fact that the inductor was a very low value. A higher inductance in the circuit would result in better filtering.

4.3 Reactive Power Compensator Oscillograms and Observations

4.3.1 Results from sample circuit

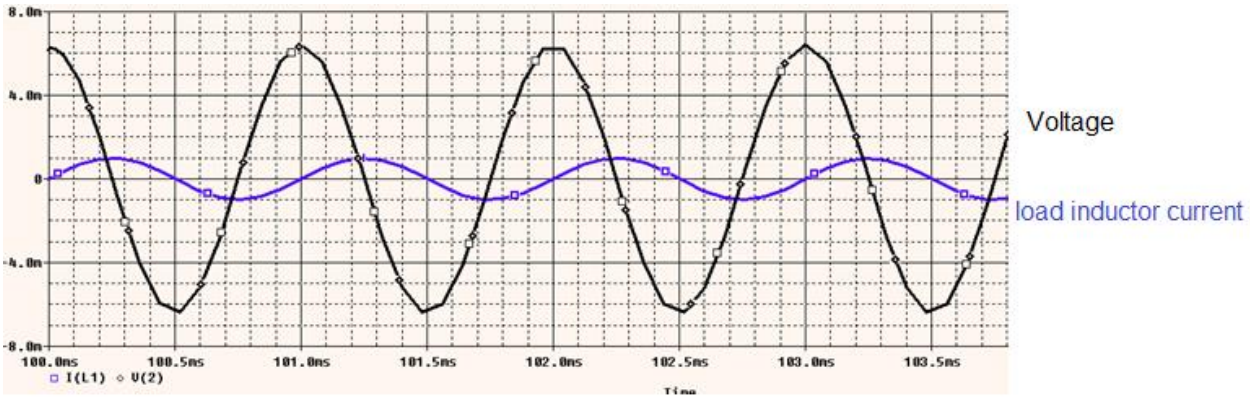

Figure 43: Voltage and current Oscillograms from AC voltage and inductor in series

The black waveform was the voltage across inductor L1. The blue waveform was the current through inductor L1. Notice that the current was lagging the voltage by approximately 90^{O}.

4.3.2 The results of the coupled H- Bridge

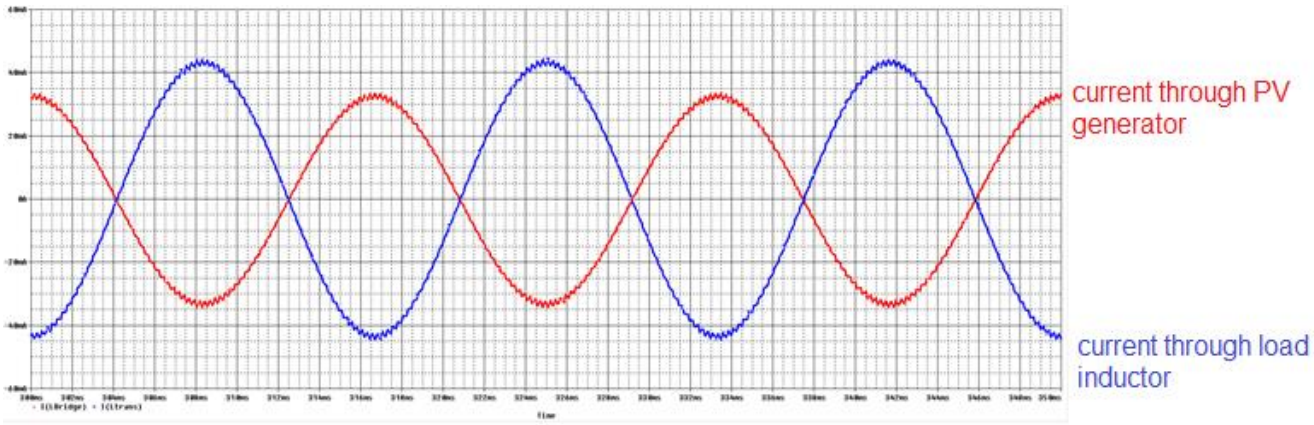

Figure 44: Capacitive and Inductive currents from the circuit in Figure 29

The red wave form in the figure was the capacitive current produced in the H-bridge compensator. The Blue waveform was the inductor current produced from the sample circuit RL load. It seemed to be an ideal compensator because when multiplied the differences really show.

