High Voltage Pulse-Width Generator for the Algae Biofuel Project

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT

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San Luis Obispo

By

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Acknowledgements

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Abstract

High Voltage Pulse-Width Generator for the Algae Biofuel Project

Philip Yu & Stephen Leung

This purpose of this project, sponsored by Boeing and advised by Dr. Arakaki and Dr. Taufik, is to build a high voltage pulse width generator that lyses algae cells to harvest the biofuel within. This project uses Emmanuel Loza's thesis on a cascaded high voltage converter with variable control to build a portable pulse width generator with independent control on the peak voltage, pulse width, and frequency. The project focuses on creating a pulse width generator capable of finding the most optimal pulsed electric field to lyse algae. The pulse width module ranges from 10V-80V peak voltage, 60Hz-100 kHz frequency, 17ms-10us pulse width, and 20%-80% duty cycle according to Emmanuel Loza's thesis. The pulse width generator's interface allows users without any engineering background to operate it.

I. Introduction

With the spread of globalization, demand for air travel continues to increase. The International Air Transport Association (IATA) expects to see a 31% increase in passenger numbers between 2012 and 2017. The total passenger numbers are expected to rise to 3.91 billon passengers by 2017[1]. According to IATA, this is due to an increase in domestic passengers in the United States, as well as the increasing drive for global trade and development in the Asia Pacific region. With continued increase demand for air travel all over the world, jet fuel supply and cost will become a major concern for airliners.

The demand for transportation around the world increase annually as globalization continues to strive. In 1991-1995, the average cost of jet fuel is $0.69 a gallon [2]. Now, in 2014, the average cost of jet fuel is $2.90 a gallon [3]. The reasoning behind the increase in air travel is due to rapid globalization. Many developed continues such as the United States began shifting their focus from fossil fuels to biofuels.

This algae biofuel project, sponsored by Boeing, is to experiment on different ways to lyse algae cells. Algae cell lysing demonstrates one way to extract the oil lipids from inside the cells to use as biofuel. The technique to lyse bacterial cells has existed for over 100 years.

Previous work done using RF signals to harvest algae proved unsuccessful. The project is now experimenting using a high voltage, low frequency pulse generator for lysing algae. Many different pulse electric field machines on the market can lyse bacterial cells. However, algae cell walls differ from bacteria cells walls, so the voltage required to break the cell walls varies, thus a customized pulse generator is needed. By using a pulse width generator with three variable output, finding the most optimal pulse electric field to lyse algae cells becomes likely. Currently in the researching stage, the biofuel project group consisting of biology students, experiment on different ways to lyse algae cells. The biology students will use the module to experiment and determine if high-powered pulses have enough voltage to lyse algae cells making harvesting algae possible. Our project focuses on producing a module for the biology students to use for experiments while another senior project studies the electric field analysis of the project. Currently, the biology students conduct experiments on testing for oil lipid count effectively.

Thus, the purpose of the pulse width generator project is to build a high voltage pulse width generator [4] with three variable outputs to create pulsed electric fields to lyse algae cells. By using a pulse width generator with three variable output, the most optimal pulse electric field to lyse algae cells can be found.

II. Background

Biofuels are becoming popular due to oil prices increasing and the energy security it provides. By 2035, the world's population is expected to reach 8.3 billion people meaning an additional 1.3 billion people will require energy [4]. Fossil fuels are not enough to provide the amount of energy needed to offset the energy demand in the near future. To preserve fossil fuels and increase energy security, biofuels can be used as an alternative solution to help meet the increasing use of energy.

Algae are a great source for biofuel since it is both a renewable and sustainable source of energy. Renewable means "capable of being replaced by natural ecological cycles or sound management practices" [5] and algae grow naturally in the water making it a renewable source. Algae can be harvested in the sea and in a cultivated environment making growing a mass amount of algae possible. Sustainable means "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [6] and algae can be grown indefinitely, so theoretically there can be an infinite amount of algae in the future. Algae biofuel is also an environmentally friendly operation. After being harvested, the algae go to a bio-refinery process that transforms the lipids into biofuel, which can be used to power vehicle, and excretes bio-waste. The bio-waste is put into an anaerobic digester that converts the waste into natural gas and fertilizer for plants. It is clear that biofuel is needed in the future as an important resource to fuel our energy needs.

Algae cell lysis consists of harvesting the algae and lysing the cell to extract the lipids within. Since algae cell lysing is a relatively new technique, there still needs to be research on the lysis of the algae cell wall. In the future, algae cell lysis can be one solution, out of many, to solve the current energy crisis.

III. Requirements and Specification

The main goal of this project is to create a pulse width generator with three variable outputs. In this chapter, the requirements and specifications for the pulse width generator are shown, which are to be portable, simple to use, contain variable output, safe to use, and not overheat. These requirements and specifications are determined by inputs from the project team.

Table 3-1 shown below, lists the marketing requirements, engineering specifications, and justification to define the criteria needed to fulfill this project's goals.

Table 3-1: Pulse Width Generator Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1	The module does not exceed 2.25 cubic feet	The generator should be small enough where a student can move it around. 2.25 cubic feet should provide sufficient amount of size to fit all of the internal components.
2+3	The module includes 3 individual controls for the 3 variables (frequency, duty cycle, and voltage).	The generator's output need to be customizable for the biologist to figure out the optimal output to harvest algae cells.
2+4	The module does not have any wires or components outside of the enclosure.	This is to prevent the biology students, who have no engineering background from harming themselves.
4+5	The module's internal temperature does not exceed 74.3 °F(Room Temperature)	High temperature increases chances of malfunction and potential injuries to the users.
2+3	The module's output pulse voltage ranges from at least 10V-80V, frequency ranges from 60Hz-100kHz, and duty cycle ranges from 20-80 % to the output port.[5]	The output variables of the module have a range as this pulse module intends to find the best output for harvesting algae.
2+4	The module needs a 120V AC source to operate.	Maintain the simplicity so the module does not require regularly maintenance such as battery switches.
Marketing Requirements 1. Portable. 2. Simple to use. 3. Variable output. 4. Safe to use. 5. Not over heat.		

There are four different requests established for our senior project that can be found by looking at the marketing requirements results in Table 2-1. These are: a way to lyse algae, simplistic to use, portable, and a range of outputs. The project focuses on constructing a pulse width module to create an opening for the lysing to occur so biology students can operate in a simple and safe manner.

