NECAMSID

DC/AC Pure Sine Wave Inverter

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Introduction

This report focuses on DC to AC power inverters, which aim to efficiently transform a DC power source to a high voltage AC source, similar to power that would be available at an electrical wall outlet. Inverters are used for many applications, as in situations where low voltage DC sources such as batteries, solar panels or fuel cells must be converted so that devices can run off of AC power. One example of such a situation would be converting electrical power from a car battery to run a laptop, TV or cell phone.

The method in which the low voltage DC power is inverted, is completed in two steps. The first being the conversion of the low voltage DC power to a high voltage DC source, and the second step being the conversion of the high DC source to an AC waveform using pulse width modulation. Another method to complete the desired outcome would be to first convert the low voltage DC power to AC, and then use a transformer to boost the voltage to 120 volts. This project focused on the first method described and specifically the transformation of a high voltage DC source into an AC output.

Of the different DC-AC inverters on the market today there are essentially two different forms of AC output generated: modified sine wave, and pure sine wave[1]. A modified sine wave can be seen as more of a square wave than a sine wave; it passes the high DC voltage for specified amounts of time so that the average power and rms voltage are the same as if it were a sine wave. These types of inverters are much cheaper than pure sine wave inverters and therefore are attractive alternatives.

Pure sine wave inverters, on the other hand, produce a sine wave output identical to the power coming out of an electrical outlet. These devices are able to run more sensitive devices that a modified sine wave may cause damage to such as: laser printers, laptop computers, power tools, digital clocks and medical equipment. This form of AC power also reduces audible noise in devices such as fluorescent lights and runs inductive loads, like motors, faster and quieter due to the low harmonic distortion.

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1 ABS Alaskan

Problem Statement

In the market of power inverters, there are many choices. They range from the very expensive to the very inexpensive, with varying degrees of quality, efficiency, and power output capability along the way. High quality combined with high efficiency exists, though it is often at a high monetary cost. For example, Samlex America manufactures a 600 W, pure sine wave inverter; the cost is $289[2]. Meanwhile GoPower manufactures a 600 W inverter with a modified sine wave output (closer to a square wave); this model only fetches $69[3]. The high end pure sine wave inverters tend to incorporate very expensive, high power capable digital components. The modified sine wave units can be very efficient, as there is not much processing being performed on the output waveform, but this results in a waveform with a high number of harmonics, which can affect sensitive equipment such as medical monitors. Many of the very cheap devices output a square wave, perhaps a slightly modified square wave, with the proper RMS voltage, and close to the right frequency.

Our goal is to fill a niche which seems to be lacking in the power inverters market, one for a fairly efficient, inexpensive inverter with a pure sine wave output. Utilizing PWM and analog components, the output will be a clean sinusoid, with very little switching noise, combined with the inexpensive manufacturing that comes with an analog approach.

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[2] 600 Watt Pure Sine Wave Inverter. Donrowe.com.

[3] Go Power 600 Watt Modified Wave Inverter

Background

DC and AC Current

In the world today there are currently two forms of electricaltransmission, Direct Current (DC) and Alternating Current (AC), each with its own advantages and disadvantages. DC power is simply the application of a steady constant voltage across a circuit resulting in a constant current. A battery is the most common source of DC transmission as current flows from oneend of a circuit to the other. Most digital circuitry today isrun off of DC power as it carries the ability to provide eithera constant high or constant low voltage, enabling digital logic to process codeexecutions. Historically, electricity was first commercially transmitted by Thomas Edison, and was a DC power line. However, this electricity was low voltage, due to the inability to step up DC voltage at the time, and thus it was not capable of transmitting power over long distances[4].

$$\begin{gathered} V = IR \\ P = IV = I^{(2)} R \end{gathered} \tag{1}$$

As can be seen in the equations above, power loss can be derived from the electrical current squared and the resistance of a transmission line. When the voltage is increased, the current decreases and concurrently the power loss decreases exponentially; therefore high voltage transmission reduces power loss. For this reasoning electricity was generated at power stations and delivered to homes and businesses through AC power. Alternating current, unlike DC, oscillates between two voltage values at a specified frequency, and its ever changing current and voltage makes it easy to step up or down the voltage. For high voltage and long distance transmission situations all that is needed to step up or down the voltage is a transformer. Developed in 1886 by William Stanley Jr., the transformer made long distance electrical transmission using AC power possible[5].

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[4] Charpentier

[5] Bellis

Electrical transmission has therefore been mainly based upon AC power, supplying most American homes with a 120 volt AC source. It should be noted that since 1954 there have been many high voltage DC transmission systems implemented around the globe with the advent of DC/DC converters, allowing the easy stepping up and down of DC voltages[6].

Like DC power, there exist many devices such as power tools, radios and TV's that run off of AC power. It is therefore crucial that both forms of electricity transmission exist; the world cannot be powered with one simple form. It then becomes a vital matter for there to exist easy ways to transform DC to AC power and vice versa in an efficient manner. Without this ability people will be restricted to what electronic devices they use depending on the electricity source available. Electrical AC/DC converters and DC/AC inverters allow people this freedom in transferring electrical power between the two.

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[6] Charpentier

Inverters and Applications

Power inverters are devices which can convert electrical energy of DC form into that of AC. They come in all shapes and sizes, from low power functions such as powering a car radio to that of backing up a building in case of power outage. Inverters can come in many different varieties, differing in price, power, efficiency and purpose. The purpose of a DC/AC power inverter is typically to take DC power supplied by a battery, such as a 12 volt car battery, and transform it into a 120 volt AC power source operating at 60 Hz, emulating the power available at an ordinary household electrical outlet.

Figure 1: Commercial 200 Watt Inverter[7]

Figure 1 provides a idea of what a small power inverter looks like. Power inverters are used today for many tasks like powering appliances in a car such as cell phones, radios and televisions. They also come in handy for consumers who own camping vehicles, boats and at construction sites where an electric grid may not be as accessible to hook into. Inverters allow the user to provide AC power in areas where only batteries can be made available, allowing portability and freeing the user of long power cords.

On the market today are two different types of power inverters, modified sine wave and pure sine wave generators. These inverters differ in their outputs, providing varying levels of efficiency and distortion that can affect electronic devices in different ways.

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[7] Walmart.com

A modified sine wave is similar to a square wave but instead has a "stepping" look to it that relates more in shape to a sine wave. This can be seen in Figure 2, which displays how a modified sine wave tries to emulate the sine wave itself. The waveform is easy to produce because it is just the product of switching between 3 values at set frequencies, thereby leaving out the more complicated circuitry needed for a pure sine wave. The modified sine wave inverter provides a cheap and easy solution to powering devices that need AC power. It does have some drawbacks as not all devices work properly on a modified sine wave, products such as computers and medical equipment are not resistant to the distortion of the signal and must be run off of a pure sine wave power source.

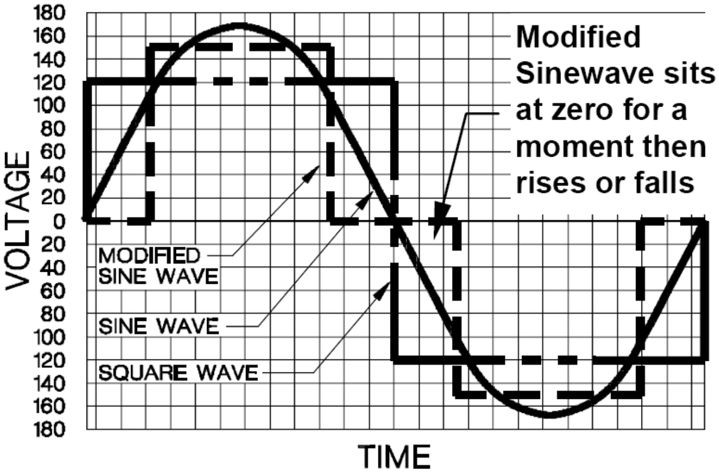

Figure 2: Square, Modified, and Pure Sine Wave [8]

Pure sine wave inverters are able to simulate precisely the AC power that is delivered by a wall outlet. Usually sine wave inverters are more expensive then modified sine wave generators due to the added circuitry. This cost, however, is made up for in its ability to provide power to all AC electronic devices, allow inductive loads to run faster and quieter, and reduce the audible and electric noise in audio equipment, TV's and fluorescent lights[9].

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8 Trace Engineering
9 Donrowe.com

Pulse Width Modulation

In electronic power converters and motors, PWM is used extensively as a means of powering alternating current (AC) devices with an available direct current (DC) source or for advanced DC/AC conversion. Variation of duty cyclein the PWM signal to provide a DC voltage across the load in a specific pattern will appear to the load as an AC signal, or can control the speed of motors that would otherwise run only at full speed or off. This is further explained in this section. The pattern at which the duty cycle of a PWM signal varies can be created through simple analog components, a digital microcontroller, or specific PWM integrated circuits.

Analog PWM control requires thegeneration of both reference and carrier signals that feed into a comparator which createsoutput signals based on the difference between the signals[10]. The reference signal is sinusoidal and at the frequency of the desired output signal, while the carrier signal is often either a sawtooth or triangular wave at a frequency significantly greater than the reference. When the carrier signal exceeds the reference, the comparator output signal is at one state, and when the reference is at a higher voltage, the output is at its second state. This process is shown in Figure 3 with the triangular carrier wave in red, sinusoidal reference wave in blue, and modulated and unmodulated sine pulses[11].

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[10] Hart, pg. 308-312

[11] Ledwich

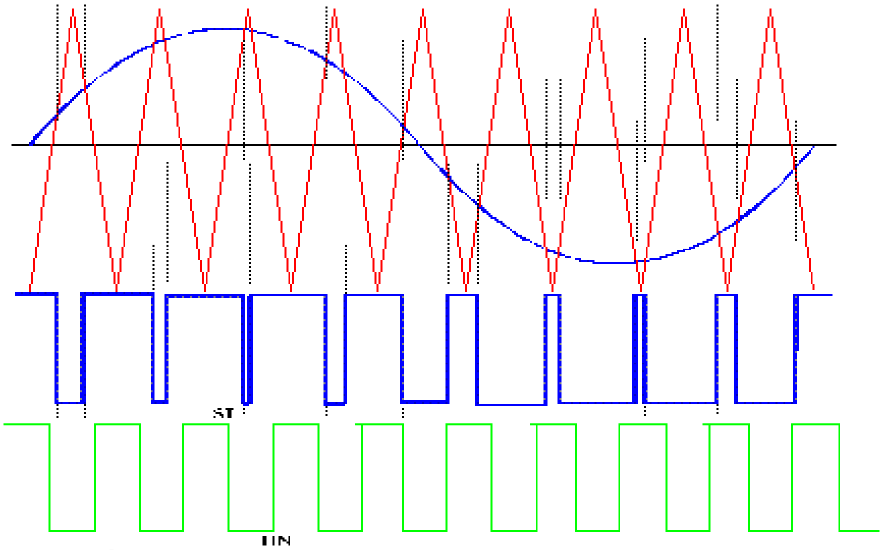

Figure 3: Pulse Width Modulation

In order to source an output with a PWM signal, transistor or other switching technologies are used to connect the source to the load when the signal is high or low. Full or half bridge configurations are common switching schemes used in powerelectronics. Full bridge configurations require the use of four switching devices and are often referred to as H-Bridges due to their orientation with respect to a load.

Bubba Oscillator

The Bubba Oscillator is a circuit that provides a filtered sine wave of any frequency the user desires based upon the configuration of resistors and capacitors in the circuit. The circuit completes this task with four operational amplifiers that either buffer or amplify the signal. This oscillator is a phase shift oscillator, but unlike other phase shift varieties that require phase shifts of 90 degrees or more, the bubba oscillator only requires a 45 degree shift in order to function. This is because of the four op amps, that when placed in series, produce a total 180° shift.

The bubba oscillator offers a few features that other oscillators cannot, the biggest factor is that the frequency stability holds while still giving a low distortion output. The reason for this involves the four filters that the signal passes through, providing a clear and stable signal at point P5, as shown in Figure 4.