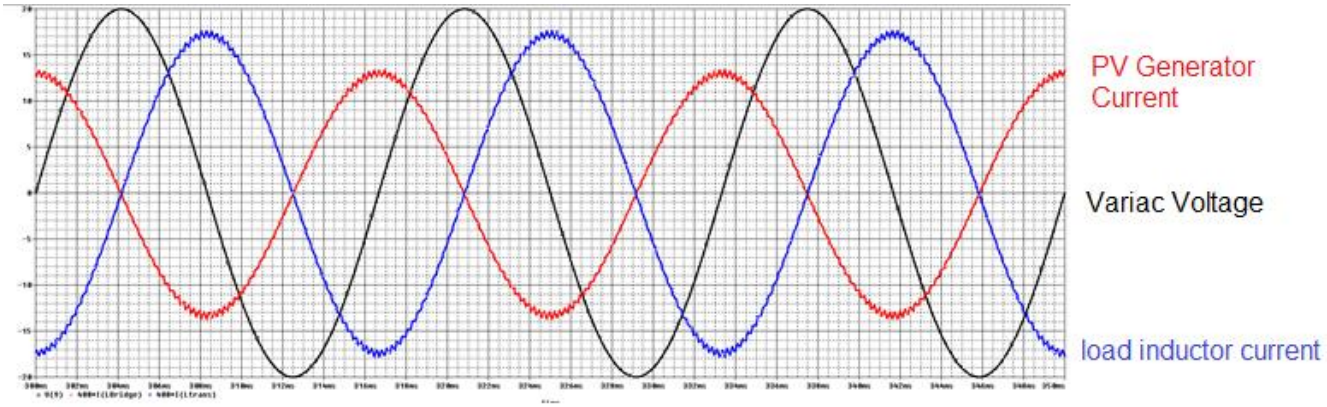

Figure 45: The opposite currents in relation to original Phase

The blue and red wave forms are the same as they were in Figure 45. The only difference is they are scaled up to match the relative magnitude of the original phase voltage. The original phase voltage was the voltage from the utility line which is VTrans in the schematic and PSPICE.

To understand how much compensation was still required the team take the sum of the two currents to help better visualize things.

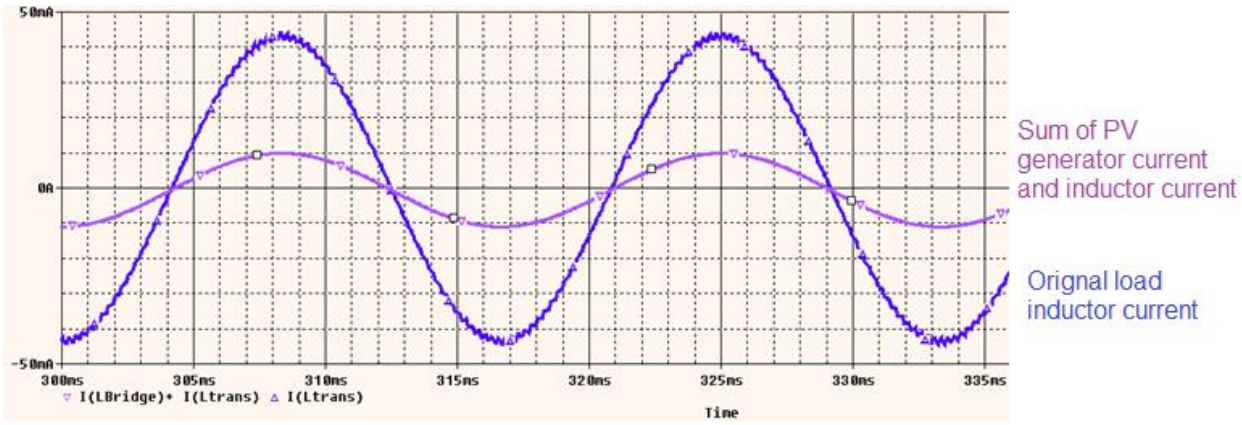

Figure 46: Compensated Current and original inductive current

The blue wave form represented the inductive current. The purple waveform was the sum of the blue and red waveforms from Figure 46. The purple was significantly smaller than the original value thus the reactive power was reduced by almost 80%. The reduction in reactive power increased the value of the TRUE power portion of the power triangle.

4.3.3 Full system results

The simulation in Figure 47 and oscilloscope image in Figure 48 was where the transformer was used as the load of the H-Bridge. It was realized that the voltage from the ‘AC line’ was too high for the circuit and therefore two resistors are added. Both are 100 ohms and cause the current on the ‘AC line’ side to look like the current below.

