MULTI-SOURCE, HIGH-POWER CONVERTER

By

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Abstract

The idea behind this project as a whole is to design, optimize, and build a high-power converter box that could take inputs of 115Vac/60Hz, 230Vac/50Hz, and 14Vdc and translate any one of those into either 115Vac/60Hz or 230Vac/50Hz at the output. The main reason to incorporate two very common AC signals into this project lies on the hope to make it more internationally compatible. The reason for the inclusion of the 14Vdc input, however, is the primary motivation for this experiment. The goal is to be able to draw current from an energized car battery (running at approximately 14Vdc) and supply it to key household items, such as sump pumps, small refrigerators, small microwave ovens, etc. in the event of a power outage. The idea is to be able to continuously provide up to 1,000W at the output in order to cope with the high power demands of some of the items mentioned previously.

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1. Introduction

The motivation for this idea is to bridge the gap between power converters and provide a universal platform that allows for multiple functions in one convenient package. The current products that are commercially available mainly focus on one type of power conversion (e.g. AC/DC, DC/AC, DC/DC, or AC/AC) and do not allow for much flexibility and user control in terms of input and output. This project aims to meet a broad range of power supply needs both in the household and on the road. Since the objective of this product is to convert 115Vac/60Hz to 230Vac/50Hz and vice versa, and 14Vdc to either of those two AC signals, it is evident that the majority of the designing and planning would take place in the actual AC/AC and DC/AC conversion processes. There is also quite a bit of control that takes place on the side to ensure the converters are receiving the correct digital waveforms to function properly. Also, there needs to be user control integrated in this design as well, where the consumer would select which AC voltage they prefer to have at the output.

1.1 Block Diagram

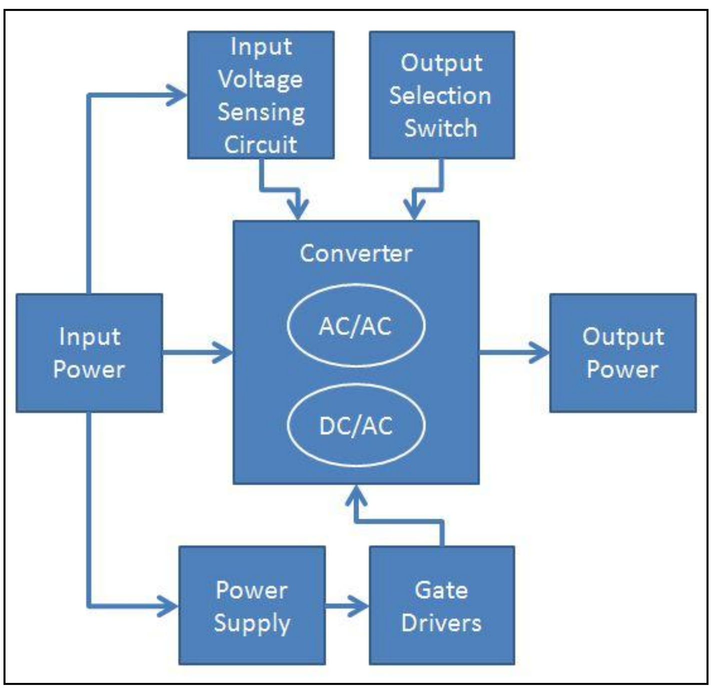

Figure 1: General Block Diagram

1.2 Block Descriptions

Input Power: 115Vac/60Hz, 230Vac/50Hz, or 14Vdc.

Input Voltage Sensing Circuit: A system of relays that senses the input voltage and switches between the terminals of a transformer to either provide a 1:2 ratio for 115 to 230V step-up or a 2:1 ratio for 230 to 115V step-down.

Output Selection Switch: A switch that selects which output the converter will supply (either 115Vac or 230Vac) and triggers relays that will finalize the conversion path.

For example, if the input selection switch is set to AC, the conversion path chosen will be AC/AC. Then the output selection switch will determine whether to provide 115Vac/60Hz or 230Vac/50Hz at the output.

Converter: All power conversion will take place here and it would be determined by the above described switches.

> **AC/AC:** If the input is 115Vac/60Hz, it would be stepped up to 230Vac/50Hz using a 1:2 transformer. If the input is 230Vac/50Hz, it would be stepped down to 115Vac/60Hz using a 2:1 transformer. After the transformer, the appropriate sinusoidal signal will be rectified by a full-wave diode bridge and a capacitor in parallel in order to achieve a near-constant DC voltage. The next step would involve inverting this DC signal into the appropriate AC signal through four MOSFET switches arranged in a bridge.
>
> **DC/AC:** The 14Vdc input will be fed into a two-stage boost converter which will step up the voltage to either 115Vdc or 230Vdc, depending on the setting of the output selection switch. This voltage will then be sent to a bridge inverter (consisting of the same four MOSFET switches again) to produce either 115Vac/60Hz or 230Vac/50Hz.

Power Supply: A circuit consisting of a transformer, rectifying diode bridge, filtering capacitor, and a voltage regulator in order to provide a steady 12Vdc power supply for the gate driver sub-module.

Gate Drivers: A collection of MOSFET driving schematics that provide the proper waveforms needed for the converter unit. This sub-module consists of the PWM h-bridge driver for the AC/AC converter, as well as the closed loop control for the two-stage boost converter.

Output Power: 115Vac/60Hz or 230Vac/50Hz.