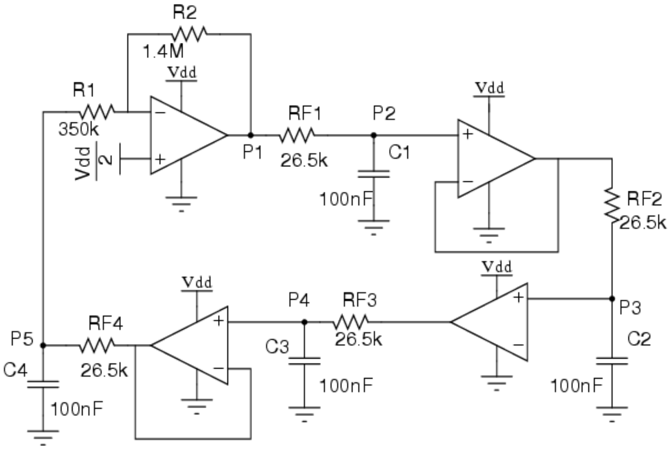

Figure 4: Bubba Oscillator Schematic

Four identical RC filters phase shift the signal 45 degrees each. This causes a 180 degree phase shift which is then returned to a zero degree phase shift with the inverting amplifier placed across the first operational amplifier. The math behind the phase shift of the filter in Figure 5 is shown in equation group (2):

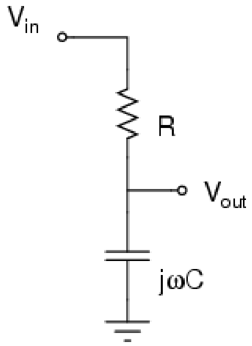

Figure 5: RC Filter Schematic

$$V_{out}=V_{in}\frac{\frac{1}{j\omega C}}{R+\frac{1}{j\omega C}}=\frac{V_{in}}{jR\omega C+1}$$
$$When\ \omega=\frac{1}{RC}$$
$$A=\frac{V_{out}}{V_{in}}=\frac{1}{j+1} \qquad (2)$$
$$\sphericalangle A=\frac{\sphericalangle 0^{\circ}}{\sphericalangle 45^{\circ}}=\sphericalangle 45^{\circ}$$

Another side effect of the filtering, however, is that the signal becomes attenuated, enough so that the signal must be amplified so that the oscillator works. It only will work if the signal being passed back into the system is the same as the one it started out as.

$$|A|=\left|\frac{1}{j+1}\right|=\frac{1}{\sqrt{2}}$$
$$A_{Total}=\left(\frac{1}{\sqrt{2}}\right)^{4}=\frac{1}{4} \qquad (3)$$

As the equations above show the total attenuation of the system is ¼ of the original signal, therefore the amplification of the inverting amplifier must be of magnitude 4. When this knowledge is coupled with the 180 degree phase shift of the filters it can be determined that the amplifier have a value of -4 in order for the circuit to pass back the original signal and thereby oscillate.

A problem that exists in all oscillators is that it is nearly impossible to get an exact amplification of the signal. If the amplification is too small then the oscillator signal will decay to nothing, however if it is too large the signal will keep on amplifying until it hits the rails of the op amps. This means that some sort of non-linear feedback must be implemented with these oscillators so that the signal provided will actually be a stable sine wave.

The bubba oscillator (as well as other phase shift oscillators) solves this problem by the very nature of the op amps, when the signal is amplified back into the circuit the signal gets clipped at the peaks of the sine wave. This is because the amplitude is reaching the rails of the op amp allowing the signal to stabilize and providing the non-linear feedback needed.

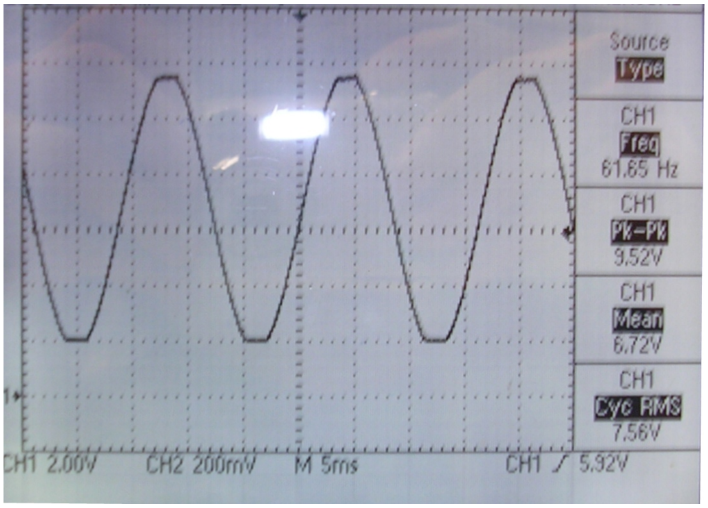

Figure 6: Signal at P1

Figure 6 shows how the signal looks when it passes through this point, which is the point P1 in Figure 4. It is acceptable for this incoming signal to be clipped at the peaks because through the 4 filters provided by the circuit all distortion associated with the signal for the most part is eliminated, providing a clean sine wave.

H-Bridge Configuration

An H-Bridge or full-bridge converter is a switching configuration composed of four switches in an arrangement that resembles an H. By controlling different switches in the bridge, a positive, negative, or zero-potential voltage can be placed across a load. When this load is a motor, these states correspond to forward, reverse, and off. The use of an H-Bridge configuration to drive a motor is shown in Figure 7.

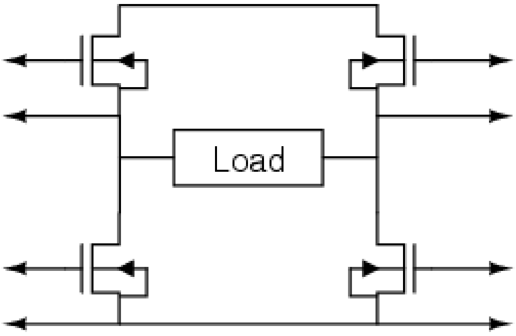

Figure 7: H-Bridge Configuration using N-Channel MOSFETs

As shown in Figure 7 the H-Bridge circuit consists of four switches corresponding to high side left, high side right, low side left, and low side right. There are four possible switch positions that can be used to obtain voltages across the load. These positions are outlined in Table 1. Note that all other possibilities are omitted, as they would short circuit power to ground, potentially causing damage to the device or rapidly depleting the power supply.

Table 1: Valid H-Bridge Switch States

High Side Left	High Side Right	Low Side Left	Low Side Right	Voltage Across Load
On	Off	Off	On	Positive
Off	On	On	Off	Negative
On	On	Off	Off	Zero Potential
Off	Off	On	On	Zero Potential

The switches used to implement an H-Bridge can be mechanical or built from solid state transistors. Selection of the proper switches varies greatly. The use of P-Channel MOSFETs on the high side and N-Channel MOSFETs on the low side is easier, but using all N-Channel MOSFETs and a FET driver, lower "on" resistance can be obtained resulting in reduced power loss. The use of all N-Channel MOSFETs requires a driver, since in order to turn on a high-side N-Channel MOSFET, there must be a voltage higher than the switching voltage (in the case of a power inverter, 170V). This difficulty is often overcome by driver circuits capable of charging an external capacitor to create additional potential. MOSFET drivers and discussion of how they achieve this higher potential are discussed in the following section.

MOSFET Drivers

When utilizing N-Channel MOSFETs to switch a DC voltage across a load, the drain terminals of the high side MOSFETs are often connected to the highest voltage in the system. This creates a difficulty, as the gate terminal must be approximately 10V higher than the drain terminal for the MOSFET to conduct. Often, integrated circuit devices known as MOSFET drivers are utilized to achieve this difference through charge pumps or bootstrapping techniques. These chips are capable of quickly charging the input capacitance of the MOSFET (Cgiss) quickly before the potential difference is reached, causing the gate to source voltage to be the highest system voltage plus the capacitor voltage, allowing it to conduct. A diagram of an N-Channel MOSFET with gate, drain, and source terminals is shown in Figure 8.

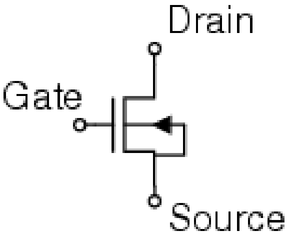

Figure 8: N-Channel MOSFET

There are many MOSFET drivers available to power N-Channel MOSFETs through level translation of low voltage control signals into voltages capable of supplying sufficient gate voltage. Advanced drivers contain circuitry for powering high and low side devices as well as N and P-Channel MOSFETs. In this design, all MOSFETs are N-Channel due to their increased current handling capabilities. To overcome the difficulties of driving high side N-Channel MOSFETs, the driver devices use an external source to charge a bootstrapping capacitor connected between Vcc and source terminals[12]. The bootstrap capacitor provides gate charge to the high side MOSFET. As the switch begins to conduct, the capacitor maintains a potential difference, rapidly causing the MOSFET to further conduct, until it is fully on. The name bootstrap component refers to this process and how the MOSFET acts as if it is "pulling itself up by its own boot strap"[13].

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[12] International Rectifier, AN-978

[13] Professor Stephen J. Bitar, Personal Communication

Circuit Protection and Snubbers

One of the major factors in any electronic device is its ability to protect itself from surges that could damage the circuitry. In the case of the inverter, inductive loads can cause special problems because an inductor cannot instantly stop conducting current, it must be dampened or diverted so that the current does not try to flow through the open switch. If not dampened the surges can cause trouble in the MOSFETs used to produce the output sine wave; when a MOSFET is turned off the inductive load still wants to push current through the switch, as it has no where else to go. This action can cause the switch to be put under considerable stress, the high dV/dt, dI/dt, V and I associated with this problem can cause the MOSFETs to malfunction and break.

To combat this problem snubber circuits can reduce or eliminate any severe voltages and currents. Composed of simply a resistor and capacitor placed across each switch it allows any current or voltage spikes to be suppressed by critically dampening the surge and protecting the switch from damage. The snubber can become more effective by the addition of a zener diode so that any large current surge the resistor-capacitor snubber cannot handle gets passed through to ground by the zener diode. The diagram in Figure 9 shows a simple representation of an inductive load (L) over a switch representation, Figure 10 and Figure 11 show how snubbers can be implemented so that a surge will be suppressed.

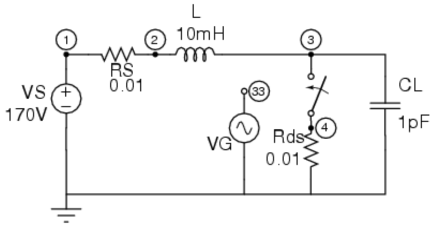

Figure 9: Inductive Load Circuit

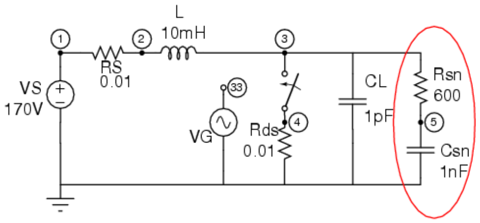

Figure 10: Inductive Load Circuit with Snubber

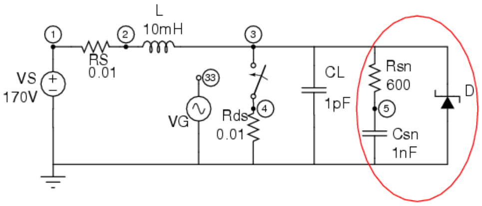

Figure 11: Inductive Load Circuit with Snubber and Zener Diode

Filtering

Filters come in many different packages, with many different advantages – and disadvantages. For example, a digital filter is easily reconfigurable and can have almost any frequency response desired. If the response is simply lowpass/highpass/bandpass behavior with a set frequency, an active filter can be made to have a very sharp edge at the cutoff, resulting in enormous reductions in noise and very little attenuation of the signal. These, however, require opamps. Opamps capable of filtering a 120V RMS sine wave exist, but are expensive and lossy, since the opamp must be able to source hundreds of watts, and must be very large to do so without burning. Digital filters have a similar drawback and, designed with TTL and CMOS technology, can only work with small signals. Lastly we come to a passive filter. Generally large in size and very resistive at low frequencies, these filters often seem to have more of a prototyping application, or perhaps use in a device where low cost is important, and efficiency is not.

Given these choices, an application such as a high power sine inverter is left with only one viable option: the passive filter. This makes the design slightly more difficult to accomplish. Noting that passive filters introduce higher resistance at lower frequencies (due to the larger inductances, which require longer wires), the obvious choice is to switch at the highest possible frequency. The problem with this choice, however, is that the switching MOSFETs introduce more switching losses at *higher* frequencies. This would imply that we should switch slower to improve our switching efficiency, which contradicts the filter's need for a higher frequency.

Methodology

The construction of the pure sine wave inverter can be complex when thought of as a whole but when broken up into smaller projects and divisions it becomes a much easier to manage project. The following sections detail each specific part of the project as well as how each section is constructed and interacts with other blocks to result in the production of a 120 volt pure sine wave power inverter.

Block Diagram

Analog circuitry, as well as discrete components, a MOSFET drive integrated circuit and a low-pass filter are all that is necessary to generate a 60Hz, 120V AC sine wave across a load. The block diagram shown in Figure 12 shows the varying parts of the project that will be addressed. The control circuit is comprised of three basic blocks, the six volt reference, sine wave generator and triangle wave generator; when these blocks are implemented with comparators and other small analog circuitry they control the PWM signals that the two MOSFET drivers will send. The PWM signals are fed into these MOSFET drivers that perform level translation to drive four N-Channel MOSFETs in an H-Bridge configuration. From here the signal is sent through a low-pass LC filter so that the output delivers a pure sine wave. The specific operation, construction, and resulting output waveforms for each block will be discussed in detail in the following sections.