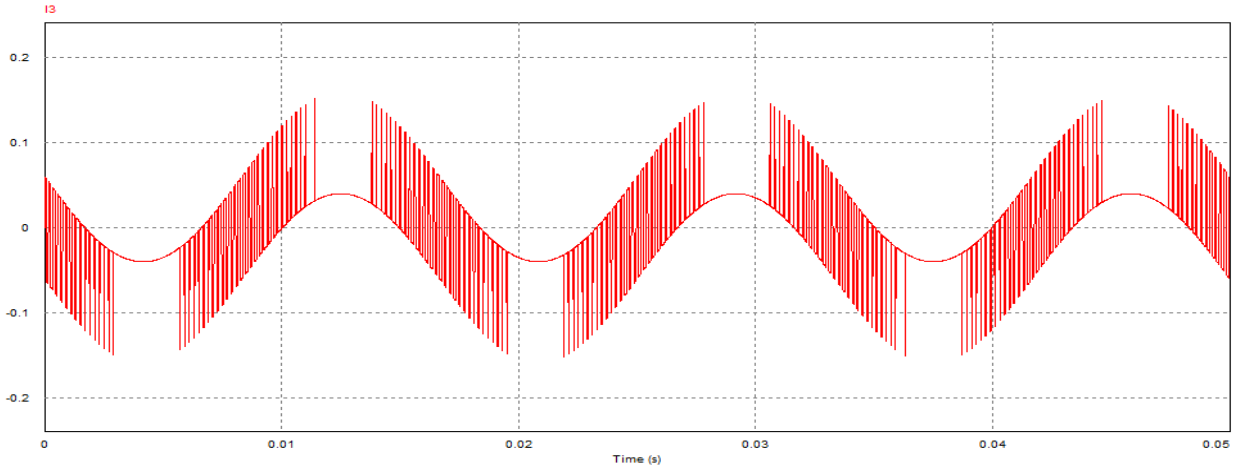

Figure 47: H-Bridge Current with Transformer

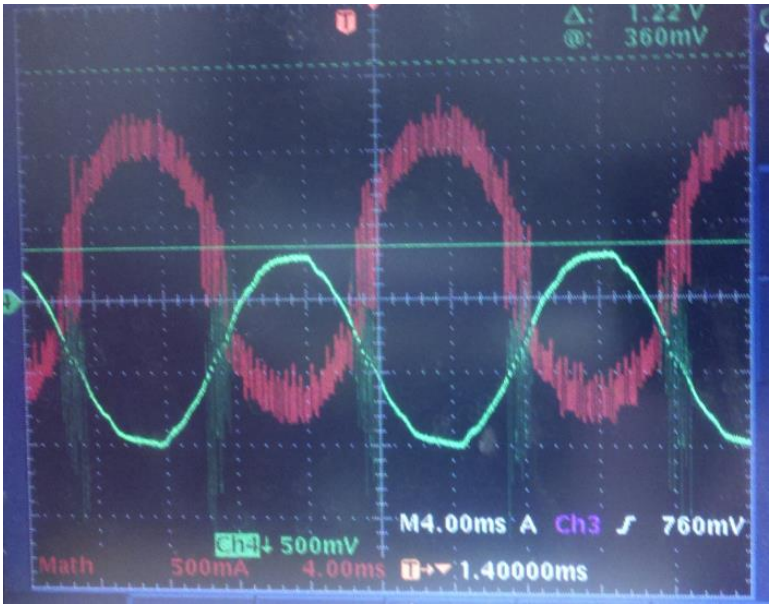

Figure 48: Voltage and Current Output from Transformer

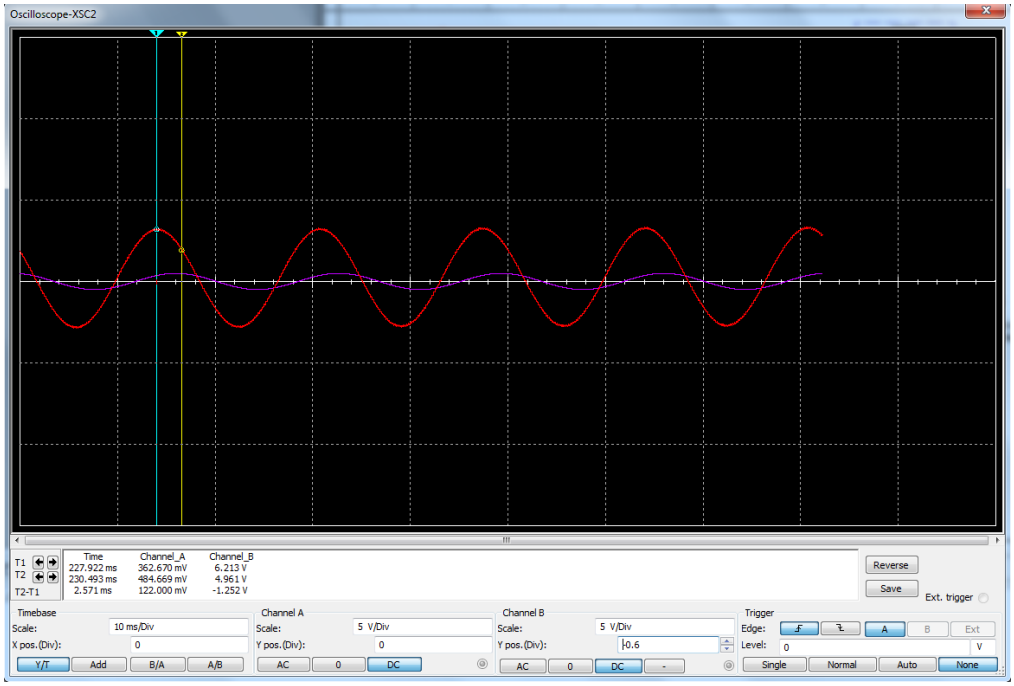

Figure 49: Output when potentiometer is 2%

The red waveform in Figure 49 is the current through the resistor in the H-bridge. The purple wave form is the voltage across the potentiometer. The phase shift is (2.571/16.667)*(360) = 55^{O}