2. Design

2.1 AC/AC Converter

In this sub-module, the idea again is to convert between 115Vac/60Hz and 230Vac/50Hz. Figure 2 displays the overall circuit schematic for this portion of the project. It begins with the input. The AC waveform is fed into the relay control circuit where a system of relays selects between the appropriate terminals of the transformer. If the input is 115V, it would be attached to the transformer in a 1:2 ratio. Otherwise, if the input is 230V, it is guided through a 2:1 ratio. After the transformer stage, the sinusoidal signal is rectified using a full-wave diode bridge and a filtering capacitor to level it out to a constant DC voltage. This DC voltage is then switched at the appropriate frequency, either 60Hz for 115Vrms or 50Hz for 230Vrms, by the h-bridge. The VSI control circuit is used to provide the proper waveforms to the gates of the MOSFETs. The presence of a VSI waveform is vital for this design to work. This was not accounted for in the original design but had to be revised and corrected. The importance of having a VSI instead of a 50% duty ratio full square wave comes from the fact that the DC voltage obtained from the rectifying bridge is the peak value of the input sinusoidal voltage, not the RMS. If this peak voltage is used to switch the h-bridge at a 50% duty ratio full square wave, the output function would have an RMS value equal to the peak value of the input. For example, if the input is 115Vrms, the transformer would step it up to 230Vrms, then it would be rectified to 325Vpeak, and that would become the RMS value of the output waveform, which is highly undesired. Instead, the actual implementation of this design accounts for this and incorporates a VSI driving circuit in order to provide for the appropriate dead time and allow for the correct RMS value at the output.

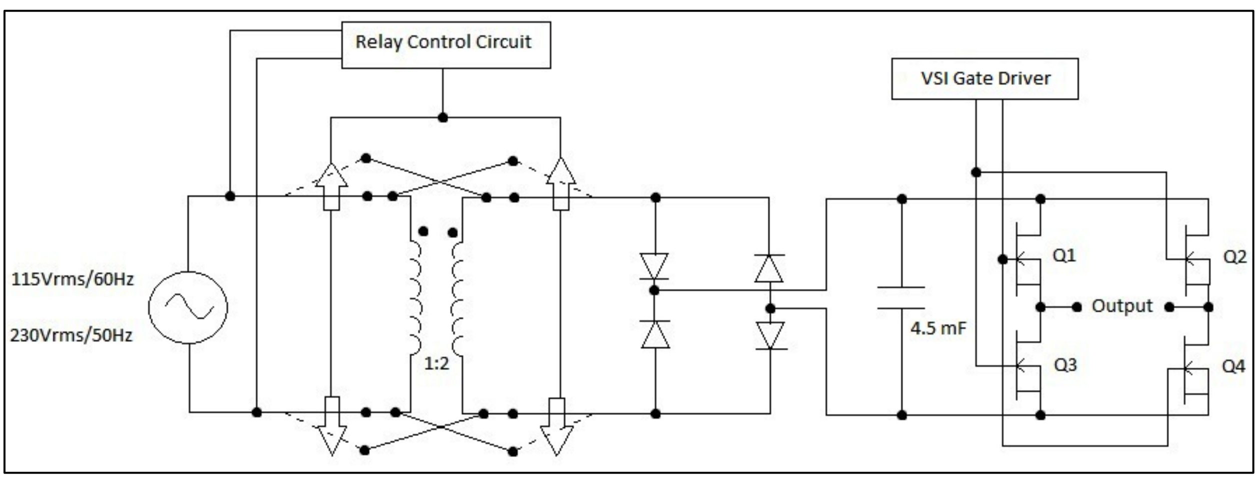

Figure 2: AC/AC Converter Full Schematic

2.1.1 Relay Control

In order to perform the two types of AC/AC conversion, the main transformer needed to function as both a step-up and step-down transformer. To utilize the transformer in this manner a control circuit was needed such that the input would either be connected to the primary windings or the secondary windings of the transformer. This control circuit consisted of a small step-down transformer, bridge rectifier, filtering capacitor, potentiometer (voltage divider), and an N-channel MOSFET. Figure 3 shows the schematic of the relay control circuit. Once the user has provided an input voltage, the control circuit will rectify that voltage to either 11.5Vdc (from a 115V input) or 23Vdc (from a 230V input). The DC voltage is then divided through a potentiometer and supplied to the gate terminal of the MOSFET. For the 11.5V case, the voltage on the gate terminal is less than the threshold voltage and the MOSFET behaves like an open circuit, prohibiting current to flow through the coil of each relay within the AC/AC converter, and allowing them to remain in their original position. In the 23Vdc case, voltage supplied to the gate terminal is higher than the threshold voltage, causing the MOSFET to behave like a closed circuit, allowing current to flow through the coil of each relay and switching them to their secondary position.

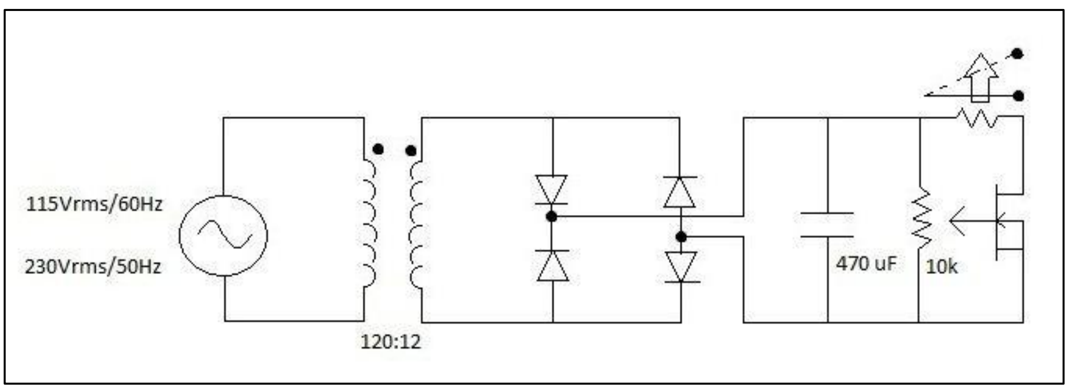

Figure 3: Relay Control Circuit for AC/AC Converter

2.1.2 VSI Waveform Generator

The VSI gate driver schematic, the importance of which was discussed earlier, is portrayed in Figure 4. The way this circuit works is that the correct PWM signal, depending on the position of the output user selection switch, is fed into an inverter. The original and inverted signals are then guided through timing chips that provide a delay to account for the correct dead time needed for the VSI waveform. The respective signals from there are fed into half bridge drivers in order to be able to supply the correct voltage across the gate and source of each MOSFET and successfully drive each device in the h-bridge.