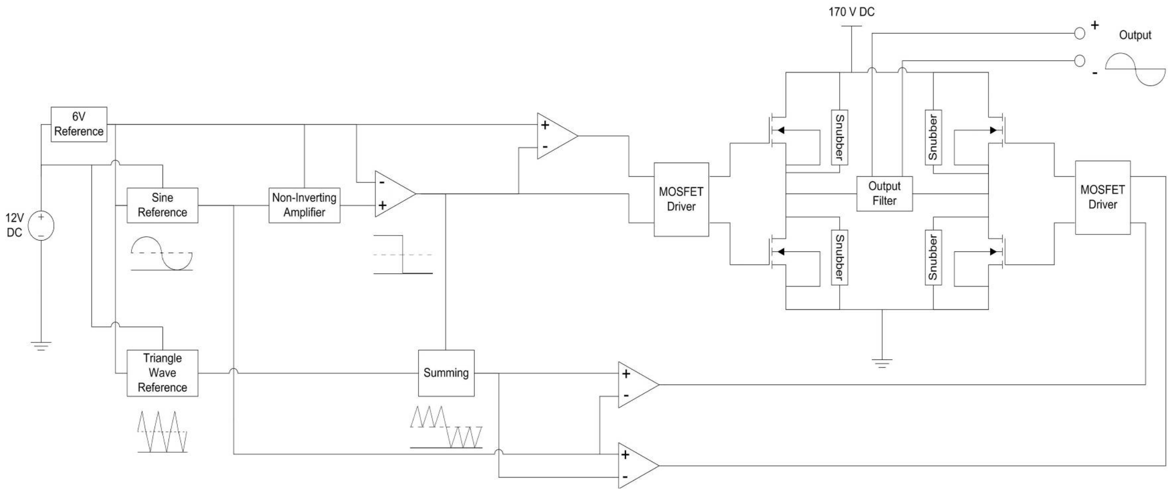

Figure 12: Block Diagram

Sine Wave Generator

The first step to creating an accurate pulse width modulation signal using analog circuitry is to construct an accurate representation of the signal you wish to duplicate. In the case of a pure sine wave inverter the team wanted to construct a 60 Hz sine wave output. Therefore an oscillator was needed to produce a stable 60 Hz sine wave that had little distortion so that the output could be as accurate as possible. A “Bubba” oscillator was chosen as the means to produce this signal because of its ability to produce a stable sine wave that contains very little distortion. The circuitry and values chosenare shown in Figure 13 and the opamp chip chosen to complete the task was an LM348 as it is an inexpensive part and meets all the requirements of creating this sine wave.

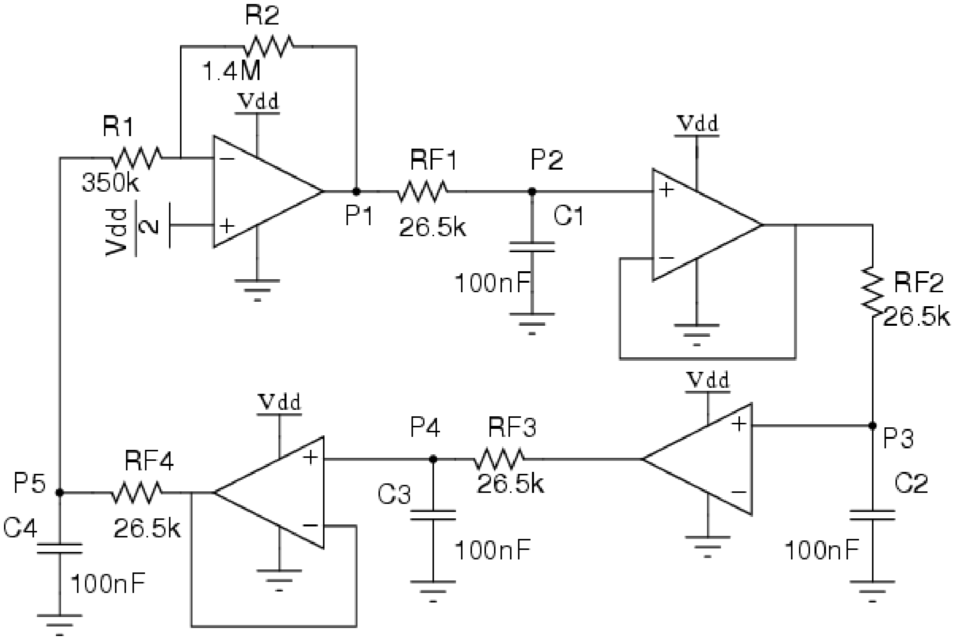

Figure 13: Bubba Oscillator Circuit

The bubba oscillator has 4 different output points (P2-5) where the signal can be taken from. P2 has the largest amplitude, however it is also the most distorted; P5 is the least distorted, however it has the smallest amplitude. Figure 14 and Figure 15 compare the two signals below.

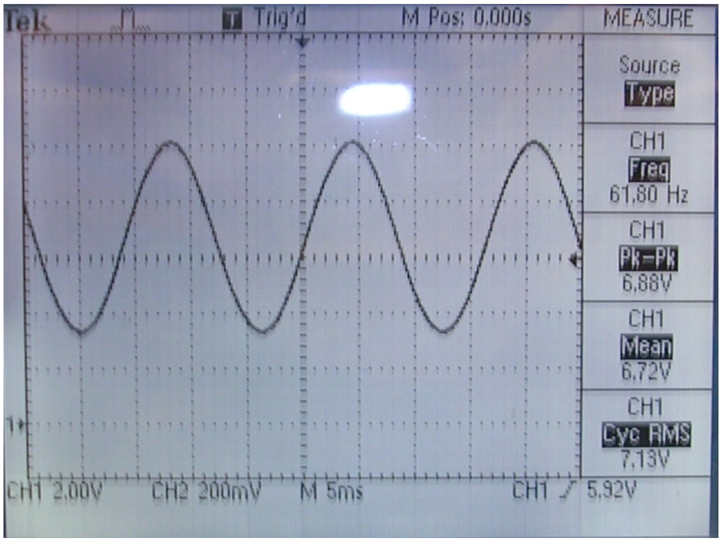

Figure 14: Oscillator Signal at P2

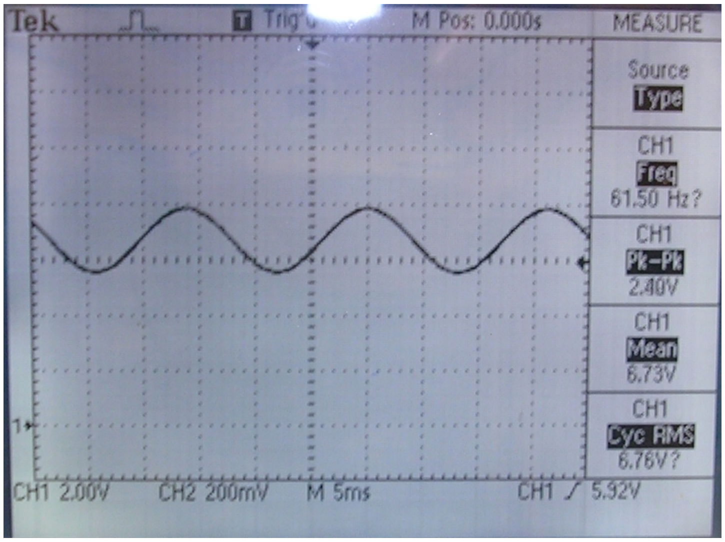

Figure 15: Oscillator Signal at P5

Taking the signal from P5 is the best way to get the least distorted signal, the amplitude of the wave is not a factor as much because there is a non-inverting amplifier that this signal will run through before being used in any of the control circuitry.

Carrier Wave Generator

Generating a sine wave at 60Hz requires both the reference sine wave and a carrier wave at the switching speed of the power supply. Carrier waves can be either sawtooth or triangular signals; in this case, a triangular wave will be used. This wave will be at 50KHz as determined in optimal power loss simulations. The generation of the triangular carrier wave will be done with analog components. The circuit for the construction of the triangle wave generator consists of a square wave generator and integrator, as shown in Figure 16.

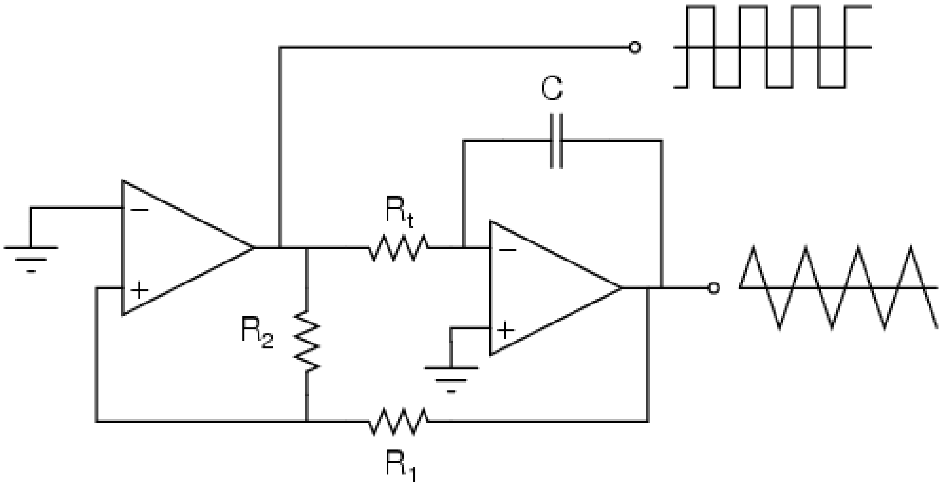

Figure 16: Triangle Wave Generator [14]

The above circuit will oscillate at a frequency of 1/4RtC, and the amplitude can be controlled by the amplitude of R1 and R2. The frequencies that can be generated by this circuit depend greatly on the slew rate of the operational amplifiers. Using a TL-084, output waves with frequencies of up to 40KHz can be generated. Speeds of 50KHz require an op-amp with a faster slew rate. Using the TL-084 op-amp, with Rt=1K, R1=R2=10K, and C=.1uF, this circuit generates square and triangle waves oscillating at 5Khz. The slew rate of this operational amplifier is 12V/uS and will allow switching speeds up to 43KHz. With an op-amp with a higher slew rate, the capacitor will be replaced with a .01uF capacitor, increasing the frequencies to 50KHz.

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[14] Bigelow, pg. 1

The operation of this device is based on basic Schmitt Trigger and Integrator circuits. The square wave generator uses positive feedback, and as the capacitor, C, charges , the Schmitt trigger saturates to the positive rail. The feedback eventually causes the trigger to change states, and as the capacitor discharges, the output is at the opposite rail. The amplitude of the square wave is determined by the rail voltage powering the MOSFET, as well as the ratio of R2/R1. The 5KHz square wave generated in this circuit is shown in Figure 17.

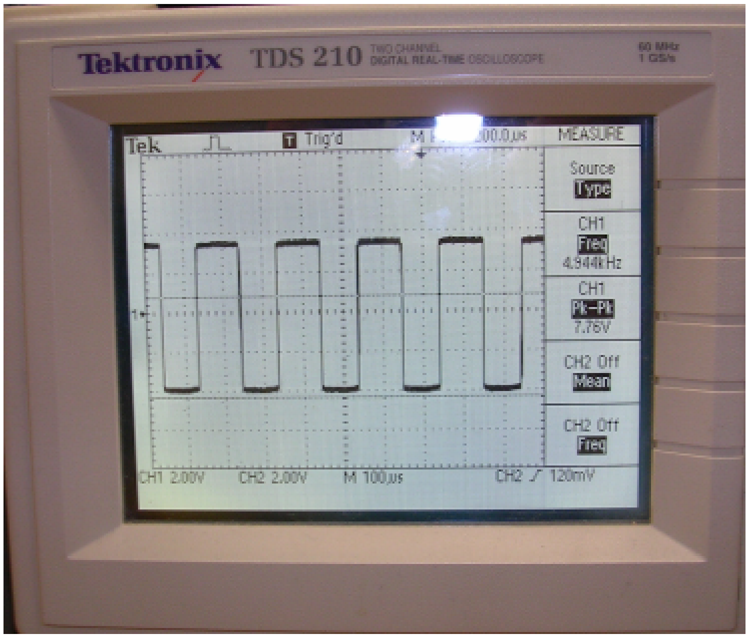


Figure 17: Square Wave Output

The second part of the circuit consists of an integrator circuit. When the output of the Schmitt trigger is positive, the capacitor is charging and the output voltage ramps down. The inversion of the triangle wave with respect to the square wave is due to the negative feedback to the second op-amp. The generated triangle wave at 5KHz is shown in Figure 18.