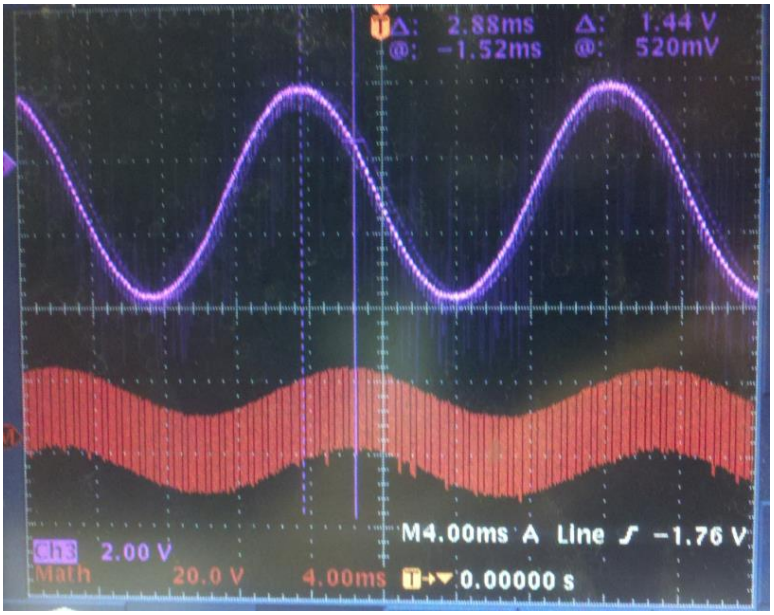

Figure 50: Potentiometer about 2%: Voltage and Current from H-Bridge side of transformer

The red wave form in Figure 50 was the current through the resistor in the H-bridge. The purple wave form was the voltage across the potentiometer. The phase shift is calculated (2.88/16.667)*(360) = 62^{O} which was about the same as the simulated result.

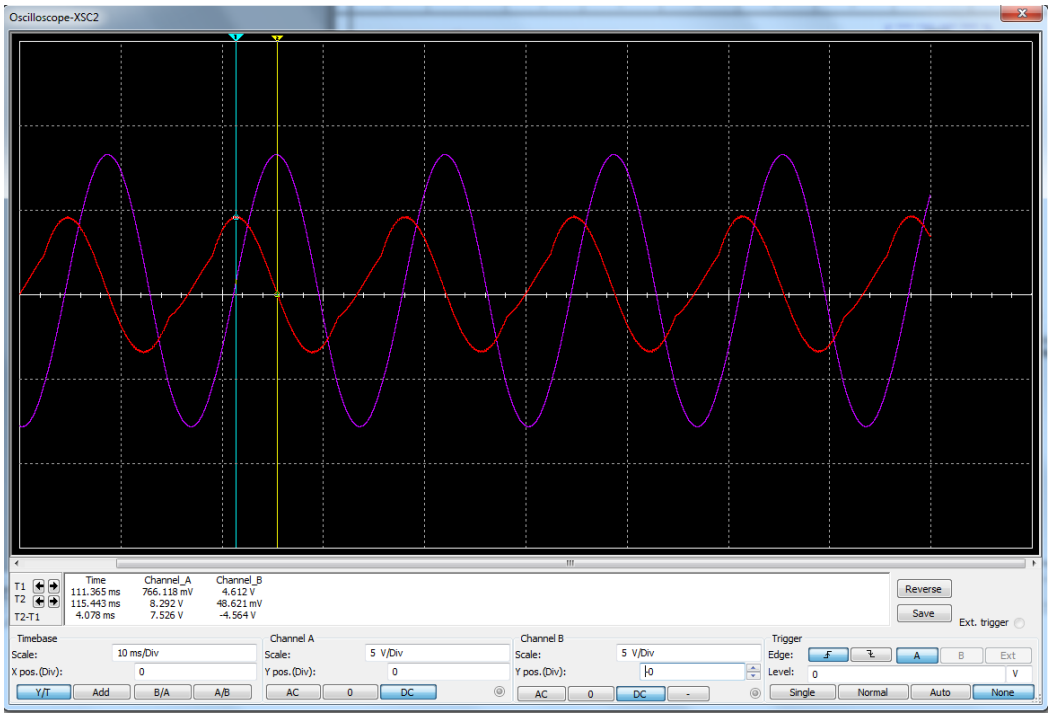

Figure 51: Output When Potentiometer is at 50%

The red waveform in Figure 51 was the current through the resistor in the H-bridge. The purple wave form was the voltage across the potentiometer. The phase shift is calculated at (4.078/16.667)*(360) = 88^{O}.

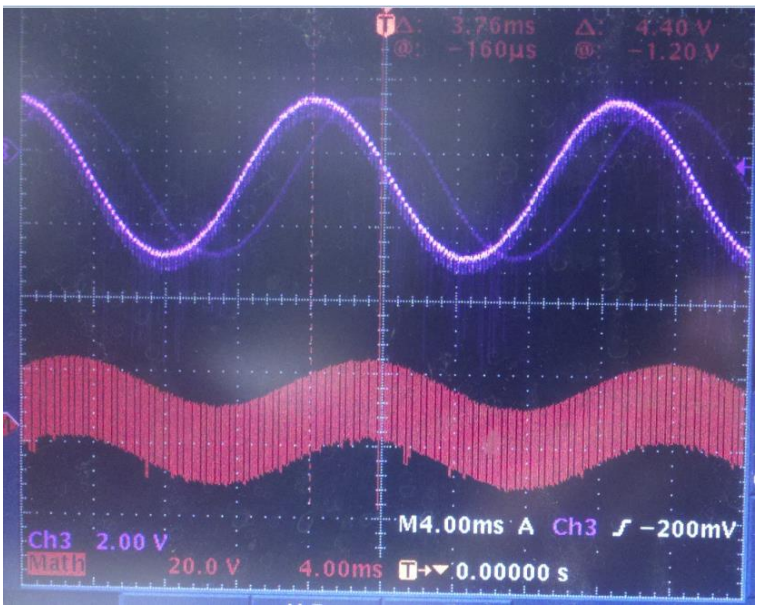

Figure 52: Potentiometer 50%: Voltage and Current from H-Bridge side of transformer