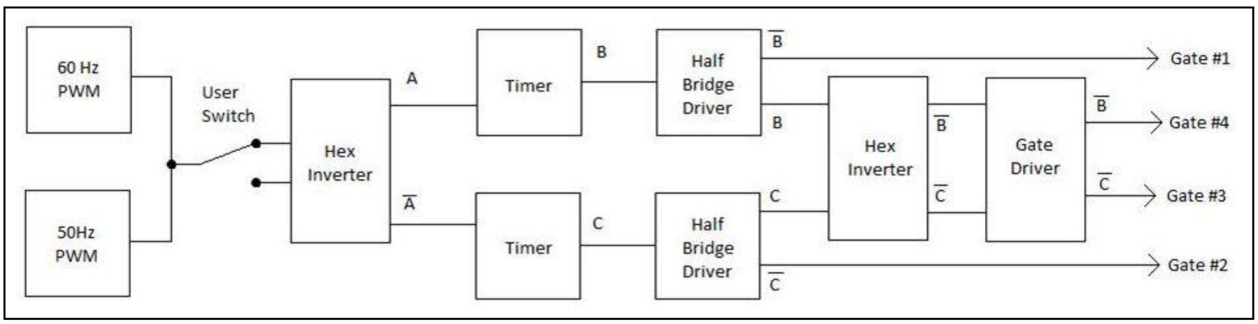

Figure 4: VSI Waveform Circuit for AC/AC Converter

Figure 5 depicts the actual PWM schematic, as part of the above described VSI waveform generator. This design incorporates the UC3843 PWM chip, and the two potentiometers displayed are used to control the frequency and duty ratio.

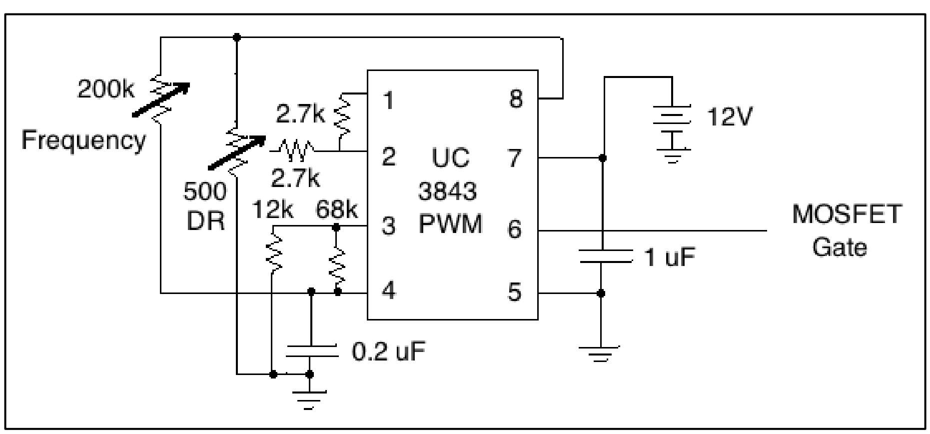

Figure 5: PWM Circuit for VSI Waveform Generator

2.2 DC/AC Converter

In this sub-module, the idea again is to convert 14Vdc from an energized car battery to either 115Vac/60Hz or 230Vac/50Hz, depending on the output user selection switch. Figure 6 displays the overall circuit schematic for this portion of the project. It begins with the 14Vdc input. It is fed through a two-stage boost converter. The first stage steps up the voltage to about four times the amount, and the second stage amplifies it to the appropriate level, either 115 or 230V. The output from the second stage boost is fed into the same h-bridge that is used for the AC/AC converter. This MOSFET bridge again switches the DC signal into the appropriate frequency to provide the desired output. In this case, a VSI waveform is not necessary because the DC voltage coming from the second boost converter is the proper one, either 115 or 230V, to cause the correct RMS value when switched at a full square wave function with a 50% duty ratio on the output. It can be observed in Figure 6 that there are two types of control sub-circuits: one is the current sensor and the other is the closed loop control, both of which were not accounted for in the initial design considerations. The purpose of the current sensing sub-module is, by utilizing hall sensors, to detect the magnitude of the input current to each stage of the boost converter and to select the appropriate inductor for the detected current level. This design technique ensures that the inductors are sized correctly for the proper application and that they do not saturate. The other form of control introduced in this section is the closed loop control. This circuit changes the duty ratio of the switching function of the MOSFETs in both boost converters with a changing load to ensure proper output voltage levels.