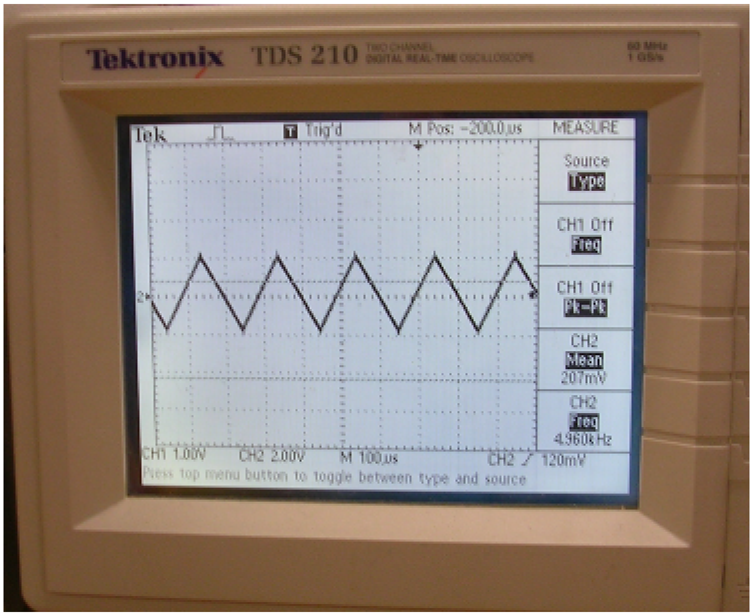


Figure 18: Generated Triangle Wave

As stated above, the triangle wave will be inverted with respect to the square wave due to the negative feedback. This is shown in Figure 19.

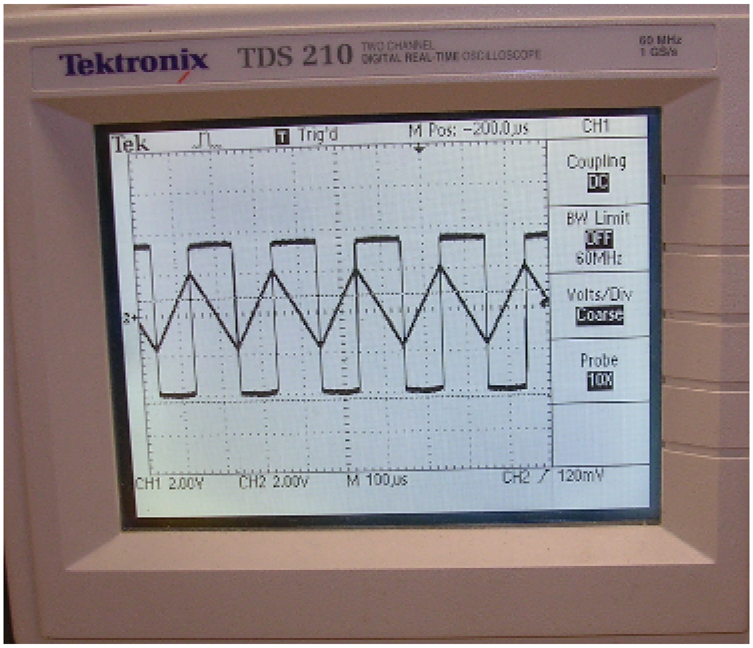


Figure 19: Square and Triangle Waves

Difficulties with this circuit are caused mainly by the operational amplifier selected in its design. The square and triangle waves may be skewed due to the op-amp's inability to reach output rails. Also, if the frequency is too high for the op-amp to handle, the square wave will be skewed and the triangle wave will be noticeably clipped or distorted. Currently, the op-amps are powered by separate positive and negative supplies adjusted to obtain a proportional output, but in the final design, a single source and offset will be used. This can be achieved by setting the high rail to the available 12V and setting a dc offset by inputting the inverting terminal of the Schmitt trigger op amp and the noninverting terminal of the integrator op-amp with a 6V reference signal. This will result in the same waveforms,with a DC offset of 6V oscillating between 0V and 12V.

Pulse Width Modulation

Bilevel pulse width modulation is a simple concept, and not difficult to implement. Trilevel PWM is not a far stretch from bilevel, but is significantly more difficult to implement. Below is shown a sample trilevel PWM wave.

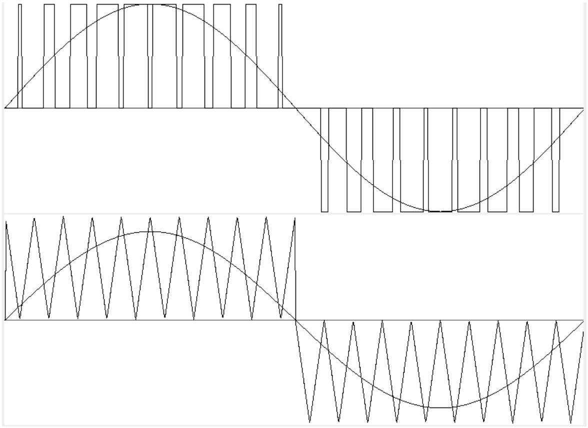


Figure 20: PWM Signal

The top picture shows the input reference waveform, and the generated PWM signal overlaid. The bottom picture shows the signals which are passed into a comparator to achieve the PWM waveform. The triangular wave is simple to create, utilizing an opamp driver. It must then be modified such that it switches between a mid-to-high triangular wave, to a mid-to-low triangular wave. This is accomplished by generating a triangular wave at roughly half the amplitude of the reference sine, centered at the same voltage. This wave is then passed into a voltage summer with a square wave (made from the sine reference, to create one with identical frequency), which creates the modified triangle wave shown.

The triangular and sine reference generators are discussed separately in the document, this section will assume those waves already exist, and will modify them for the purposes of trilevel PWM. First, a picture of the sine reference, the above stated square wave, and the triangular wave:

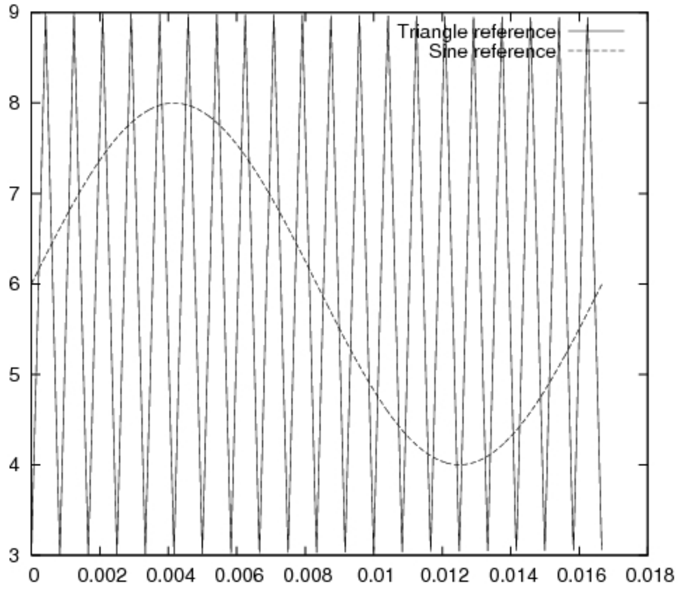


Figure 21: Sine Reference, Triangle Wave, and square wave reference

Now, applying the triangular wave and square wave to a voltage summer (the square wave is attenuated by a factor of 12), we obtain:

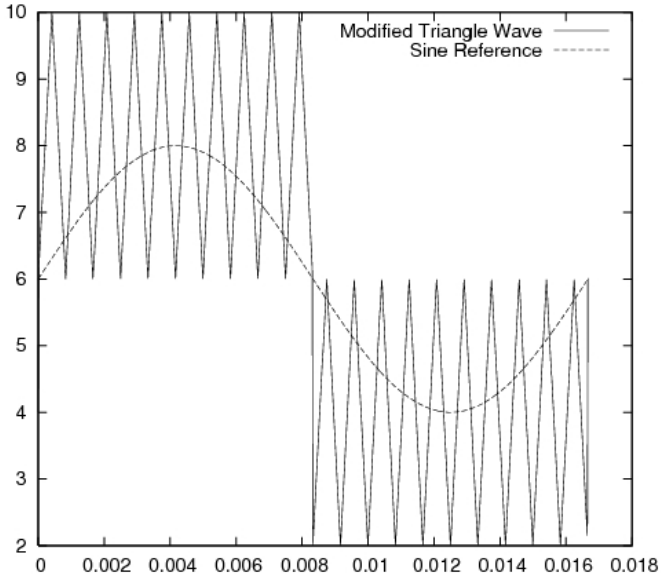


Figure 22: Modified triangle wave, overlaid with sine reference

The sine reference is included to show the result of modifying the triangle wave. If these waveforms are passed into a comparator, we will obtain:

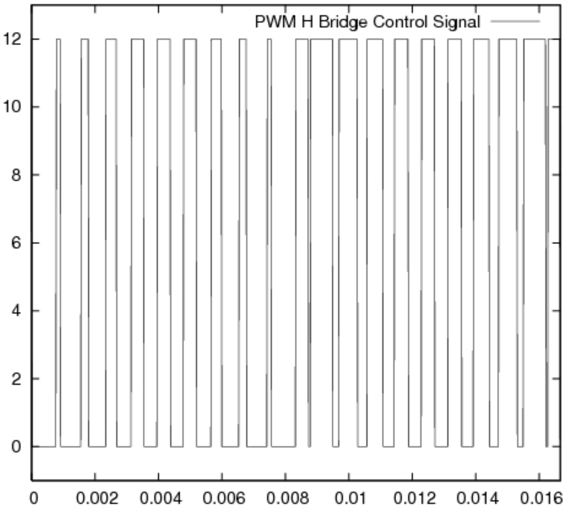


Figure 23: PWM control signal

This signal will be used to control MOSFETs. As you can see by close inspection, the duty cycle approaches 1 (or zero) at the peaks and, though it may not be entirely visible, at the zero crossing of the sine wave, the duty cycle first approaches zero, then switches to one (as the square reference changes polarity). Now, using an H-Bridge MOSFET configuration, and utilizing both the above PWM signal and the square wave generated, we can obtain:

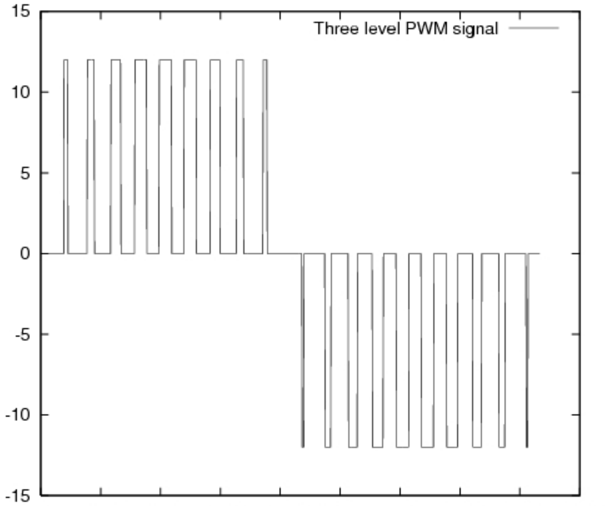


Figure 24: Trilevel PWM signal

This is the final signal. If filtered, we will arrive at a sine wave (albeit a 12 V sine wave). If we replaced the 12 V source of these waveforms with a 170 V source, we would have a 170V peak

H-Bridge

Generating a sine wave centered on zero volts requires both a positive and negative voltage across the load, for the positive and negative parts of the wave, respectively. This can be achieved from a single source through the use of four MOSFET switches arranged in an H-Bridge configuration. To minimize power loss and utilize higher switching speeds, N-Channel MOSFETs were chosen as switches in the bridge. Level translation between PWM signals and voltages required to forward bias high side N-Channel MOSFETS, the IR2110 MOSFET driver integrated circuit was chosen. A diagram of the H-Bridge circuit with MOSFETS and drivers is shown in Figure 25.