The senior project consists of five marketing requirements. These marketing requirements requires the pulse width generator to become portable, simple to use, variable outputs, safe to use, and not over heat. The module must be portable as the end user's work environment switches often. This project consists of biology students that use it on their own without technical support once the final product is complete. Also, heat produced by the components can render the module inoperable due to overheating.

The senior project consists of five engineering specification. Our first engineering specification requires "The module should not exceed 2.25 cubic feet". This fulfills our marketing requirement 1 of portability. 2.25 cubic feet would allow the module's size to be transportable by one person.

The second engineering specification requires "The module should have 3 individual controls for the 3 variables (frequency, duty cycle, and voltage)". This fulfills marketing requirement 2, as the biology students will be changing the variables to find the optimal output to harvest algae.

Engineering specification 3 requires "The module should have 0 wires or components outside of the enclosure. This fulfills marketing requirement 2 and 4 as safety becomes a top concern since the end users lack of engineering background.

Our fourth engineering specification requires "The module's internal temperature should not exceed 74.3 °F (Room Temperature)" which drives marketing requirement 4 and 5. The temperature has to be maintained at a cool temperature since at high temperatures, the chances of malfunction increases and potential injuries to the users may occur.

The fifth engineering specification requires "The module's output variables should have a range of at least 10V-80V (Voltage), 60Hz-100kHz (Frequency), and 20-80% (Duty Cycle)". This engineering specification meets marketing requirement 2 and 3 since the intended goal of the project focuses on finding the optimal output for the pulse generator.

The last engineering specification requires “The module should only need a 120V AC source to operate.” This engineering specification meets marketing requirement 2 and 4 as well as the simplistic engineering specification.

Table 3-2 shown below, lists the deliverable assignment and its due dates. The table is used as a schedule to follow during the project.

Table 3-2: Pulse Width Generator Deliverables

Delivery Date	Deliverable Description
5/14/14	Design Review
6/6/14	EE 461 demo
6/13/14	EE 461 report
12/5/14	EE 462 demo
2/19/14	ABET Sr. Project Analysis
12/5/14	Sr. Project Expo Poster
12/12/14	EE 462 Report

Functional Decomposition (Level 0 and Level 1)

Figure 3-1, shows the pulse width generator which takes in 120V AC Voltage from a typical U.S. wall plug [10] and converts it to a pulsed output voltage. The output voltage can be adjusted with a knob which acts as a potentiometer. Frequency and duty cycle can also be adjusted using knobs. This creates a varied pulse output voltage with voltages ranging from 10V-80V, frequency from 60Hz-100kHz, and duty cycle from 20%-80%.[1]

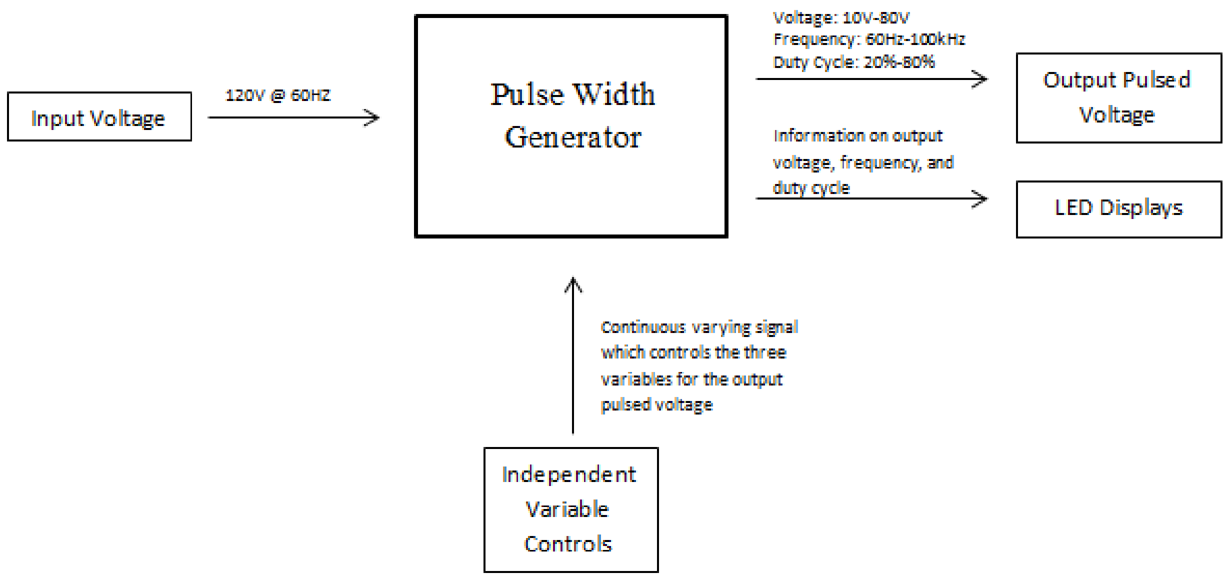

Figure 3-1: Level 0 Block Diagram

Table 3-3 shows the level 0 functional requirements. The input is 120V @ 60Hz with 3 independent variable controls and the output is a varied pulse output. The function of the pulse width generator is to produce an output pulse.

Table 3-3: Level 0 Pulse Width Generator Functional Requirements Table

Module	Pulse Width Module
Input	-Wall Voltage: 120V @60HZ AC Voltage -Independent Variable Controls: 3 knobs to adjust the variables. -Voltage: 10V-80V -Frequency: 60Hz -100KHz -Duty Cycle: 20% - 80%
Output	-Varied Pulse Output: An output pulse with a variable voltage (10V-80V), frequency (60Hz-100KHz), and duty cycle (20%-80%) -LED Displays for all 3 parameters
Functionality	The pulse width generator produces an output that varies the voltage, frequency, and duty cycle using voltage from the wall outlet as the source.

Figure 3-2, shows the level 0 block diagram of the pulse generator. The first level 1 subsystem shows the full-wave rectifier. The 120 V AC is stepped down to fulfill the flyback converter maximum input voltage. The full-wave rectifier takes in the stepped down AC Voltage and rectifies it to 90V DC Voltage. The 90 V DC Voltage is sent to the flyback converter [2] [3] [4] which regulates the pulsed output voltage ranging from 10-80V depending on the knob controls. The pulsed output voltage goes to the two switch network [9][7], which changes the frequency ranging from 60HZ-100kHz and duty cycle from 20%-80% depending on the knob controls. The output voltage flows out of the two switch network.