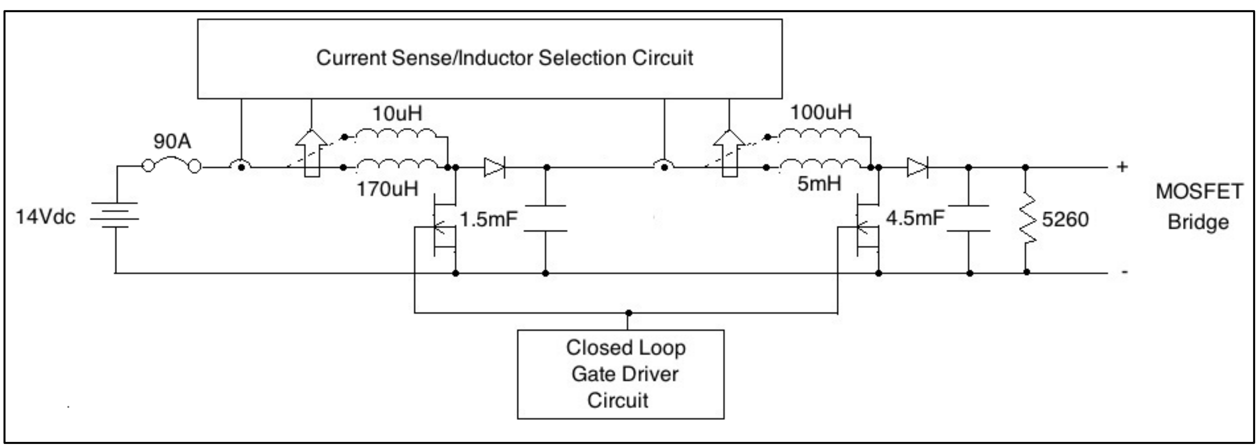

Figure 6: DC/AC Converter Full Schematic

2.2.1 Current-Sensing Inductor Selection

In order for the boost converter circuit to handle the high power levels while still remaining efficient at low power levels, a double inductor system was needed. When sizing the inductor for a boost converter is it desirable to have as much inductance as possible because it increases the overall efficiency of the circuit. However, large inductors that are also capable of handling large amounts of current are expensive and were not practical for this application. Therefore, each stage of the boost converter used two inductors, one that had a higher inductance but lower current rating, and another which had a lower inductance but a higher current rating. In order to switch between the two, a current sensor and relay was placed at the input of each stage. The current sensor output was then fed into a non-inverting amplifier whose output was used to supply voltage to the gate terminal of an N-channel MOSFET, similar to the method described in the relay control circuit of the AC/AC converter. Once the sensed current was large enough, the voltage on the gate terminal would surpass the threshold voltage creating a closed circuit and allowing current to flow through the coil of the relay and switching it to it's secondary position. For each stage of the boost converter, the primary position of the relay corresponded to a low current and high inductance while the secondary position corresponded to a high current and low inductance structure. Figure 7 depicts the current sensing schematic that is used in the DC/AC converter.

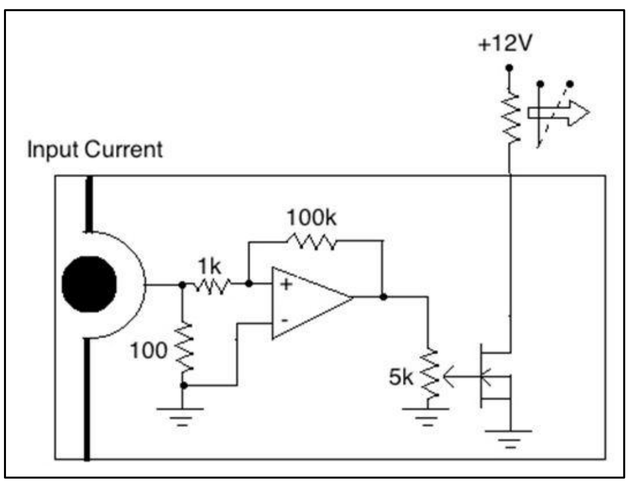

Figure 7: Current Sensing Circuit for DC/AC Converter

2.2.2 Closed Loop Control

One challenge encountered was the ability to control the output voltage of the two-stage boost converter. As the input voltage varied or higher power loads were connect the output voltage of the converter tended to fluctuate. To correct this problem a closed loop control circuit was added which sensed the output voltage and increased or decreased the duty ratio accordingly. Figure 8 shows the schematic for the closed loop control circuit, which consisted of potentiometers, resistors, zener diodes an op-amp, and a capacitor. This circuit is commonly referred to a PI control and it creates a signal voltage that is both proportional and inversely related to the input voltage of the amplifier. In this circuit the output voltage of the two-stage boost converter is fed into two potentiometers. Each potentiometer serves as voltage divider, the left pot is calibrated such that when the output of the boost converter is 115V, the middle terminal is 6V, and the right pot is calibrated such that when the output of the boost converter is 230V, the middle terminal is 6V. As the output from the boost converter varies so does the middle terminal of the potentiometer, which affects the voltage seen at the inverting input of the amplifier. This causes the output voltage of the amplifier to change along with the input to the PWM controller. As the output voltage of the boost converter decreases below the desired level, the signal sent to the PWM controller increases effectively telling the controller to increase the duty ratio, which will increase the output voltage of the boost converter. Inversely, if the output voltage of the boost converter is above the desired level the signal sent to the PWM controller allows the duty ratio to decrease, which will decrease the output voltage of the boost converter. The zener diodes keep the duty ratio within a specified range regardless of the output voltage of the boost converter. In this application that range was 50% to 90%.