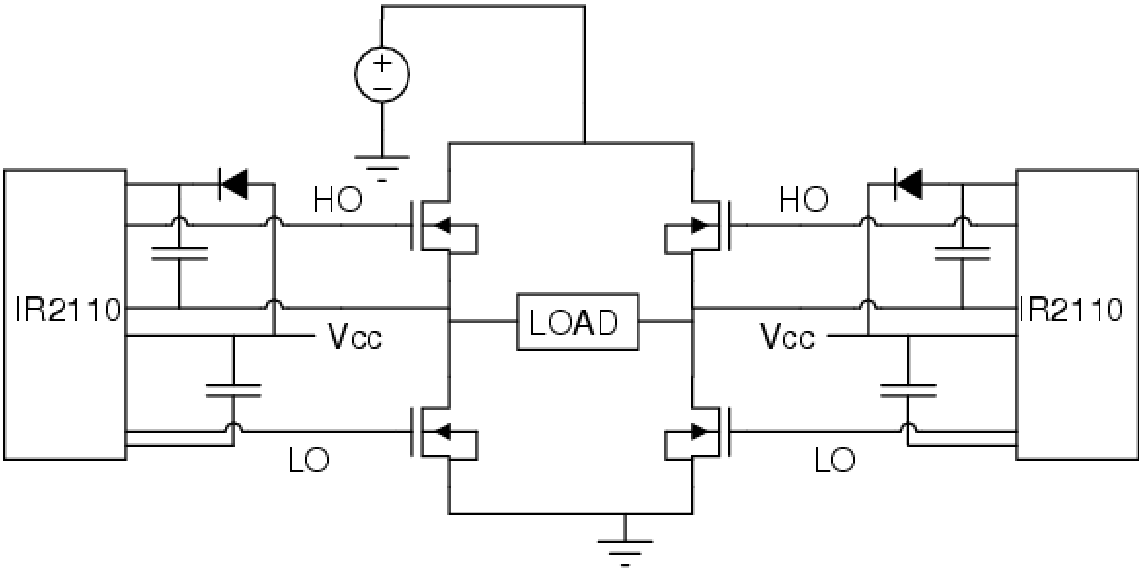
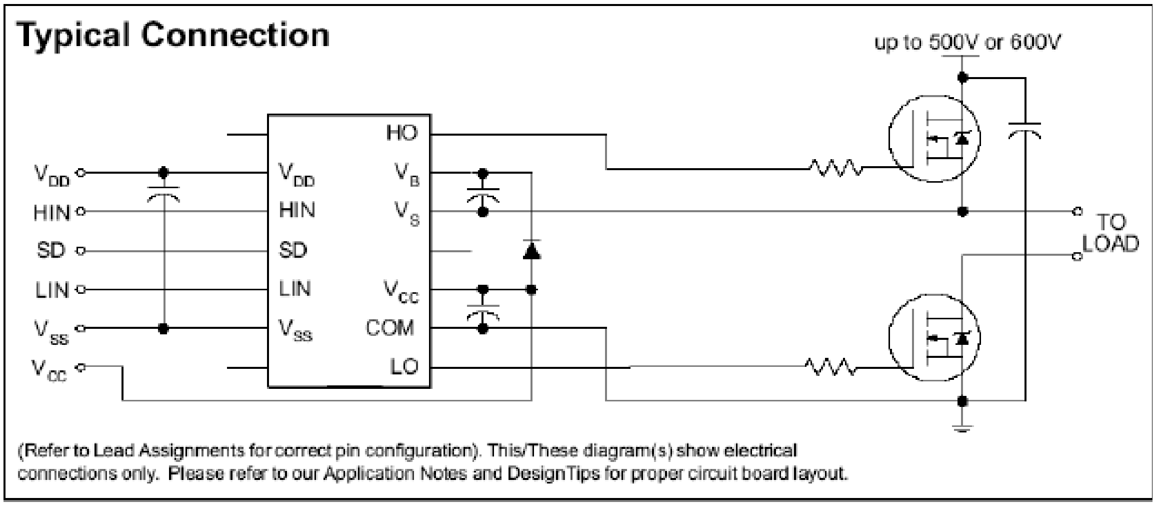


Figure 25: H-Bridge with MOSFET Drivers

The IR2110 High and Low Side Drive device exceeds all requirements for driving the MOSFETs in the bridge. It is capable of up to 500V at a current rating of 2A at fast switching speeds. This device is required to drive the high side MOSFETS in the circuit designated HO, due to the fact that the gate to source voltage must be higher than the drain to source voltage, which is the highest voltage in the system. This device utilizes a bootstrapping capacitor to maintain a voltage difference of approximately 10V above the drain to source voltage. With a full bridge configuration, two of these devices are utilized, as shown in the above figure. A typical connection of a single IR2110 device is shown in Figure 26.


Typical Connection

(Refer to Lead Assignments for correct pin configuration). This/These diagram(s) show electrical connections only. Please refer to our Application Notes and DesignTips for proper circuit board layout.

Figure 26: Typical Connection for IR2110 MOSFET Driver [15]

Operation of the IR2110 device will be controlled through generated PWM signals. The PWM signal will be fed to the HIN and LIN pins simultaneously. If the internal logic detects a logic high, the HO pin will be driven; if a logic low is detected, the LO pin will be driven. The SD pin controls shut down of the device and will be unused and tied to ground. Additional pins that require external connections are the Vss pin which will be tied to ground, the Vcc pin which will be tied to 12V, pins requiring connections to bootstrapping components and outputs to the MOSFETS.

Bootstrapping capacitors and diodes will be connected as designated. The values for these components are calculated from International Rectifier's AN-978 application note, HV Floating MOS-Gate Driver ICs. The formula for minimum bootstrap capacitor value obtained from this document is shown below.

$$C \geq \frac{2\left[2Q_g + \frac{I_{qbs(max)}}{f} + Q_{Is} + \frac{I_{Cbs(leak)}}{f}\right]}{V_{cc} - V_f - V_{LS} - V_{Min}} \quad (4)$$ [16]

Minimum capacitor values were calculated to be 2uF for the 60Hz side of the bridge and 51nF for the 50KHz side of the bridge. The elements of the equation above were determined from datasheets as follows:

---

[15] International Rectifier, IR2110

[16] International Rectifier, AN-978

Q_g = Gate Charge of High Side FET = 110nC
I_{qbs} = Quiescent current for high side driver circuitry = 230uA
Q_{ls} = Level shift charge required per cycle = 5nC (given in application note)
$I_{cbs(leak)}$ = Bootstrap capacitor leakage current = 250uA
f = Frequency = 60Hz for left side of bridge, 50Khz for right side of bridge
V_{cc} = Supply Voltage = 12V
V_f = Forward voltage drop across bootstrap diode = 1.3V
V_{ls} = Voltage drop across low side FET = 1.5V

Components to be used according to the calculations above are the 2.2uF +/-20%, 50V Kemet C330C225M5U5TA capacitor and the .056uF +/-10%, 200V Kemet C330C563K2R5CA capacitor. The diode to be used is the International Rectifier 8ETu04-ND 8Amp 400V Ultrafast Rectifier.

Driving four MOSFETs in an H-Bridge configuration allows +170, -170, or 0 volts across the load at any time. To utilize PWM signals and this technology, the left and right sides of the bridge will be driven by different signals. The MOSFET driver on the left side of the bridge will receive a square wave at 60Hz, and the right side will receive the 50KHz PWM signal. The 60Hz square wave will control the polarity of the output sine wave, while the PWM signal will control the amplitude. The MOSFETs to be used in the design are the IRFB20N50KPbF Hexfet Power MOSFET, rated for 500V at 20A with a Rds of .21ohm.

Filter

In order to optimize the efficiency, a switching frequency must be chosen which is low enough to keep the switches in line, but high enough to make sure the filter inductor is not unnecessarily large. Many engineering tools will assist with this decision, but here we chose to utilize MatLab. Using this it is possible to model the switching losses in the MOSFETs, based on their capacitance and switching rise times (which depends on the frequency), as well as their resistive losses (independent of frequency). Also included in this simulation should be the resistive losses in the filter inductor (dependent on the inductor value/size, the requirement for which is dependent on frequency).

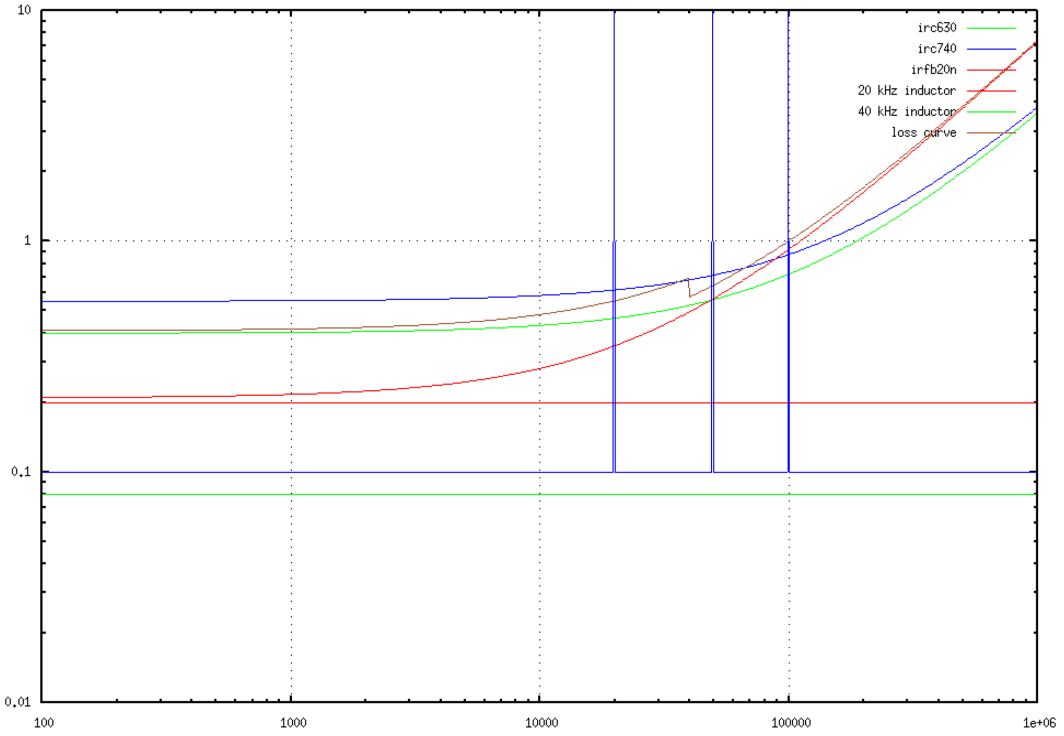


Figure 27: Frequency plot of losses

The above plot shows the frequency losses of 3 different MOSFETs and 2 different inductors. The IRFb20n is an International Rectifier MOSFET with lower resistance than its siblings, the IRC740 and the IRC630, but has a higher capacitance. This is why the losses for this switch start out significantly lower, but rise dramatically at higher frequencies. The curve with the 'notch' around 40 kHz shows the loss curve using the IRFb20n (the MOSFET of choice), added to the resistive losses in the filter inductors. The notch occurs at the frequency where the required inductance value dropped. Based on this curve, 50 kHz switching introduces little extra loss over 20kHz, but will have a dramatically improved output accuracy (less voltage ripple). All plots in this chart may be viewed separately in the appendix. This curve resulted in a decision to switch at 50 kHz, with a 2 mH inductor (coupled with a 1uF capacitor to create a lowpass filter).

Implementing the Design

To actually implement the design of this DC-AC power inverter, certain steps had to be taken to ensure that every block of the project functions correctly. In order to do this the entire project was first placed on a breadboard to ensure functionality and where any glitches or inaccuracies due to small uncalculated losses could be accounted for. The project had to be placed on the breadboard in a specific order so that each block could be tested to see if the desired output occurred before moving onto the next step.

The first function blocks to be constructed were the six volt reference, sine wave and carrier wave generators. The sine and carrier wave generators work independently of each other and therefore were able to be constructed at the same time. Some time was spent on these two sections of the project because their functionality at the precise frequency, shape and amplitudes will affect the outcome of the PWM signal. Some problems also arouse out of the original design of these function blocks that will be discussed below in the difficulties section. Following the successful operation ofthese blocks the PWM signal could then be constructed, by routing the sine signal through an amplifier (for ensuring the correct amplitude) and by routing both the sine wave and carrier wave through the correct comparators to the H-Bridge drivers the PWM signal was successfully implemented.

The H-Bridge driver chips were the next to be breadboarded, followed by the H-Bridge whice consisted of four n-channel MOSFETs. The final portion of our project to be constructed was our filter to be placed across the load of the H-Bridge. The team had no difficulties with finding or implementing the design for our original filter with low-voltage, low-current components. However when it came to finding parts that could handle the amount of voltage and current that this device needed no matches arouse which led to another difficulty in the total implementation of our design.

Difficulties

As was stated the team ran into quite a few problems while actually piecing together the circuit, the two main difficulties involved the construction of the sine wave oscillator and filter. The team worked together to solve these difficulties as they arose, in both cases where it set off the schedule of our project due to the huge part each blcck plays in the overall functionality of the power inverter.

Sine Wave Generator

When the oscillator was first pieced together, all that was being output was a 6 volt signal, all of the calculations were correctly made and all of the components were correct in their choosing, therefore the team had to understand why the circuit wasn't running. In order to understand if the circuit was operating at all, the power to the circuit was turned on and off while attached to an oscilloscope. While doing this the team noticed that there was some oscillation present but it would attenuate to the 6 volt signal in under a second.

The phase shift oscillator works in such a way that if the amplitude of the inverting amplifier is not high enough the system will continually attenuate the signal until the amplitude is zero, it was therefore decided to change the amplification power of the inverting amplifier. By increasing the amplification value the circuit eventually oscillated, in a perfect to the naked eye, sine wave, upon measuring it was seen that the frequency was not as calculated either, looking for a 60Hz sine wave, the oscillator was producing a 57Hz sine wave.