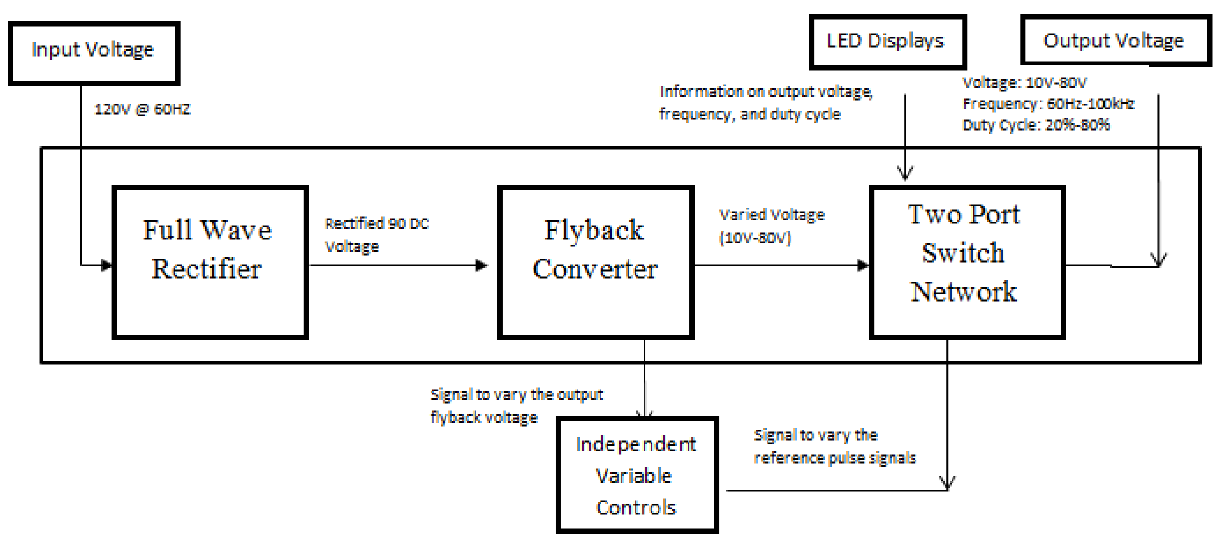

Figure 3-2: Level 1 Block Diagram

Table 3-4 shows the level 1 functional requirements of the full wave rectifier. The input is 120V @ 60Hz and the output is a rectified 90V DC voltage. The function of the full wave rectifier is to produce a rectified voltage.

Table 3-4: Level 1 Sub system – Full Wave Rectifier Functional Requirements Table

Module	Full Wave Rectifier
Input	-Wall Voltage: 120V @60HZ AC Voltage
Output	-Rectified 90V DC Voltage
Functionality	Converts the source voltage 120V @60Hz AC Voltage to a 90V DC voltage.

Table 3-5 shows the level 1 functional requirements of the flyback converter. The input is a rectified 90V DC voltage and the output is a DC voltage ranging from 10V- 80V. The function of the flyback converter is to step down the voltage to 10V - 80V.

Table 3-5: Level 1 Sub system – Flyback Converter Functional Requirements Table

Module	Flyback Converter
Input	-Rectified 90V DC Voltage -Independent Variable Control (to adjust the output voltage of the Flyback Converter)
Output	-DC Voltage ranging from (10V - 80V) depending on the Independent Variable Control
Functionality	Using the 90V DC Voltage from the Full Wave Rectifier, it steps down the voltage to 10V- 80V depending on the settings controlled by the independent variable controls.

Table 3-6 shows the level 1 functional requirements of the two port switch network. The input is flyback DC voltage and the output is a pulsed peak voltage. The function of the flyback converter is to output a pulsed peak voltage.

Table 3-6: Level 1 Sub system – Two Port Switch Network Functional Requirements Table

Module	Two Switch Network
Input	Output flyback DC voltage
Output	Pulsed Peak Voltage ranging from (10V - 80V) with frequency ranging from (60Hz - 100kHz) and duty cycle ranging from (20% - 80%)
Functionality	Taking the Pulsed Peak Voltage, it adjusts the frequency and duty cycle depending on the independent variable control. During the reference voltage set by function generator chips, it outputs the differences between the input and the reference signal.

IV. Design and Simulation Results

Input Rectifier Simulations

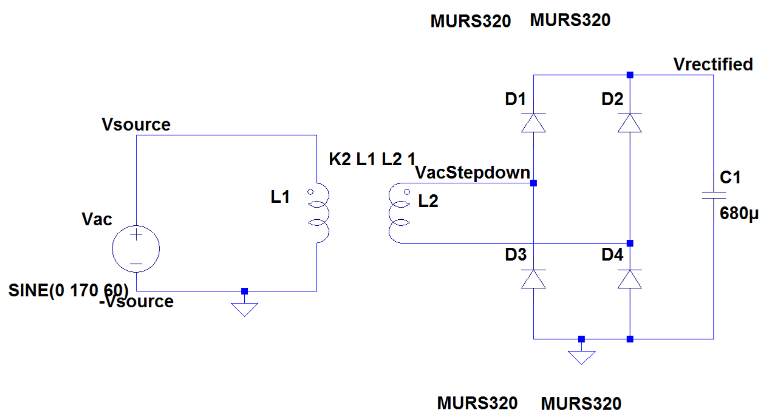

Figure 4-1: Input Rectifier Design Schematics

Figure 4-1 shows the schematics of the input rectifier circuit that performs rectification from an AC input to a DC output voltage. It consists of a 1.88:1 ratio transformer and a four diode connected bridge as shown above. The input voltage (Figure 4-2), stepped down input voltage (Figure 4-3), and output voltage (Figure 4-4) shows the relationship of this schematics. The objective of this circuit is to rectify the 120V_{rms} to 90V DC.