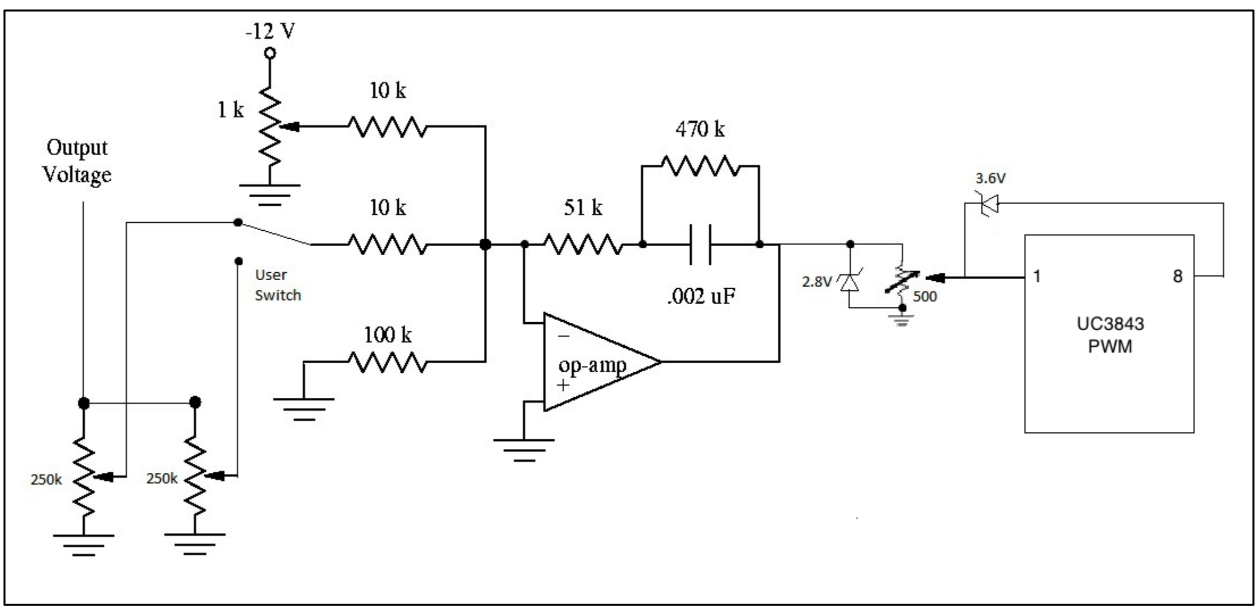

Figure 8: Closed Loop Control Circuit for DC/AC Converter

2.2.3 Snubber

Yet another sub-circuit component that was not accounted for in the initial planning is the snubber circuit. This one is actually fairly important. Figure 9 shows the schematic for both snubbers: the first stage on the left and the second stage on the right. The main purpose of the snubber circuits is to dissipate the power when all the switches turn off, and also, to reduce the switching losses associated with the very high frequency at which the two-stage boost converter is operated (50kHz). The simple RCD snubbers shown in Figure 9 are designed with appropriate values for the resistance and capacitance to provide for the correct time constants in order to successfully dissipate the power in the off state.

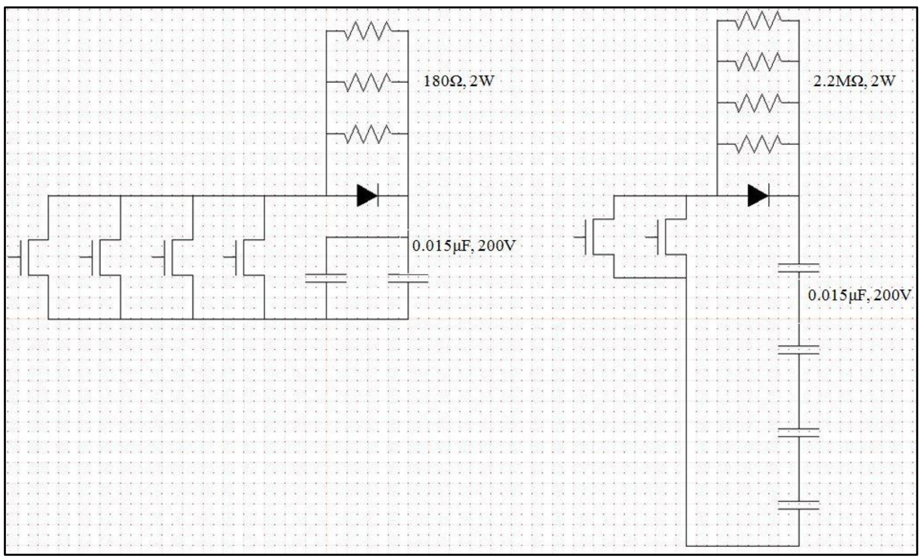

Figure 9: Snubber Circuits for DC/AC Converter

3. Design Verification

3.1 AC/AC Converter

Although the project as a whole did not fully function under all conditions, especially high-power, different components from the box were ripped out and tested separately in order to prove individual functionality. Firstly, it can be observed in Figure 10 that a successful VSI waveform was achieved for the 115Vrms case. Similarly, Figure 10 also displays a successful VSI waveform for the 230Vrms case. These also show the AC/AC converter operating under low-load conditions.