The next task therefore was to return this value to 60Hz, the frequency of the oscillator is controlled by the 4 filters comprised of a resistor and capacitor. The team found that by controlling the size of the resistor in one of the four filters the frequency could be adjusted. Therefore to get the correct size signal, a potentiometer was put in place of one of the resistors and adjusted while measuring the output on an oscilloscope to determine what size resistor should be used to oscillate at 60Hz.

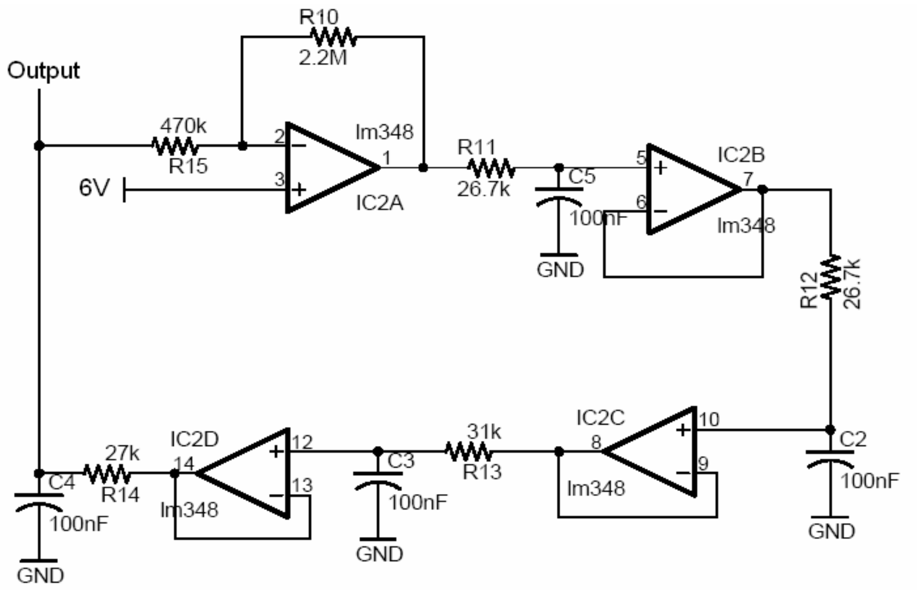


Figure 28: New Sine Wave Oscillator Circuit Diagram

The reasons for trouble with both of these aspects of the sine wave oscillator can most likely be attributed to losses in the circuit through components. The change in resistance needed to fix the frequency problem was to increase one of the four filter resistors from 27.5k to 31k , not a large difference. Another spot that could have caused problems, specifically where a larger amplification was needed could be attributed to the LM348 op-amp chip. The op-amp has properties within itself that might have caused the circuit not to oscillate, such as the rail to rail operating voltages or resistances within itself.

Filter Design

The other major obstacle in the implementation of this project was the design of the filter, the original design was a simple one pole inductor-capacitor low pass filter designed for passing all signals under 50kHz. When first breadboarding the circuit the team used low voltage, low power capacitors and inductors that were available in the WPI ECE shop. Using this method the filter worked as it was designed and the only hurdle was to order parts designed for the voltage and current needed. The problem arouse when searching for these parts, because the filter components needed to be capable of handling at least 400volts and 4amps (for reliability reasons) these parts were very large and bulky. The inductor alone was to weigh five pounds and have a length of six inches, for our application this would not do.

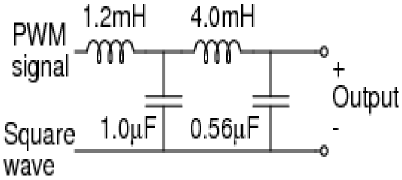


Figure 29: Two Pole Output Filter

Therefore in order to rectify this problem the team went back to scratch in designing the low pass filter, instead of a simple first order low pass filter, a two pole low pass filter would be used. Using this approach there would be twice as many components in the filter but the size of these components would be considerably smaller, lighter and cost less. After first verifying that this filter would work with low voltage/current parts from the shop, the team bought components that could handle the current and voltage demanded of the filter and tests on the new filter were conducted. The simulated frequency response of the filter is shown below in Figure 30.

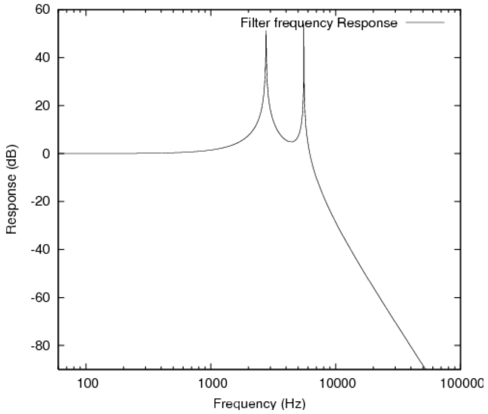


Figure 30: Filter Frequency Response

When we tested this new filter with the high voltage/current components we noticed that it was not acting as we though when small loads were applied across it. We then decided to double check all of the component values with a capacitor-inductor analyzer, upon measuring the inductors it was determined that their values were much greater then what we had wanted. In order to get inductances of 1.2mH and 4mH we decided to unwind portions of the toroids and then compare them with the analyzer to determine the correct number of windings. Although this allowed us to effectively create a precise filter, which functioned properly, the output still distorted significantly when under load. We investigated the distortion and discovered a 50kHz frequency, which meant that the filter was not filtering.

The inductors we selected, it turns out, have low quality cores, which saturated around 0.75 A. This is obviously far less than our rated 2A output, and would not do for a finished product. If we buy better inductors, or if we replace the capacitances with higher values (in order to allow for lower inductances), or raise the switching frequency (also intending to lower the inductances), the saturation current will increase significantly, and our system will again behave properly.

Putting the Design to Work

After the successful debugging of the breadboarded circuitry it was time to transfer this work to a PCB board. Using the full schematic in Appendix B and Eagle PCB program the team was able to construct the circuitry for a PCB board and have it made so that the team could piece together the entire circuit on a neat board. The full plans for the PCB board are located in Appendix D. Putting the circuit onto a board of this kind will get rid of all the extra wires and the possibility of any extra noise that can be attributed to the length or crossing of wires typical on a breadboard, thus allowing a neater, more presentable and less noisy circuit.

The first revision of our PCB board, and the board our circuit was mounted on, is shown in the picture below. This revision had a few traces that were not drawn correctly and so wires had to be added and some traces cut. The other detail with this revision was that traces were not made for the final filter design and instead space was left for this addition. With these few changes to be made, the team went back and redesigned the PCB board, as seen in Appendix D, however time was not available to construct this board again.

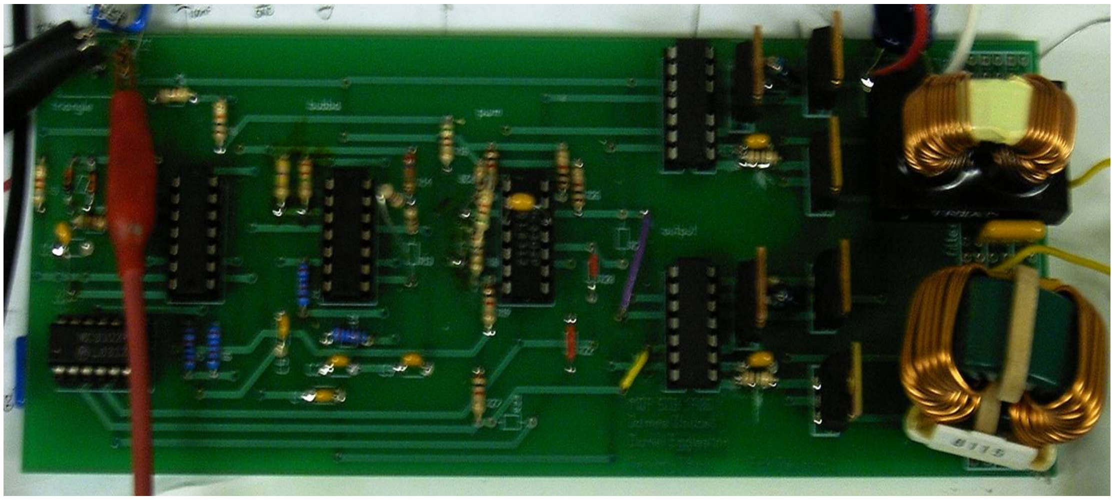


Figure 31: Project on PCB Board

Results

Through careful handling of control signals in the circuit, the MOSFETs in the H-bridge were correctly switched, resulting in a 60 Hz sine wave output, as shown in Figure X.

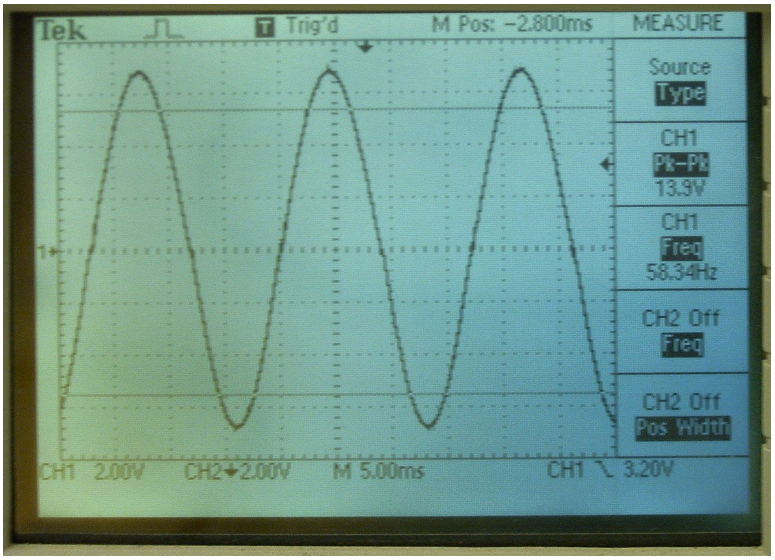


Figure 32: 60 Hz Sine output

The output shown above was for an input voltage of 12V and a 300 Ω load after the filter. The amplitude of the output wave was only 14V pk-pk, a discrepancy easily explained by the low ratio of sine wave to triangle wave control signals. Once tuned for high voltage operation, the gain on the noninverting amplifier for the reference sine will be increased to output a 340V pk-pk signal when the input is 200V. If necessary, the frequency of the signal can be adjusted by changing resistor values in the sine wave generator (Bubba) circuit.

While the operation of the inverter works under light or medium loads (above 50 with 12V input), its output was affected by high frequency oscillations when heavier loads were connected. This occurrence was caused by the components in our filter design. Use of chokes as inductors resulted in core saturation when the current in the circuit was above approximately .5A. Chokes are intended for AC filtering applications, but are intended to be connected in a different manner to prevent high frequency noise from corrupting a clean source. Core saturation resulted in our filter acting more like a resistance and thus allowed oscillations at the carrier frequency through to the source.

Even with the filter problems experienced, the three-level PWM signals were generated correctly and could be used to power resistive loads before the filter. Although this is true, we avoided the core saturation problem by doubling the switching frequency and reducing the inductance values in the filter. Through proper component selection in another revision, the switching frequency could be returned to 50Khz. This would involve the use of a higher capacitance/voltage non-polarized capacitor and a smaller inductor to avoid core saturation. While components capable of meeting these requirements exist, there was insufficient time to order them and test their operation in the circuit.

With the exception of the filter problems mentioned above, the circuit is functioning as designed and correctly inverts a DC voltage to an AC voltage. The efficiency and THD of the inverter was not calculated due to the amount of time spent in design verification and testing, a problem addressed in the Recommendations section.

Recommendations

Although all goals in this project were met there are many ways in which this project can be improved upon. The project called for producing a 120 volt RMS pure sine wave output, therein lies a problem however, in the way that this project is designed, differing loads will allow the output of this project to vary from the 120 volt RMS output. One way in which this problem could be combated would be to introduce a closed loop monitoring system. This system would look at the output of the inverter and check to ensure that this is the correct output, if this output is not what it should be then this system has the power to go back and adjust the settings in the control circuit so that the output is the desired 120 volt RMS sine wave. A simple diagram shown below demonstrates the basic idea of a closed loop control system.