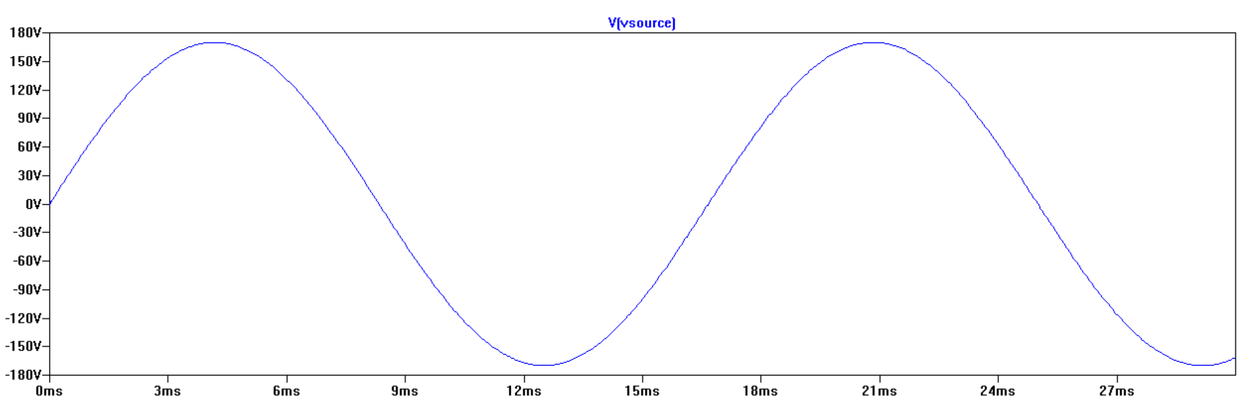

Figure 4-2: Input Rectifier Input Signal

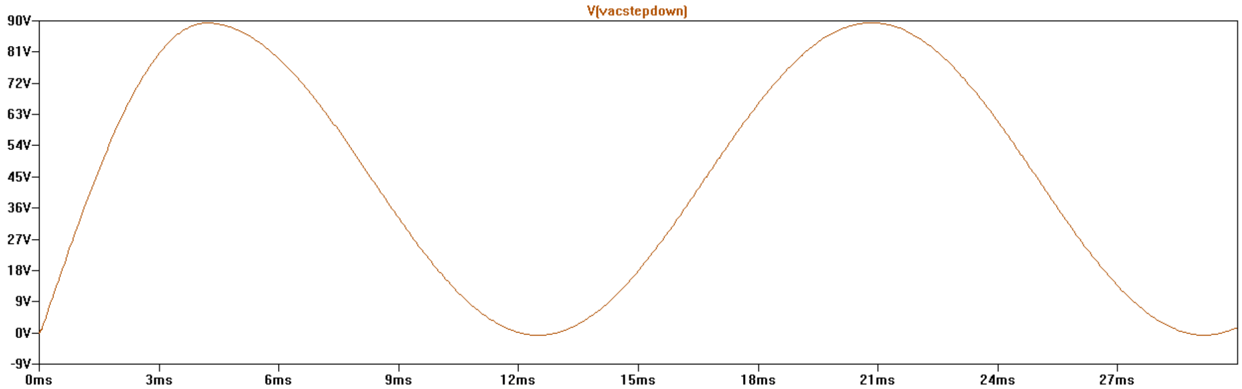

Figure 4-3: Input Rectifier Stepped Down Signal

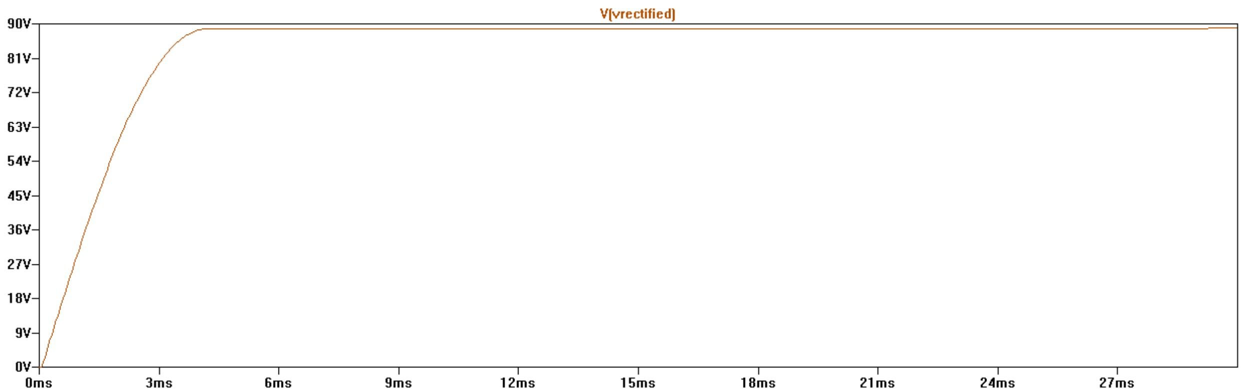

Figure 4-4: Rectified Signal

These are two key differences between the input rectifier in this project and Emmanuel Loza's design. The first key difference is the addition of the transformer between the input signal and the input rectifier. This is due to the integration of one source for all components in the system. Since the absolute max input voltage for the flyback converter is 100V, the input voltage needs to be stepped down. Calculation for the transformer ratio is shown below.

INPUTS: Vac = 120Vrms single phase,

CONSTRAINTS: Vpk <100V

$$Vpk = 120\ Vrms * \sqrt{2} = 170\ Vpk$$

$$Transformer\ Ratio = \frac{Vpk(in)}{Vpk(out)} = \frac{170\ V}{90\ V} = 1.88$$

Since 100V is the absolute max input voltage, 90V was chosen to perform the calculation to have a 10% safety margin. The basic diode rectifier was replaced by an IC Bridge Rectifiers due to time and labor cost. The bridge rectifier has a V_{RRM} of 400V which is more than the required $90V_{PK}$. The forward voltage drop is 1.1V in normal operating conditions. The simulations are still done with MURS320 due to the inability to simulate with the bridge IC. There would be a slight margin of error, but it is negligible.