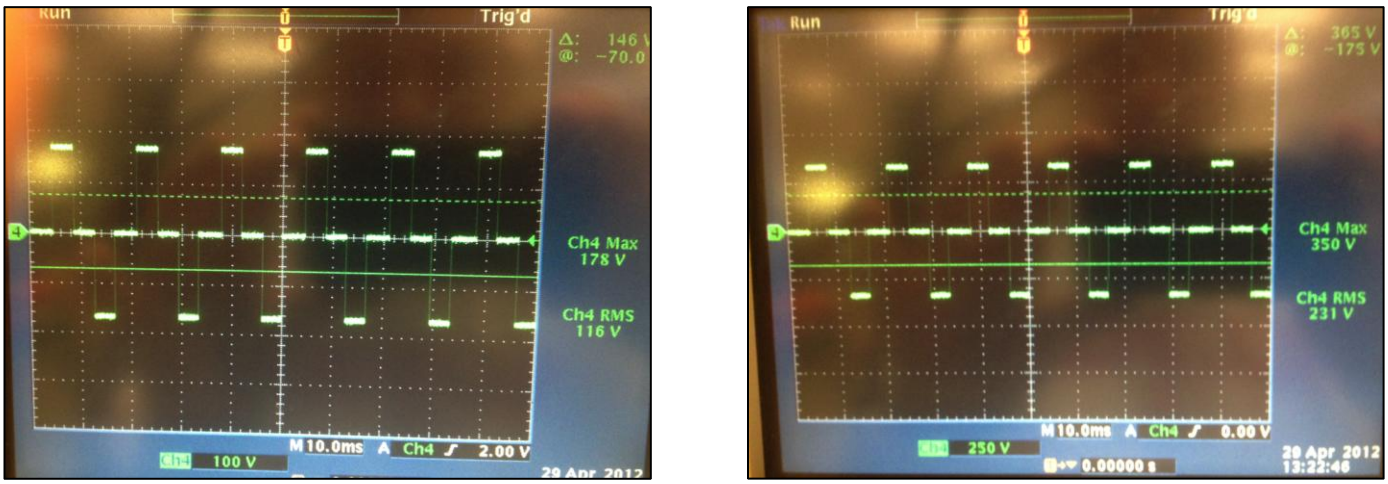

Figure 10: VSI Waveform for 115Vrms (left) and 230Vrms (right)

In order to obtain decent efficiency results, the efficiency of individual modules were examined and the results were gathered in Figure 11. The left plot indicates the efficiency of the bridge rectifier as compared to the amount of output power, and the right plot depicts the efficiency of the h-bridge again with respect to output power. These efficiency levels are fairly promising. The combined efficiency range of the AC/AC converter falls between 64.3% - 88.9%, whose average value of about 76.6% exceeds the goal of 70% set at the beginning of the semester.

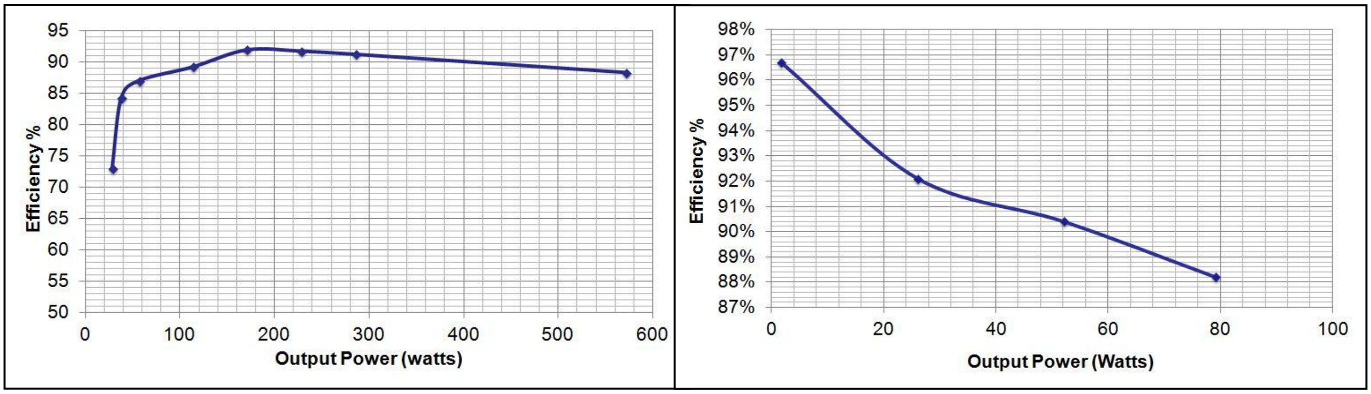

Figure 11: Efficiency of Rectifier (left) and H-Bridge (right)

3.2 DC/AC Converter

Just like the AC/AC converter, the DC/AC converter was tested by ripping out the components from the overall box in order to perform isolated testing. Since the closed loop control was not functioning properly, a FET box with a tunable duty ratio was utilized to simulate the closed loop control in order to test the two-stage boost converter. The DC/AC converter worked well for both 115 and 230V, and the smooth DC output waveforms of the second stage boost can be seen in Figure 12.

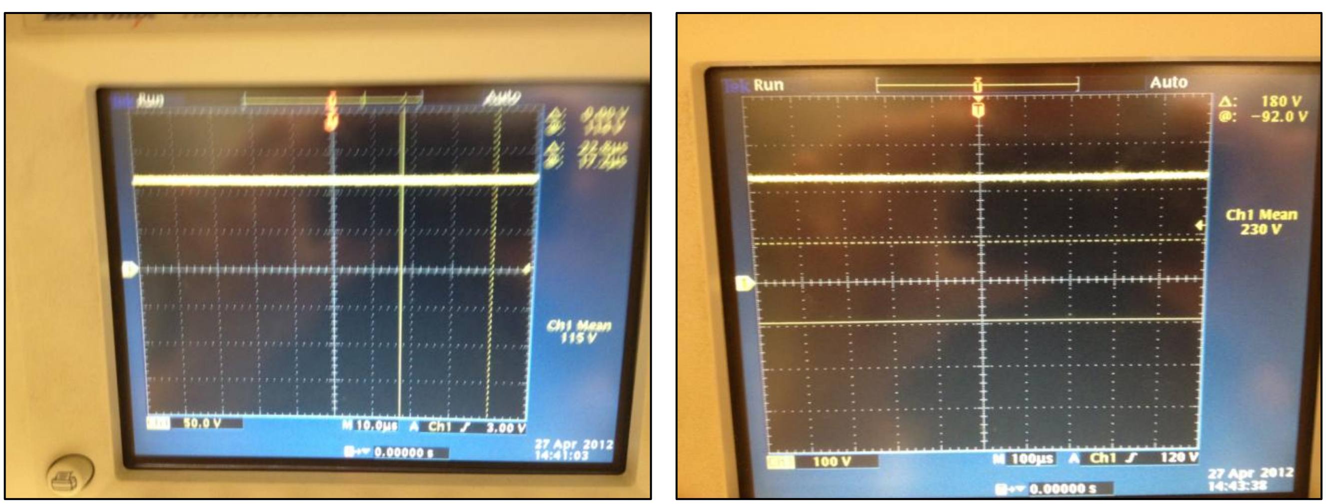

Figure 12: Two-Stage Boost Converter DC Output Waveform for 115V (left) and 230V (right)

One important characteristic that was tested was the output voltage ripple of the DC/AC converter. As can be seen from Figure 13, the plots of the output voltage ripple indicate very good ranges: 7.2Vp-p for the 115V case and 14Vp-p for the 230V case. These ripples only account for 3.1% and 3%, respectively, meeting the goal of maximum output ripple of 10%, which was established in the initial planning.