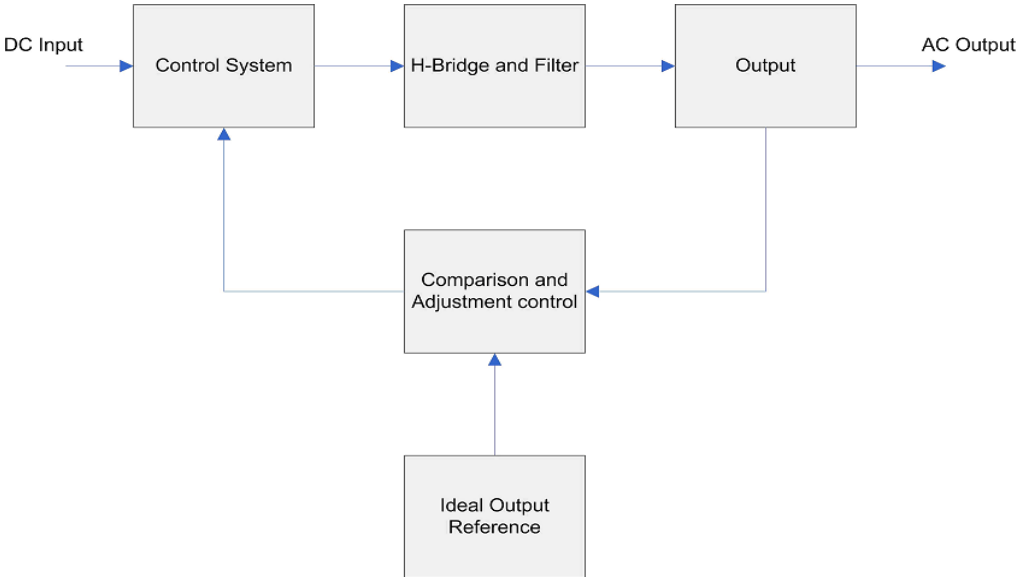


Figure 33: Closed Loop Flow Chart

The output would be scaled and compared to an ideal output reference, perhaps the sine wave reference (Bubba Oscillator) in the control circuit (its size and shape do not change), so that the change in voltage output can be accounted for. When this change is detected the amplification factor of the noninverting amplifier for the sine wave reference (shown in Figure 34) could be adjusted thereby changing the PWM signal and effectively adjusting the output.

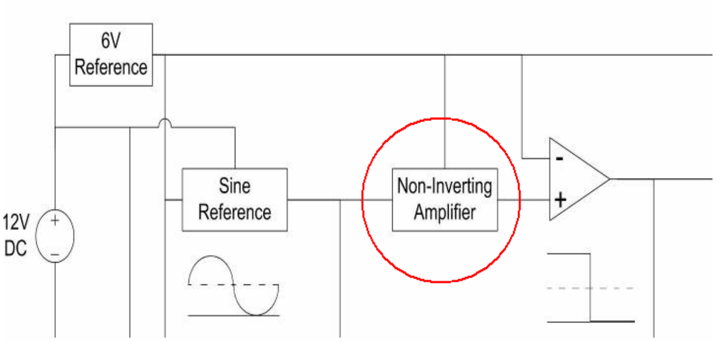


Figure 34: Non-Inverting Amplifier Block

The closed loop control system would allow the system to output the correct voltage and power no matter what the load. Sometimes certain loads can cause fluctuations and voltage spikes within the driving portion of the circuit, specifically around the MOSFETs. This project intended to take into account these voltage and current spikes and protect the MOSFETs with the additions of RC snubbers and zener diodes across each of the MOSFETs. Information on these types of devices can be found in the background section of this report under: Circuit Protection and Snubbers. The team completed more research and discovered this problem can easily be solved with the introduction of Transient Voltage Suppression (TVS) diodes.

These diodes are zener diodes with special characteristics (such as suppression of high transient voltages) that make them ideal for these types of power applications. The team even went so far as to order these diodes, however time was not available to apply them to the circuit. TVS diodes are special in that they are able to withstand the quick voltage and current spikes that can occur in the MOSFET switching as well as being a cheap alternative to RC snubbers. For this application a TVS diode of rating 170 volts would be used, and to ensure that they would last a 1500 Watt rating was chosen. This team recommends that in any future projects that these diodes or any other circuit protection be applied across each of the 4 MOSFETs used in the H-Bridge to protect them from surges that can occur in basic switching or by inductive loads.

Conclusion

The goals for this project were to produce a pure sine wave DC-AC inverter that would output at 60 Hz, 120 volts RMS with 250 watt output, would be cheap to manufacture, and fairly efficient in the method in which it produces it. Taking a look at these goals and the end result it can be said that they were met, the circuitry and total cost of all the components used in the construction of the circuit was around $65 (Appendix E) ascompared to the $300-600 pure sine wave inverters on the market now. This cost however, is when buying parts one at a time, if manufactured this price tag would drop greatly due to the quantities of parts that would be bought.

The second goal, to produce a 120 volt RMS sine wave with the capability of providing 250 watts of power was not actually tested, but the team is confident in its ability to produce this waveform. Using parts in the driver portion of the circuit that are rated for at least twice the operating parameters, 170 volts and 2 amps, the team can be assured that these devices will work with the same functionality as they do at 12 volts. At 12 volts powering, the H-Bridge output is a clean 60 Hz sine wave that can easily be controlled in size by the size of the sine reference in the control circuit. It is in this capability that the option of a closed loop control circuit could be implemented.

In looking at how efficient this project is, there is no hard data that can be referred to as not enough time was available to collect it. In looking at the components selected and the simulations created before the actual construction of the inverter, everything was built in mind for the purpose of efficiency and keeping power losses to a minimum. One of the major factors in the power savings is the use of a three level PWM signal instead of a two level, this allows a much lower average power output to produce the sine wave needed and assisting in the efficiency of the device.

This project is a stepping stone to a cheaper and efficient pure sine wave inverter, by using the data collected in this report as well as the schematics and recommendations the product produced here can be improved upon. Simple additions such as circuit protection and a closed loop control system could greatly improve the performance of this project. The project, in its present condition, does work in the manner the team wished and has met every goal set at the commencement of this venture.

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Appendix A: Switching Frequency Charts

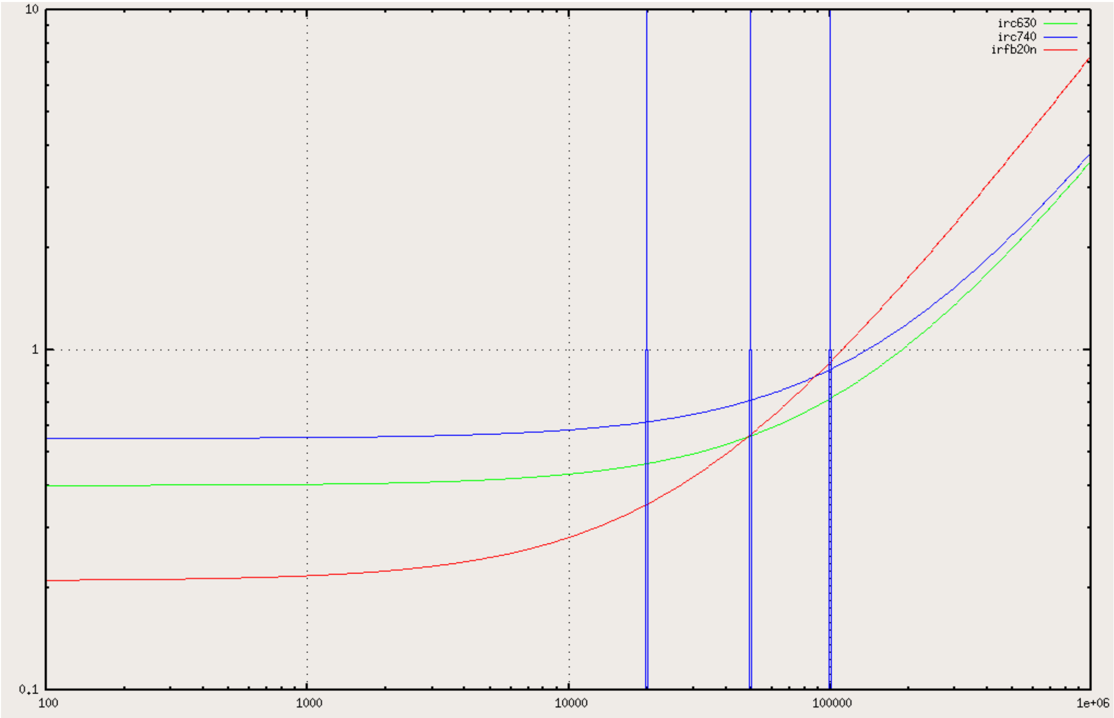


Figure 35: Frequency plot of MOSFET losses

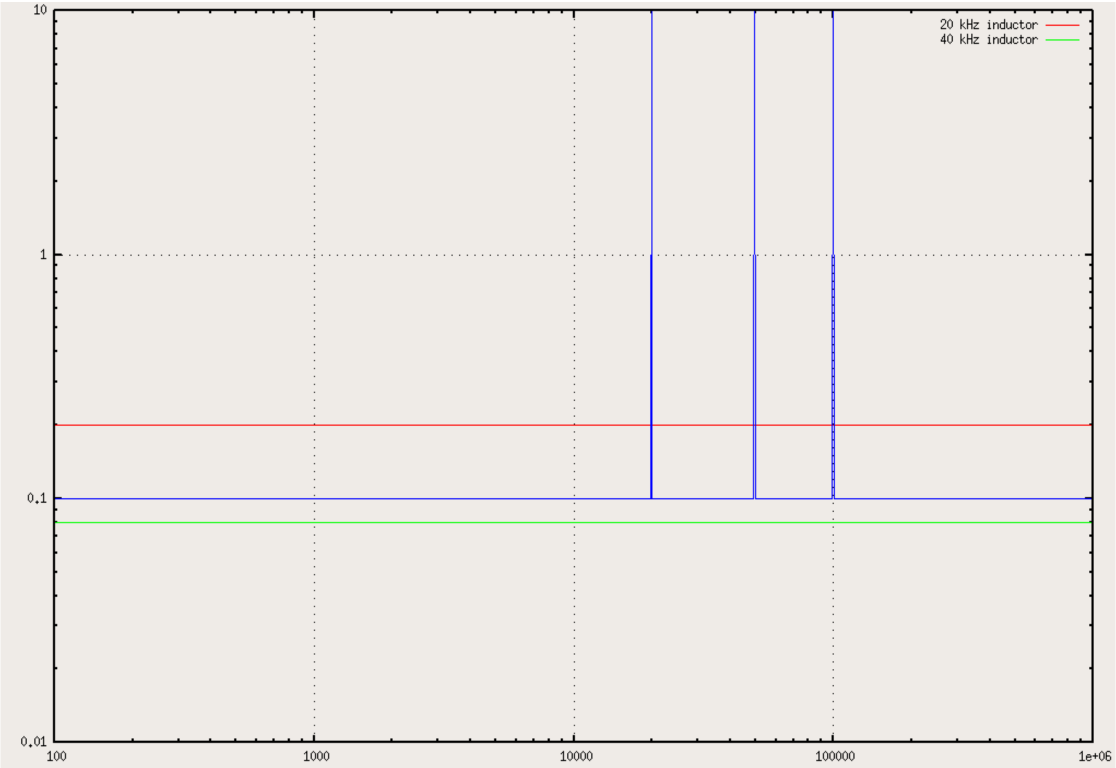
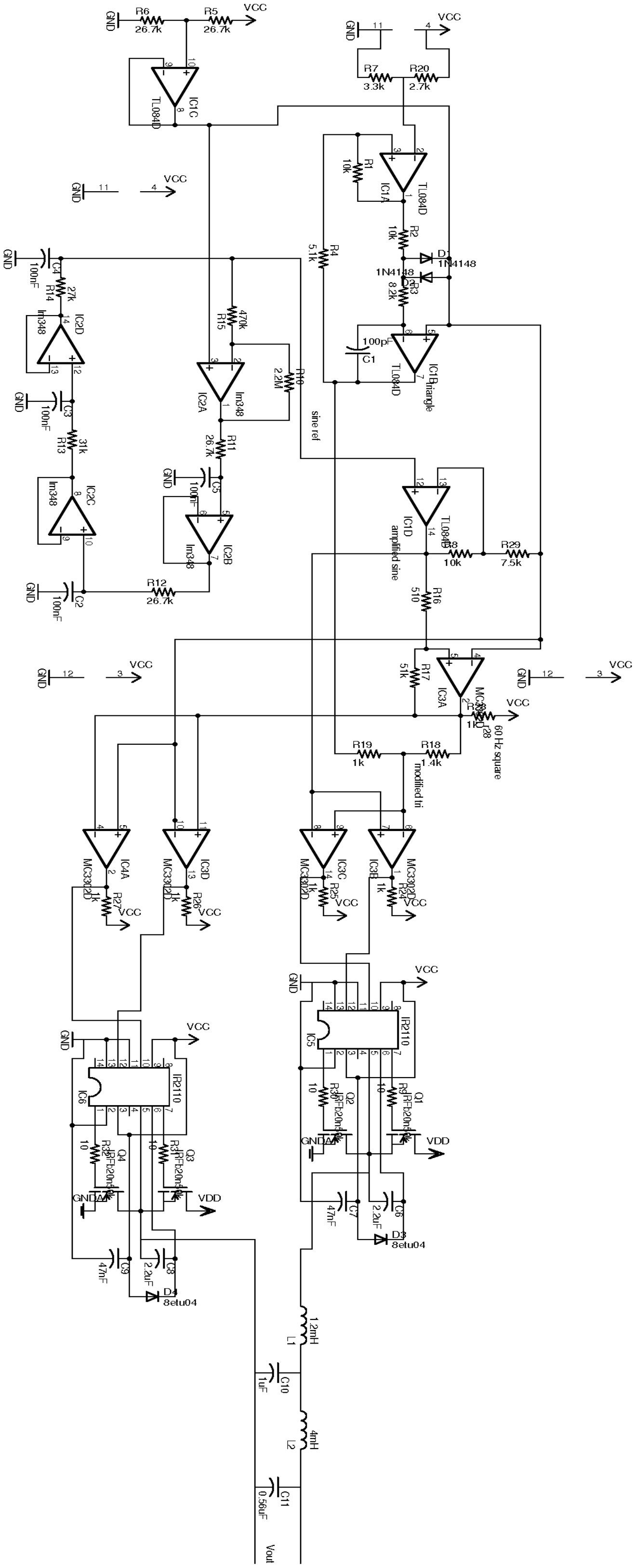
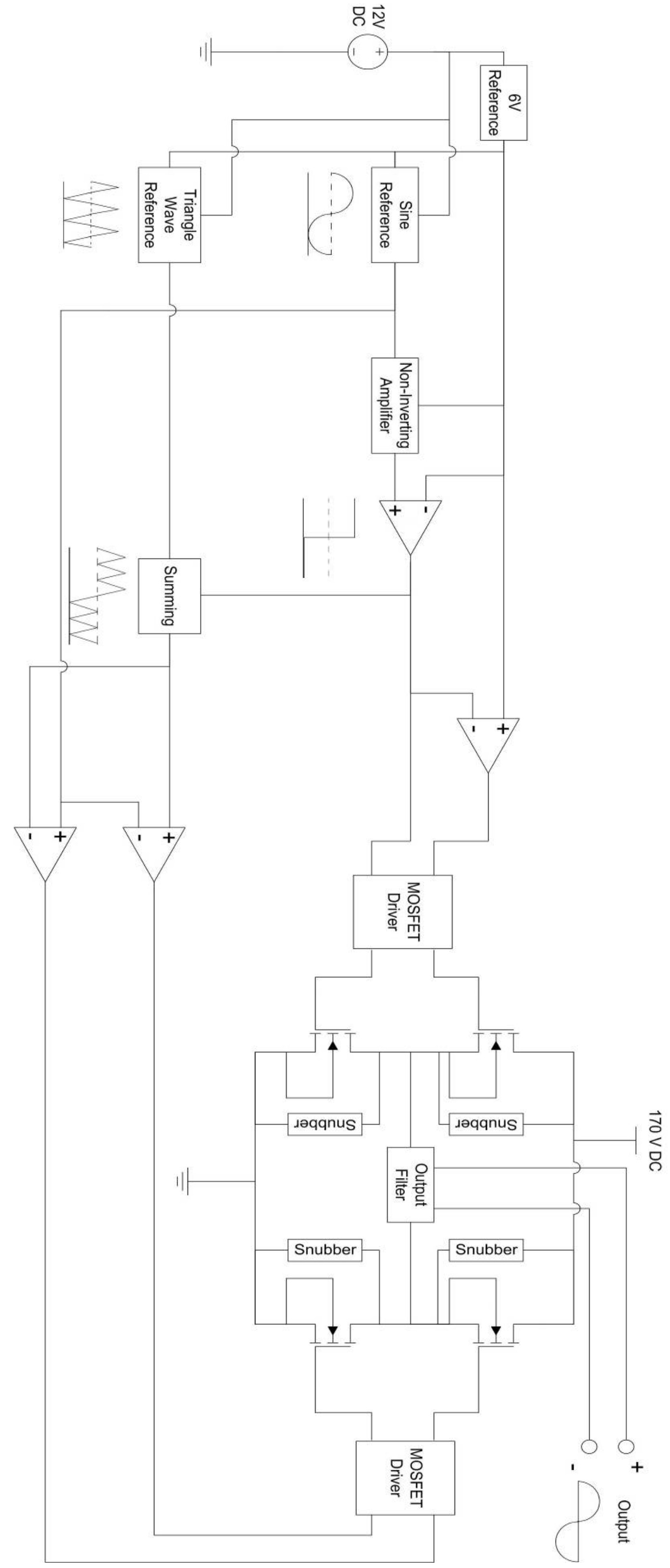