Flyback Converter Design

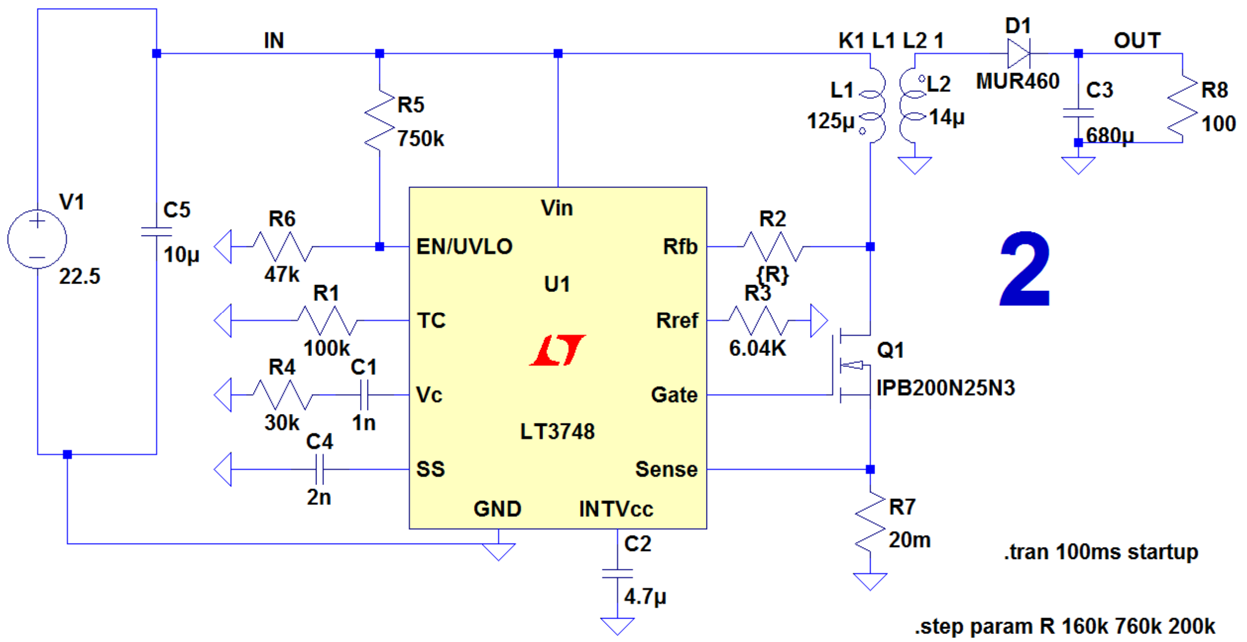

Figure 4-5: Flyback Converter Design Schematics

The flyback converter is used to create the variable DC voltage. Figure 4-5, shows the schematic the flyback converter. This circuit achieves the output voltage by changing the feedback resistor R2.

The LT3748 was selected as the IC for the controller of the flyback converter. The chip is a top of the line controller which does not need a transformer third winding for regulation and a high maximum input voltage of 100V. The elimination of the third winding for regulation reduces the amount of parts, which is essential for a portable design. The high maximum input voltage is needed for the rectified voltage from the AC source.

When selecting the flyback transformer, the following requirements has to be met. The saturation current must be above 2.0A, and the voltage isolation must be above 500V. A high turns ratio flyback transformer allows for low output voltages without causing too much stress on the controller. For these reasons, the Wurth Electronics Midcom 750311771 transformer was selected. The transformer contains a main 6:1 ratio windings, high voltage isolation of 2500V, and a saturation current of 2.5A. This fulfills all the requirements needed for the flyback transformer. In addition, the flyback transformer must meet the inductance requirements set by the flyback controller listed in figure 4-6.

$$L_{PRI} \geq \frac{\left(V_{OUT} + V_{F(DIODE)}\right) \bullet R_{SENSE} \bullet t_{SETTLE(MIN)} \bullet N_{PS}}{V_{SENSE(MIN)}} \qquad L_{PRI} \geq \frac{V_{IN(MAX)} \bullet R_{SENSE} \bullet t_{ON(MIN)}}{V_{SENSE(MIN)}}$$

$$L_{PRI} \leq V_{IN(MIN)} \bullet (V_{OUT} + V_{F(DIODE)}) \bullet N_{PS} / (f_{SW(MIN)} \bullet I_{LIM} \bullet ((V_{OUT} + V_{F(DIODE)}) \bullet N_{PS} + V_{IN(MIN)}))$$

Figure 4-6: Inductance Requirements for Flyback Controller LT3748

In order to fulfill the inductance requirements, the primary winding was changed from a series configuration to a parallel configuration. This reduces the primary winding inductance winding from 500 uH to 125 uH. This can be done since the primary winding is composed of 2 identical windings.

Primary Inductance in series = Ls = 250 uH+ 250 uH = 500 uH

Primary Inductance in parallel = Lp = 1/((1/250uH)+(1/250uH))= 125 uH

In order to fulfill the 80V requirements for the system, the maximum power for the MOSFET and output diode must be rated accordingly. The maximum V_{DS} and maximum output diode reverse voltage equation is given in Figure 4-7 to rate both MOSFET and output diode. Using the Equations in 4-7 the rated V_{DS} is 340V and rated V_R is 114V.

$$V_{DS\ max} = V_{IN\ max} + (V out * N) \qquad V_R = V_{OUT\ max} + \left(\frac{V_{IN\ max}}{N}\right)$$

Figure 4-7: Equations for Maximum V_{DS} and Maximum Output Diode Reverse Voltage

The output capacitors are critical to the ripple of the output voltage. The minimum size for output capacitor equation is given in figure 4-8.

$$C_{min} = \frac{D}{R_{min} * f_{min} * \frac{\Delta V}{V_o}}$$

Figure 4-8: Equation for output capacitor

The input capacitor is needed to source AC in the system. A 10uF capacitor was selected as the input capacitor.

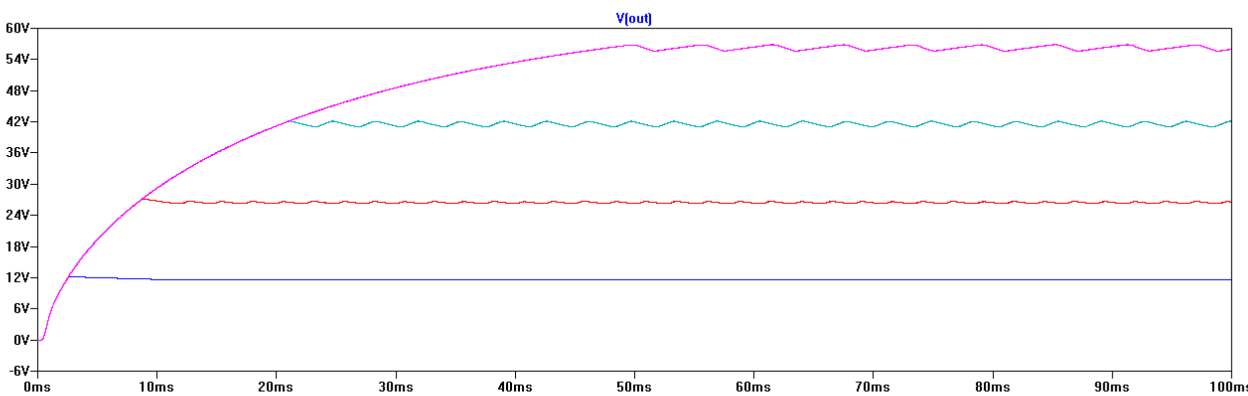

Figure 4-9: Flyback Converter Output Voltage

Figure 4-9 shows the feedback resistor at different resistances and the resulting output voltages.