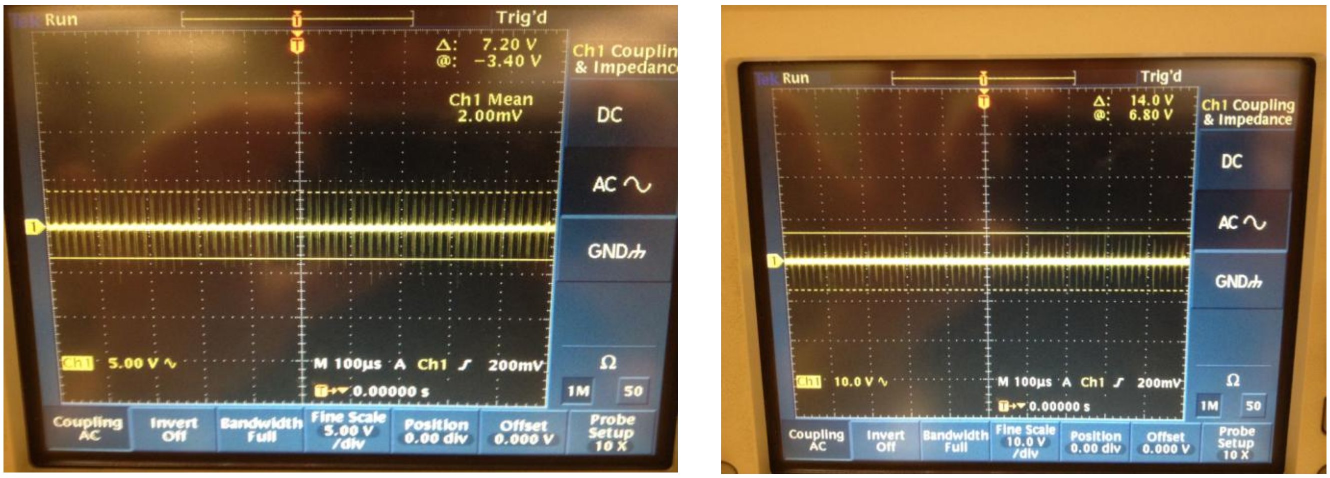

Figure 13: DC/AC Converter Output Voltage Ripple of 115V (left) and 230V (right)

Efficiency results were gathered for the DC/AC converter circuit as well. The data is plotted in Figure 14. Again, it can be seen that the efficiency is at a very good range between 76% - 94%, which is well above the desired and anticipated 70% goal.

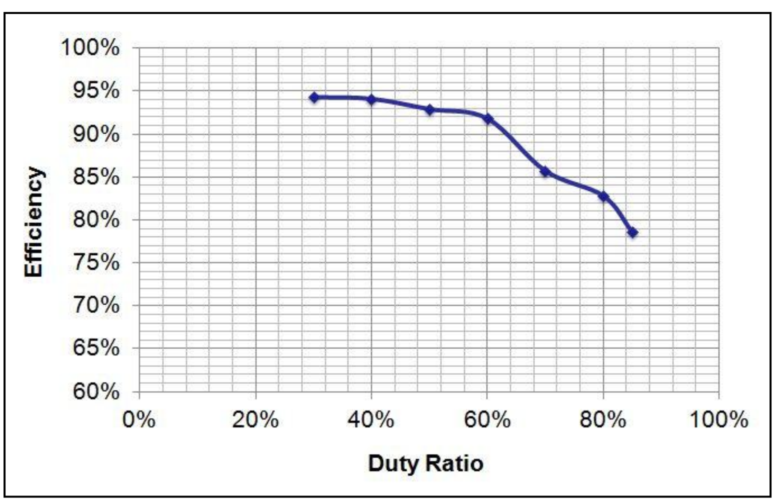

Figure 14: Two-Stage Boost Converter Efficiency

4. Cost Analysis

4.1 Parts

Table 1: Cost Analysis for Parts

Part Description	Model Number	Supplier	Quantity	Price / Unit	Total
50A 60V MOSFET (N-channel)	50N06	Power Lab	6	$1.39	**$8.34
400V 27A MOSFET (N-channel)	IRFP360	Power Lab	6	$3.79	**$22.74
30A Power Diode	MUR3040	Power Lab	10	$4.30	**$43.00
Transformer (1KVA)	1100-OF	Power Lab	1	$104.50	**$104.50
Inductor (270uH)	1140-271k-RC	DigiKey	1	$13.81	$13.81
Inductor (5mH)	159zj	Newark	1	$34.34	$34.34
Capacitor 400V (4.5mF)	LNX2V272MSEG	Power Lab	1	$31.10	**$31.10
Capacitor 100V (2.7mF)	EEU-EB2V470	Power Lab	1	$1.64	**$4.92
USA/Euro Plug Adapter		RadioShack	1	$4.94	$4.94
3 Prong USA Plug		Power Lab	1	$3.89	**$3.89
3 Prong USA Socket		Graduate Lab	1	$2.19	**$2.19
15V Buck Converter	M57182N	DigiKey	1	$7.63	$7.63
Euro Wall Socket		RadioShack	1	$7.00	$7.00
4 Guage Jumper Cables		Wal-Mart	1	$23.91	$23.91
30A SPDT Relay	RT314730	Auto-Zone	4	$10.89	$43.56
Rocker Switch	M2023TJW01	Parts Shop	2	$1.65	**$3.30
Gate Driver	UC3843	Parts Shop	3	$0.94	**$3.76
Vector Board		Power Lab	1	*$15.00	**$15.00
Assorted Wires		Parts Shop	N/A	*$25.00	**$25.00