Figure 36: Frequency plot of inductor losses (resistive)

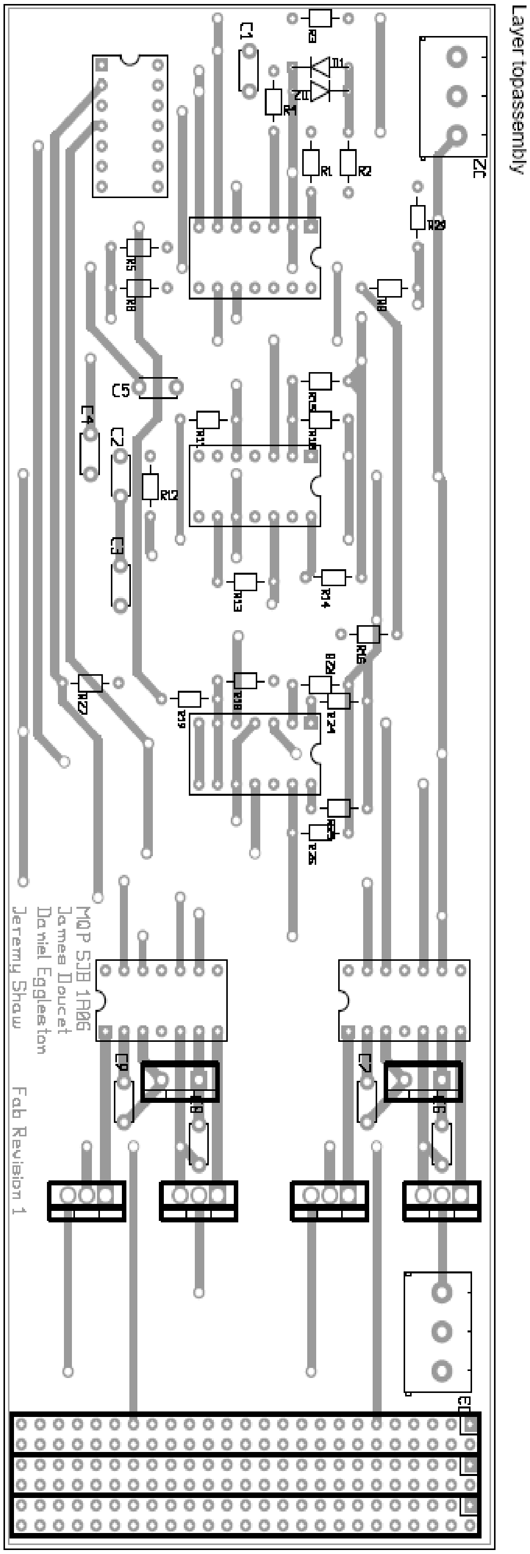
Appendix B: Circuit Diagram

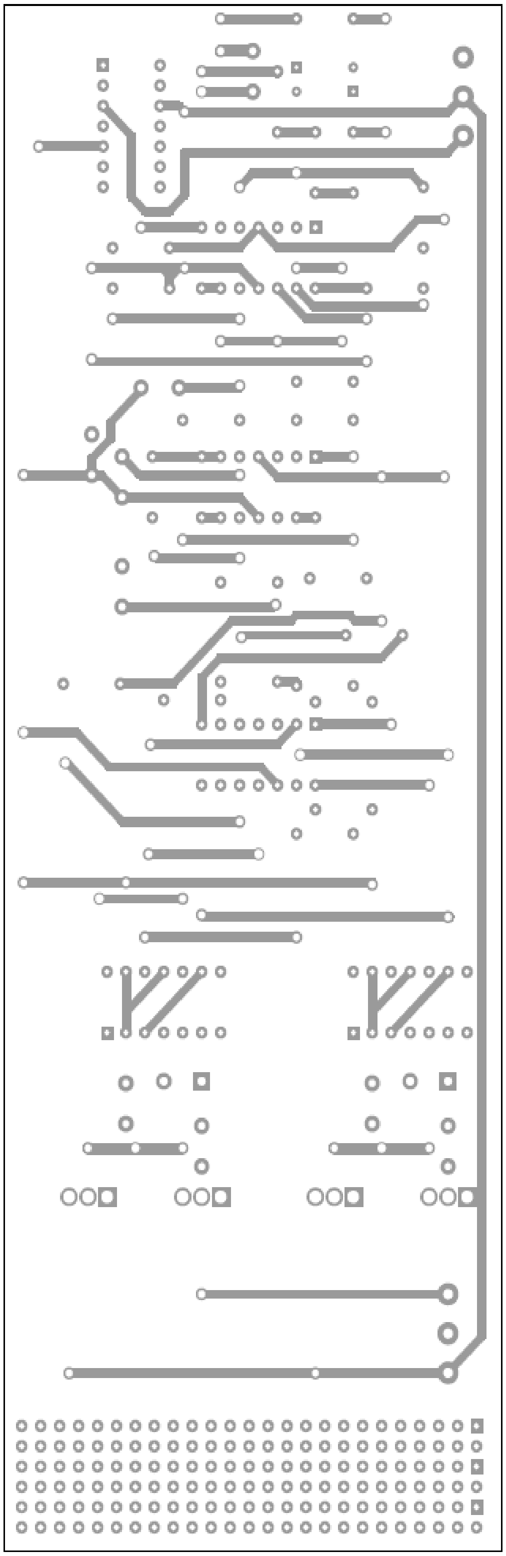

VCC
GND
R6
26.7k
R5
26.7k
IC1C
TL084D
R7
3.3k
R20
2.7k
IC1A
TL084D
R1
10k
R2
10k
D1
1N4148
D2
1N4148
R3
8.2k
R4
5.1k
C1
100pF
IC1B
TL084D
triangle
IC2A
lm348
R15
470k
R10
2.2M
sine ref
C4
100nF
R14
27k
IC2D
lm348
C3
100nF
R13
31k
IC2C
lm348
C2
100nF
R12
26.7k
R11
26.7k
C5
100nF
IC2B
lm348
IC1D
TL084D
amplified sine
R8
10k
R29
7.5k
R16
510
R17
51k
IC3A
MC3302D
R28
1k
60 Hz square
R19
1k
R18
1.4k
modified tri
IC4A
MC3302D
IC3D
MC3302D
IC3C
MC3302D
IC3B
MC3302D
R27
1k
R26
1k
R25
1k
R24
1k
IC5
IR2110
IC6
IR2110
Q1
IRF120n
Q2
IRF120n
Q3
IRF120n
Q4
IRF120n
R9
10
R30
10
R31
10
R32
10
VDD
GNDA
C6
2.2uF
C7
47nF
C8
2.2uF
C9
47nF
D3
8etu04
D4
8etu04
L1
12mH
C10
1uF
L2
4mH
C11
0.56uF
Vout

Appendix C: Flowchart



Appendix D: PCB Board Diagrams





Layer bottomassembly

Appendix E: Parts List

Inductors	**Quantity**	**Digi-key Catalog Number**	**COST**
4mH High Current Inductor	1	237-1231-ND	$4.78
1.2mH High Current Inductor	1	M9850-ND	$12.54
1% Resistors	**Quantity**		
10 Ohm	4		$0.40
2.2M Ohm	1		$0.10
475k Ohm	1		$0.10
27.5k Ohm	3		$0.30
31k Ohm	1		$0.10
300k Ohm	1		$0.10
1k Ohm	9		$0.90
10k Ohm	1		$0.10
7.5k Ohm	1		$0.10
510 Ohm	1		$0.10
1.5k Ohm	1		$0.10
26.7k Ohm	2		$0.20
2k Ohm	1		$0.10
200k Ohm	1		$0.10
510k Ohm	1		$0.10
Capacitors	**Quantity**		
.1uF	6		$2.40
2uF	2		$0.80
51nF	2		$0.80
1nF	1		$0.40
.01nF	1		$0.40
.1nF	1		$0.40
680pF	1		$0.40
Diodes	**Quantity**		
1n4148 Diode	2		$0.10
IR150F Diode	2	8ETu04-ND	$4.46
Chips and Semiconductors	**Quantity**		
LM348	1		$0.55

TL084	2		$1.80
MC3302	1		$0.55
IR 2110	2	IR2110PBF-ND	$11.70
IR549P Mosfet	4	IRFB20N50KPbF-ND	$22.56
		TOTAL	**$67.54**