Two Port Switch Network Design

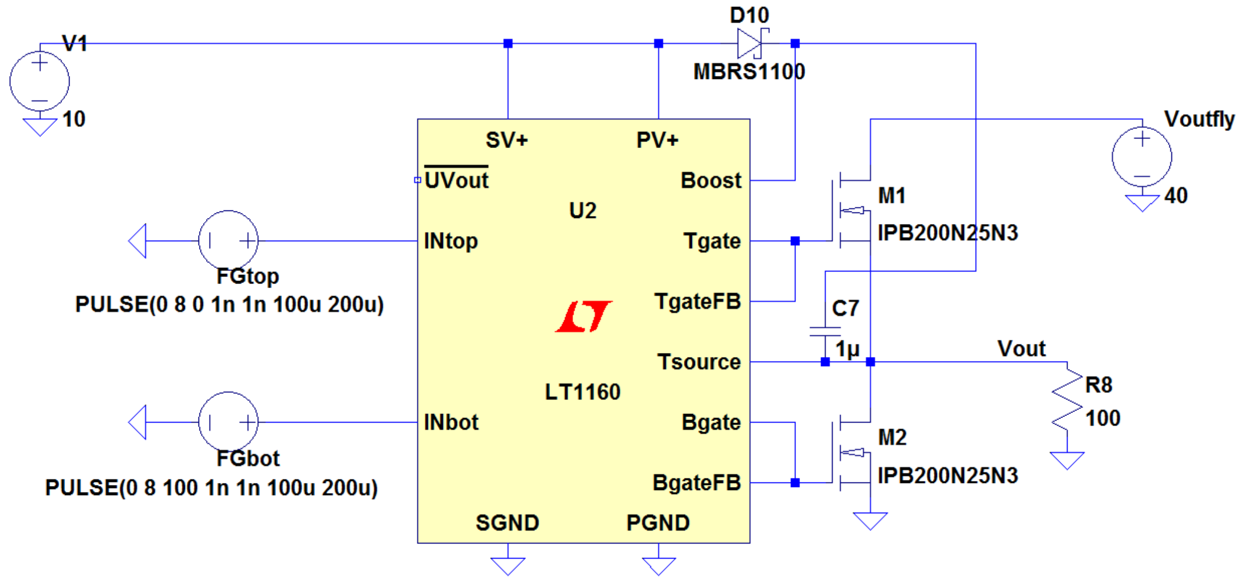

Figure 4-10: Two Port Switch Network Design Schematics

The two port switch network is used to create the output voltage pulses at variable pulse width and frequencies. In Figure 4-10, the schematic is shown of the two switch network. This circuit achieves the output voltage pulses by taking two reference pulses (FGtop and FGbot) to control when to output and not output voltage. The references pulses send a signal to Tgate and Bgate to turn on the MOSFETs which regulates the Vout.

The LT1160 was selected as the IC for two port switch network. The chip is a two port switch network IC which has internal logic to prevent both MOSFET from turning on at the same time and prevents shoot-through currents. Both of these features guarantee that it will only be high or low.

When selecting the diode, D10, it should be rated above the output voltage of 80V. The MBRS1100 was selected for this project. It has a breakdown voltage of 100V, which is higher than the output voltage. When selecting the MOSFET, M1 and M2, it should also be rated above the output voltage of 80V for V_{DS}. To add a significant safety margin, 200V MOSFETs were used.

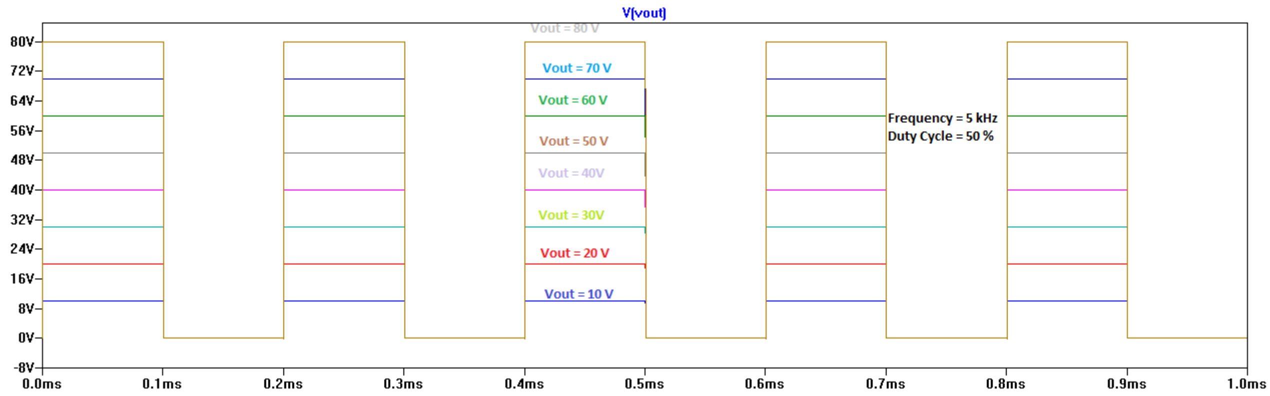

Figure 4-11: Output Pulse @ 5 kHz, 50% Duty Cycle, and 40V

The frequency of the output voltage can be varied by changing the total period at which both pulse signals operate. Figure 4-12, 4-13, and 4-14 shows output pulse at 60Hz, 50 kHz, and 100 kHz. As shown, the two port switch network can produce both ends of the frequency required for the system.