The red wave form in Figure 52 was the current through the resistor in the H-bridge. The purple wave form was the voltage across the potentiometer. The phase shift is calculated at (3.76/16.667)*(360) = 81^{O} which is about the same as the simulated result.

The simulated results were pretty consistent with the measured results from the actual system. The numbers had a few differences but the overall simulations provided a waveform phase shift range of around 30^{O}. The values actually measured from the breadboard set up provided a waveform phase shift range of around a little less than 30^{O}. This proved that an H-bridge can compensate reactive power through a coupled inductor with a pretty wide range of phase shift through the adjustment of a potentiometer controlling the PWM signal used to control the switching mechanism of the transistors.

5 Conclusion

In conclusion, the ever-increasing reliance of electronic devices that utilize AC power has increased the amount of harmonics that pollute the distribution systems. This project demonstrated that a photovoltaic generator can be used to provide reactive power and harmonic compensation. The simulated circuits and reduced scale circuits were constructed and confirmed the feasibility of an active filter. The results of this project showed that a photovoltaic source can be used to actively filter harmonics by compensating for reactive power, thus completing and proving the original concept.

There was a clear difference in the voltages and currents when the power supply was turned on. That suggests that the system was compensating for some of the reactive power and that the results for the output are accurate. The overall goal was to create a PWM and H-bridge, use a variac and transformer, and compensate for the reactive power. All of these elements were used or built in order to make this project work. Numerous hours were put into this project, and with the help of the project advisor, it was possible to have a completed MQP that did compensate for the reactive power.

Most of the parts came within the ECE lab kits, or parts were borrowed from the shop which will be returned at the completion of this project. The only pieces that were bought were the IR2110 chips, otherwise the team stayed well within the budget. Buying the variac and transformer new, however, may have possibly put the team above the budget.

This project can be built upon more in the future, and it definitely should be. There are a lot of things that can be focused on and improved for the longevity of this idea. In the future, it would be great to see this being used in practical applications, but that will only happen with continued technological breakthroughs from MQP students.

5.1 Recommendations

In the future, the team recommends that this project be improved upon based on the work that already had been done. A lot of time was spent getting the IR 2110 to work, but now that it has been proven to work, a future group could take this project further. More functionality could be added, the sine wave could be cleaner, or a way to make this project more compact. Any of these things could turn into a new MQP as they each present a new challenge for future students to tackle.

Right now, the team has a lot of very large components that take up a lot of space. It isn't very feasible to move this project to show, because of how easily wires can become lose and break the entire project. In the future, it should be soldered together once the best combination of parts are put together. The team also has two pieces that are very difficult to decrease the size of. The transformer and the variac are very large since they are older pieces that the team got from the shop and didn't have the budget or time to purchase brand new. Soldering the boards in the future would save a lot of space, especially if a circuit board was designed especially for this project. The project was spread across 4 bread boards that were all connected together. The power supplies and grounds were all connected, but it was very easy for something to slide out of place, fall out, or to not make contact with the board. In the future, a new design would be necessary in order to make this more compact and more practical for real life applications.

There was also a lot of extra components that could be added in order to make a better triangle wave. The triangle wave isn't as clean as it could have been, so in trials the team used the function generator in order to have a clean and precise wave with the frequency that was desired. The team did this to make sure that the results were right, but in a real life situation a

function generator wouldn't be used at all because it would all be dependent upon components within the circuit.

If there is more time, a 12V battery could be used in place of the power supply. The team used 5V and -5V rails, so a simple circuit would regulate the voltage to what it needs to be. The team did some research on this, but decided that it would be better to continue to use the power supply so that components wouldn't be damaged. That would make the project slightly easier to move around for presentation reasons. However, the variac still needs to have a wall outlet so a battery for the power supply only helps with mobility slightly, but improves the quality of the project and the overall feasibility. In real life situations, power supplies can't be used for practical applications.

The last thing to be improved is the output of the sine waves. There was some noise in sine wave that could be filtered out with a little more research and work. This would give an even cleaner sine wave than what the team is getting. It was possible that the components are so old and that newer and more efficient pieces could really change the output of this project. With a larger budget, a better wave could possibly become the new output because newer components could be purchased.

Any of these recommendations would be really beneficial to this project. There was only so much that can be done in three terms, so building off of work that is already done was a major stepping stone into a new MQP that tackles the problems and improves the current project. There was a lot of insight in this project, so future teams interested in power would really benefit from this work.