Aluminum Housing		Machine Shop	1	*$20.00	**$20.00
Assorted 1/4 Watt Resistors		Parts Shop	≈20	*$0.05	**$1.00
Assorted Small Capacitors		Parts Shop	≈10	*$0.15	**$1.50
		Total Cost of Parts = $425.43			
*Denotes Estimation					
**Denotes Bootstrapped Part					

4.2 Labor

Table 2: Cost Analysis for Labor

Name	Salary	Hours	Total
Viktor Terziysky	$30.00 / hr	150	$11,250.00
Eric Kapinus	$30.00 / hr	150	$11,250.00
		Total Cost of Labor = $22,500.00	

Total Cost of Project = $425.43 + $22,500.00 = $22,925.43

5. Conclusion

5.1 Accomplishments

Throughout the course of this project many of the original goals were accomplished. The circuit was capable of producing the correct rectified voltage at the filtering capacitor regardless as to whether the input was 115V or 230V. In addition, the MOSFET Bridge, utilizing a VSI waveform, was able to take 163Vdc or 325Vdc and convert it to AC values of 115Vrms or 230Vrms respectively. For the DC/AC converter, the circuit was able to take 14Vdc and maintain a constant output of 115Vdc or 230Vdc regardless of fluctuations in the input voltage or load attached to output. While the circuit failed for high power conditions, it was able to meet the efficiency and ripple targets for low power conditions.

5.3 Ethical Considerations

Since this project revolved around high voltage and current levels, safety was the main ethical consideration. Therefore, several types of protection were incorporated into the design. In the AC/AC converter, 5A and 10A fuses were placed within the circuit prior to any component used in the conversion process. In addition, proper grounding was placed throughout the circuit, which eliminated the possibility of user harm in the event of malfunction or fault. Lastly, circuit breakers were used in the DC/AC converter prior to any component used in the conversion process. These circuit breakers were auto resetting which eliminated the need for the user to dismantle the circuit in the case of an overload.

5.4 Future Work

After concluding the testing and verification there are several design aspects, which would be modified before this project were to be taken further. The first would be the method of stepping up 14V to 115V or 230V. Instead of using a two-stage boost converter, a transformer would be implemented which would be capable of performing the step-up needed, but at higher efficiencies. Also, the PWM and closed loop control would be operated via a micro controller, which would be more efficient and precise than analog control circuits. Furthermore, better isolation of digital components and power components would be used through opto-coupling such that digital components would not be affected from failure on the power side. Lastly, a slow start circuit would be introduced at the input, which would prevent a sudden inrush of current during circuit startup or load connection.

Appendix: Requirement and Verification Table

Table 3: Requirements and Verification

Module Description	Requirement	Test Procedure	Verification Status
Input Voltage Sensing	• Sense input voltage and if it is 115V connect to 1:2 terminals of transformer and if 230V connect to 2:1 terminals	• Use ohm meter to test which components are connected/disconnected to ensure current follows correct path	*YES
Transformer	• Step-up or step-down AC voltage with a 1:2 or 2:1 ratio • Stable operation with 1,000W input power	• Use function generator and multi-meter to test transformer voltage characteristics • Supply transformer with 1,000W input and monitor temperature, current, and voltage	YES
Diode Bridge	• Rectify AC voltage to constant DC voltage with less than ±10% ripple	• Use function generator and oscilloscope to observe output voltage and ripple • If the desired voltage is 115V, then the measured value should be between 103.5 - 126.5V • If the desired voltage is 230V, then the measured value should be between 207 - 253V	YES
MOSFET Bridge	• Produce a modified sine wave output from a constant DC voltage with desired output	• Use power supply and oscilloscope to provide constant voltage and observe output voltage waveform • If desired voltage level	YES

	frequency determined by user	is 115V, then the measured frequency should be close to 60Hz • If the desired voltage level is 230V, then the measured frequency should be close to 50Hz	
Gate Driver for MOSFET Bridge	• Provide VSI wave switching function for the MOSFET bridge	• Use oscilloscope to measure output signal frequency, delay, duty ratio, and voltage • Frequency should be close to either 60Hz or 50Hz, whichever is desired	*YES
Output Selection Switch	• Select Bridge Gate Driver switching frequency of either 50Hz or 60Hz • Provide desired user output voltage at MOSFET bridge from 2-stage DC boost converter if DC input is selected	• Use oscilloscope to observe switching frequency at the MOSFET bridge • Use multi-meter to determine test voltage output of 2-stage boost converter	YES
2-Stage Boost Converter	• Take input of 14Vdc and step it up to either 115Vdc or 230Vdc • Handle continuous output power of 1,000W	• Use power supply to provide 14Vdc at input and use multi-meter to measure output voltage • Output of first stage should be around 56V • Output of second stage should be either 115V or 230V, whichever is desired • Attach 1,000 Watt load	YES; except power level of 1,000W

		and measure component temperature, voltage, and current characteristics	
Closed Loop Control for 2-Stage Boost Converter	• Provide square wave switching signal to boost converter MOSFETs	• Use oscilloscope to observe and measure duty ratio of switching signal • Duty ratio should be close to 65% for 115V • Duty ratio should be close to 76% for 230V	NO

* changed requirement