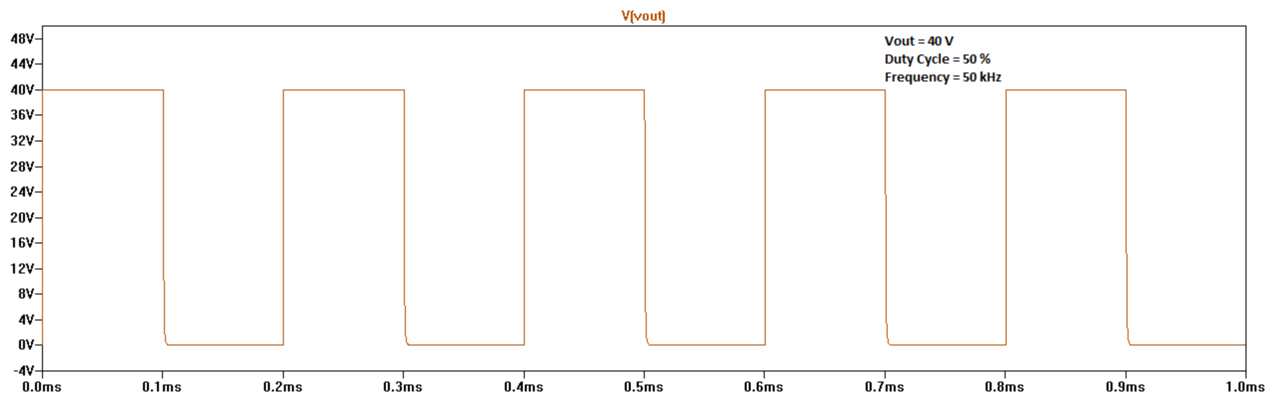

Figure 4-12: Output Pulse @ 5 kHz, 50% Duty Cycle, and 40V

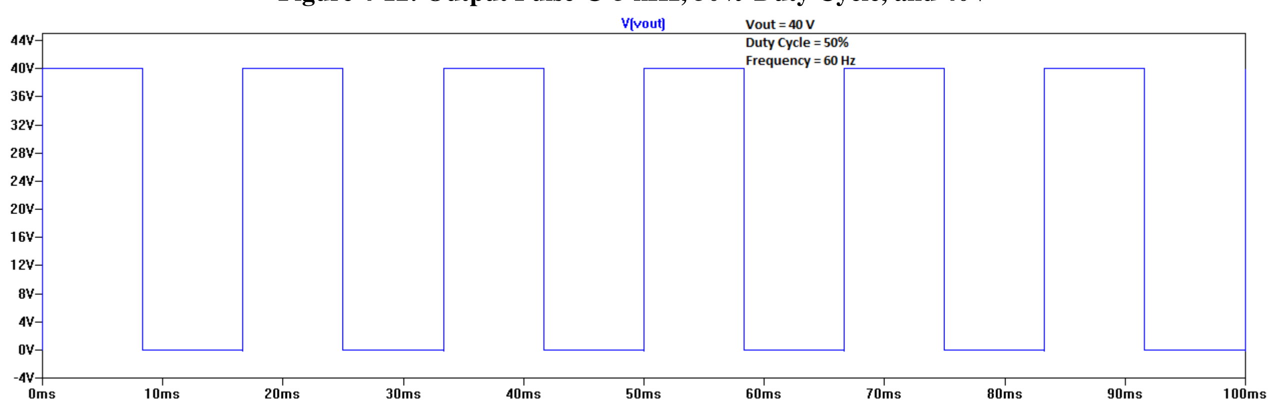

Figure 4-13: Output Pulse @ 60 Hz, 50% Duty Cycle, and 40V

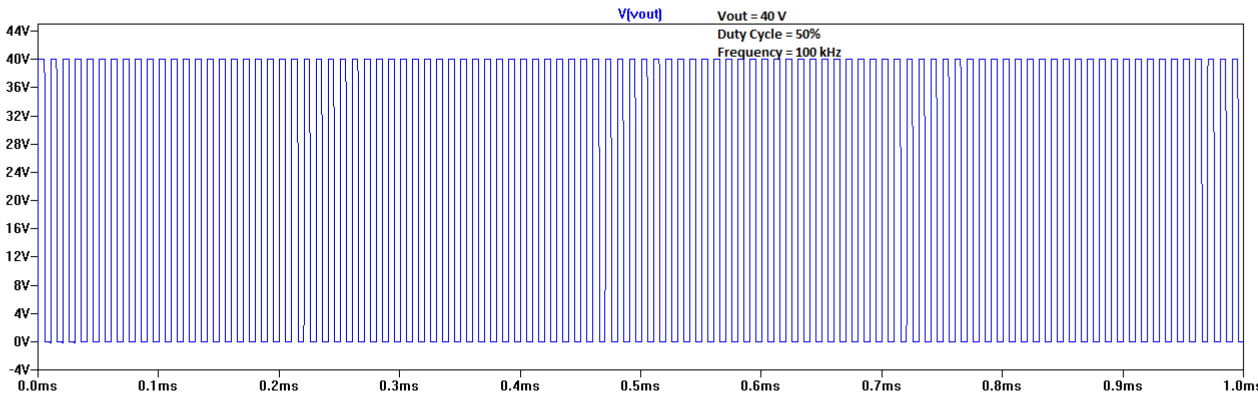

Figure 4-14: Output Pulse @ 100 kHz, 50% Duty Cycle, and 40V

The duty cycle of the output voltage can be varied by changing the period at which both pulse signals is turned on. Figure 4-15 and 4-16 shows output pulse at 20% and 80% duty cycle. As shown, the two port switch network can produce both ends of the duty cycle required for the system.