APPENDIX

A. Potential PWM harmonics solutions:

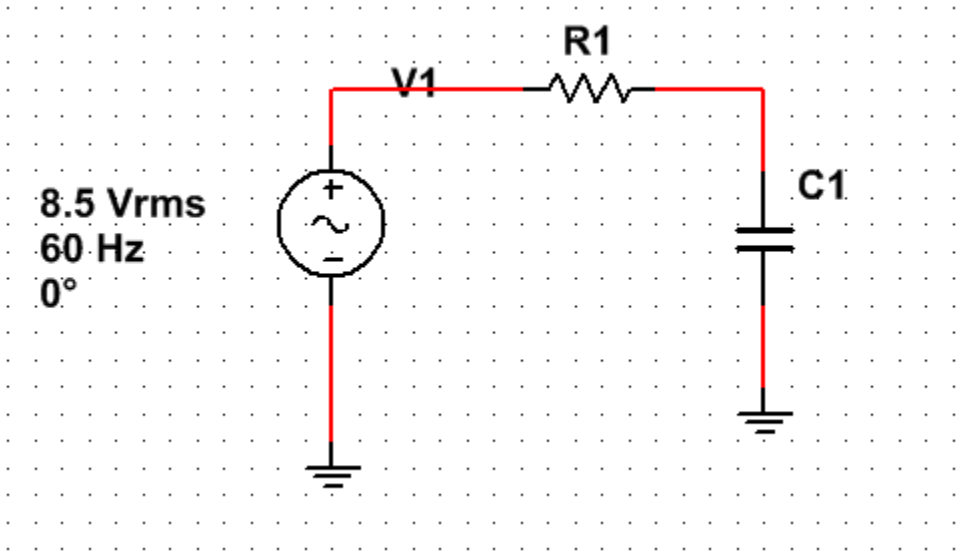

Figure 53: Low Pass Filter

It is understood that the harmonics exist in the PWM systems. Based off of the tables presented in Hart's power electronics book, it appears that simple passive filters could eliminate the high frequency harmonics. If this is the case it seems like a low pass filter could be used to reject the harmonics. The first challenge is figuring out where to connect a low pass filter. There are only two options: series or shunt with the RL load.

Low pass filters could have a pole frequency that is lower than the first harmful harmonic which sounds like it should work but then choosing appropriate values becomes a different issue. Another issue that comes up is understanding that the overall performance can be completely different from their individual performances. The sine wave is really the output of the PWM H-Bridge which means adding a capacitor (an energy storage device) to the H-bridge with the inductive load will really be a second order system. Second order systems have a resonant

frequency which could lead to different problems. Another passive filtering solution is implemented for a multiphase system. The last circuit that seemed promising is a three phase system shown below.

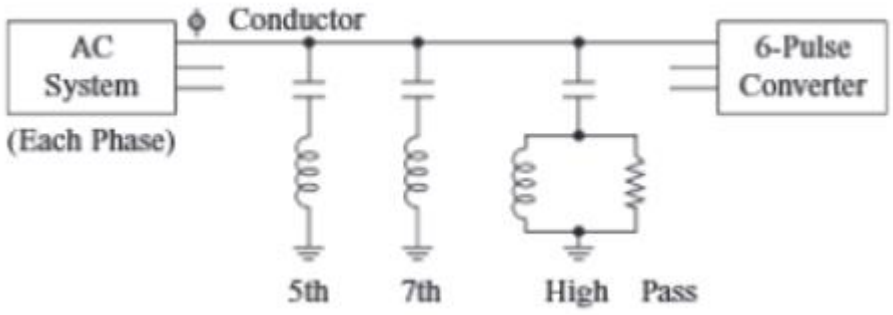

Figure 54: Multiple phase filtering [7]

This system seems to isolate certain harmonics and then just generally compensates for everything with that last filter. Each combination of the L and C seem to be used to sink the certain values.

Another idea that came up in research is Power Factor Correction. The power electronics book has some interesting configurations resulting in much higher power factors however the circuit is another bridge and its output is a DC voltage which is not exactly what we are looking for.

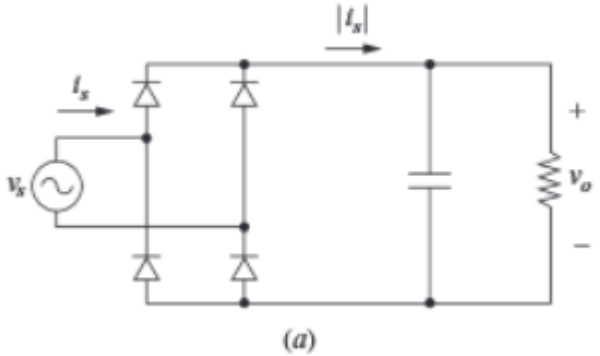

Figure 55: AC to DC Circuit [7]

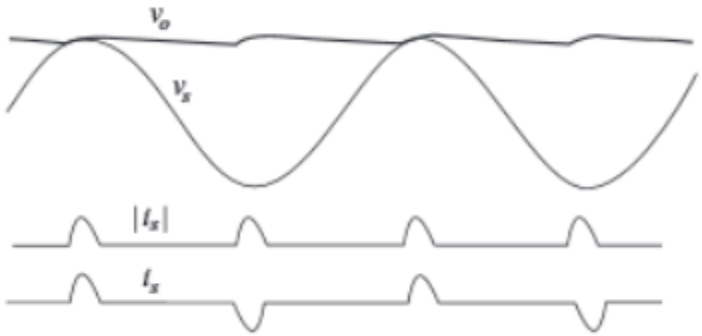

Figure 56: Waveforms corresponding to the AC to DC circuit [7]

The V_O is the top two waves. The input wave is the sine wave, the near flat line is the rectified wave. The two nonlinear, near sinusoidal ripples represent the source current. The top ripple is the absolute value and the bottom ripple is the actual ripple. Notice that the ripple is in phase with the input voltage. The power factor correction circuit works similarly to a boost inverter.

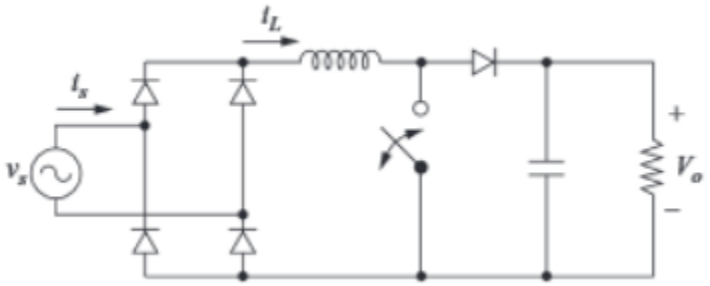

Figure 57: Power factor correction circuit for an AC to DC Circuit [7]

The circuit above uses the switch to control the amount of current in the rectifying process. This control results in a circuit practically 100% in phase with the input sine wave.

Figure 58: The current through the inductor [7]

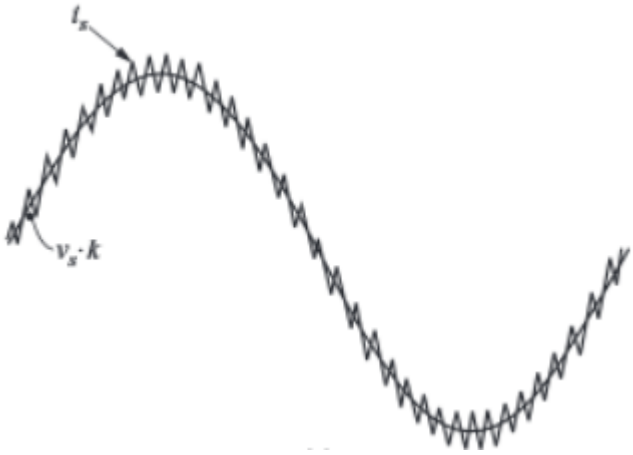

Figure 59: The source current in phase with the input sine wave [7]

With knowledge on Power Factors, apparent power, and real power this result is great. The team knows that the Power factor is

P = V_{RMS} x I_{RMS} x Cos (phase angle between the current and the voltage)

The waveforms above are in the same phase which means the power should be at the maximum value. The team studied this circuit and see if there is some comparable AC to AC circuit.

B. Potential Solutions Smart Active Filters:

In terms of the active filtering there are several ideas that could be used. The team understands that the active filtering can't be a passive operation like solving the predictable harmonics. We looked into several different circuits and tried to understand their functions. The

team also acquired some IEEE documents to review for a better understanding of the issue. Through research the team was able to get a firm understanding on the importance of implementing an active filter on the grid but still have not confidently created a solution. The ideas the team currently have involve some sort of control circuit possibly using thyristors (there are plans on running simulations with switch controlled diodes).

The circuit configuration the team wants to look into is called a single-phase AC Voltage Controller. The Single-phase AC voltage controller uses parallel thyristors which are practically voltage controlled diodes. The combination of these devices with the input voltage of a sine wave allows a portion of the input to be released across a load depending on the voltages applied to the third terminal of the thyristors. The team observed some really interesting results from this sort of circuit configuration and believe that this circuit can be used or at least pieces of it for the active filtering portion of the project.

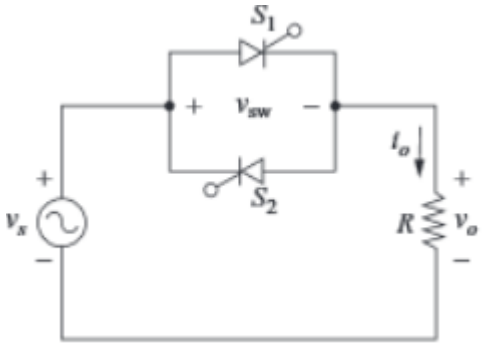

Figure 60: SCR Circuit [7]

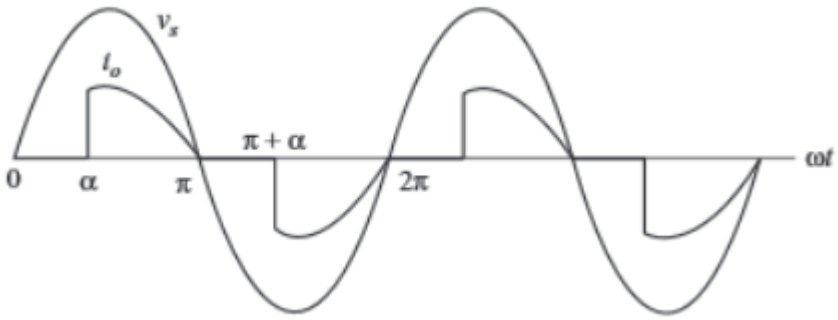

Figure 61: Sample of the output from the SCR circuit [7]

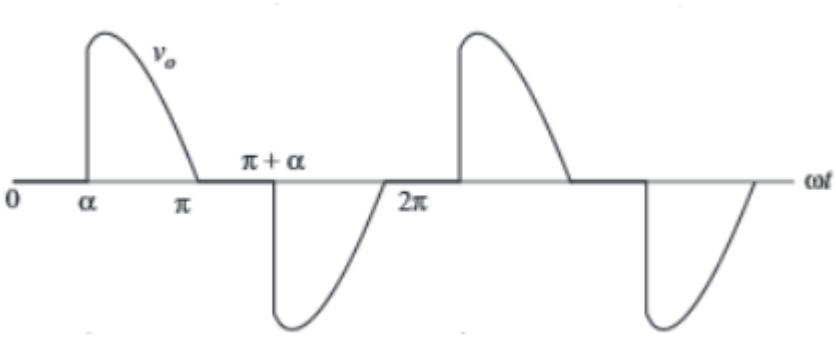

Figure 62: The voltage measured across the SCRs [7]

This wave form seems like something the team can use to compensate the nonlinear load parasitic currents.

C. Sine, triangle, and square wave circuit

Using a circuit to simulate the effects of a function generator, the team is able to completely take them out of the equation and rely more heavily on circuits that is built. The basic idea of the circuit is below, and is tweaked certain elements to work the way that is desired.

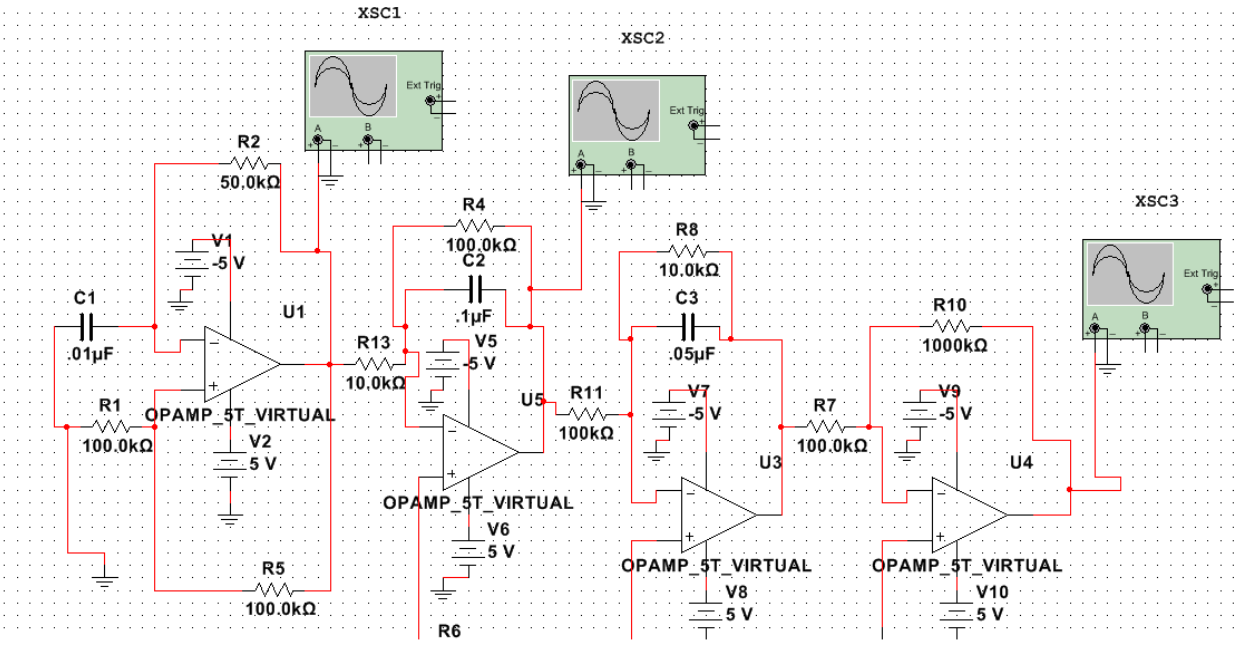

Figure 63: Function Generator Circuit

The first part of the circuit outputs a square wave. The second part outputs a triangle wave. The very end of the circuit outputs a sine wave. The team had to tinker with some of the resistor and capacitor values in order to get the desired results for each section. The results that the team is looking for were correct when a clean wave at the correct frequency for the rest of the circuit is achieved. This circuit made it possible for the project to be one step closer to being stand alone. With an added voltage regulator, the team got it even closer to that ideal image.

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