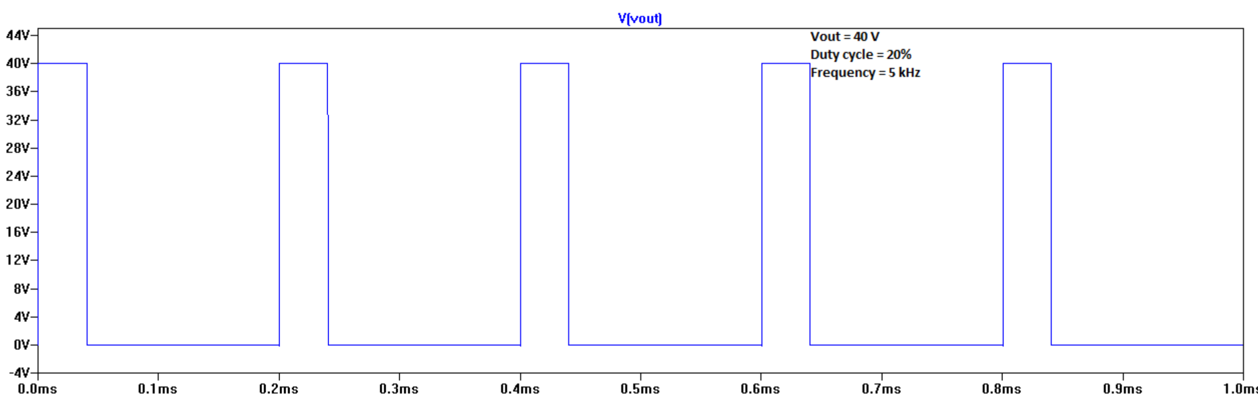

Figure 4-15: Output Pulse @ 5 kHz, 20% Duty Cycle, and 40V

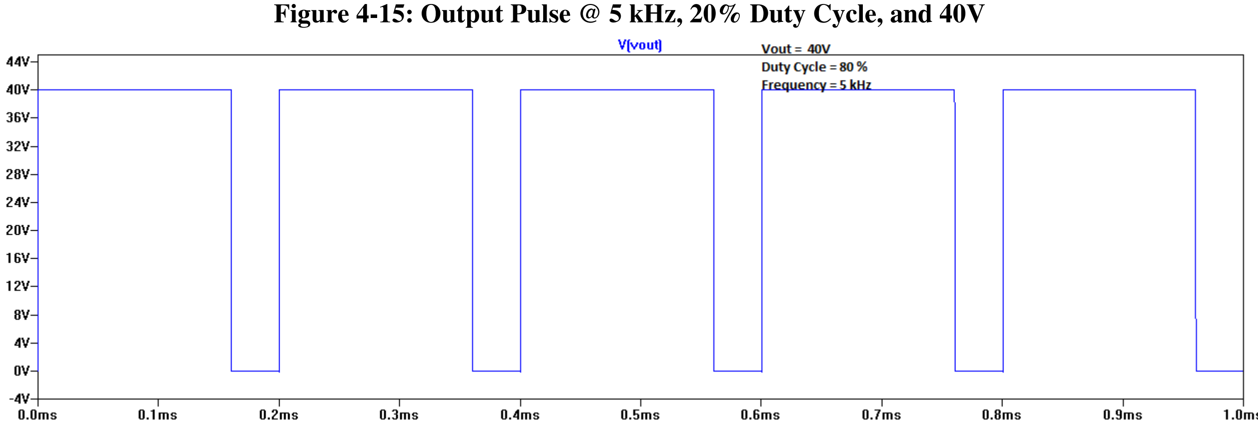

Figure 4-16: Output Pulse @ 5 kHz, 80% Duty Cycle, and 40V

Overall System Implementation and Simulations

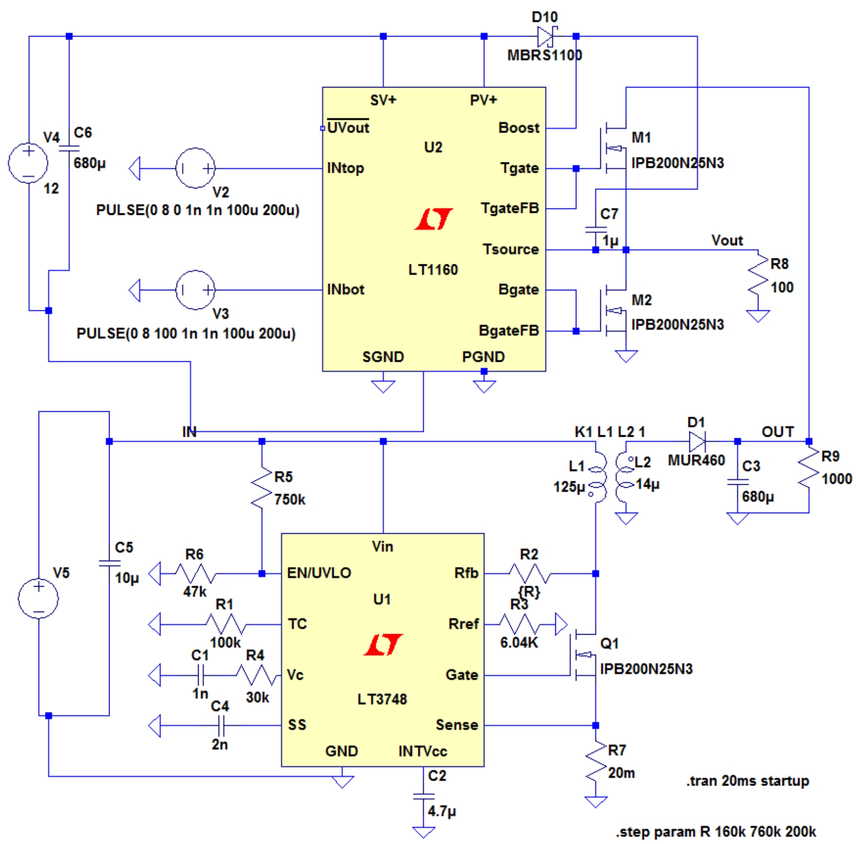

Figure 4-17: Overall System Design Schematics

A DC voltage represents the rectified voltage that will be the power source of the circuit. It was changed due to time constraints but should make very minimal difference in results.

Figure 4-18, 4-19, and 4-20 shows output pulse at 100 kHz at 20%, 50%, and 80% duty cycle. Figure 4-21, 4-22, and 4-23 shows output pulse at 60 Hz at 20%, 50%, and 80% duty cycle. All figure show results in 3 different voltages. As shown, the overall system can produce both ends of the frequency required for the system at varying voltage and duty cycle.

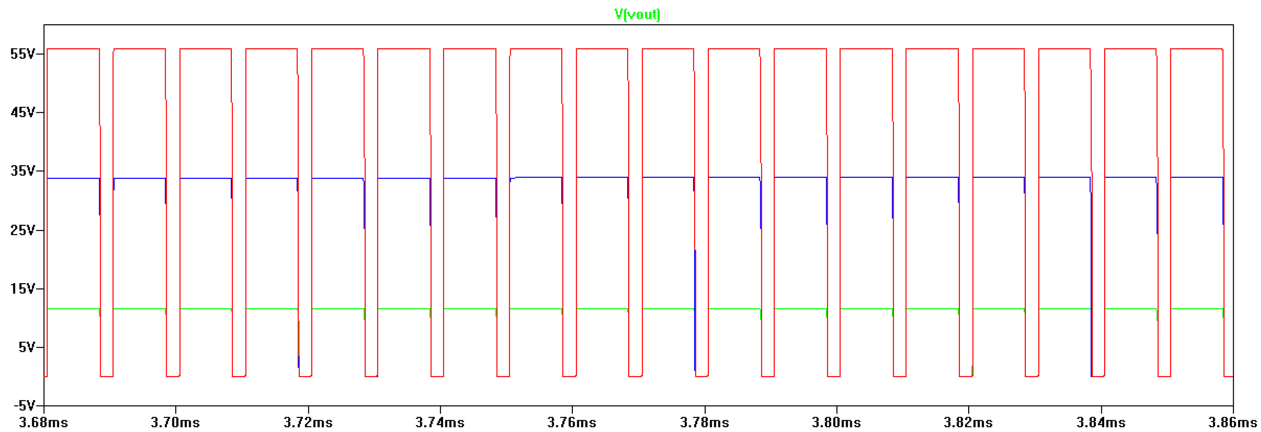

Figure 4-18: Output Pulse @100k Hz, 80% Duty Cycle

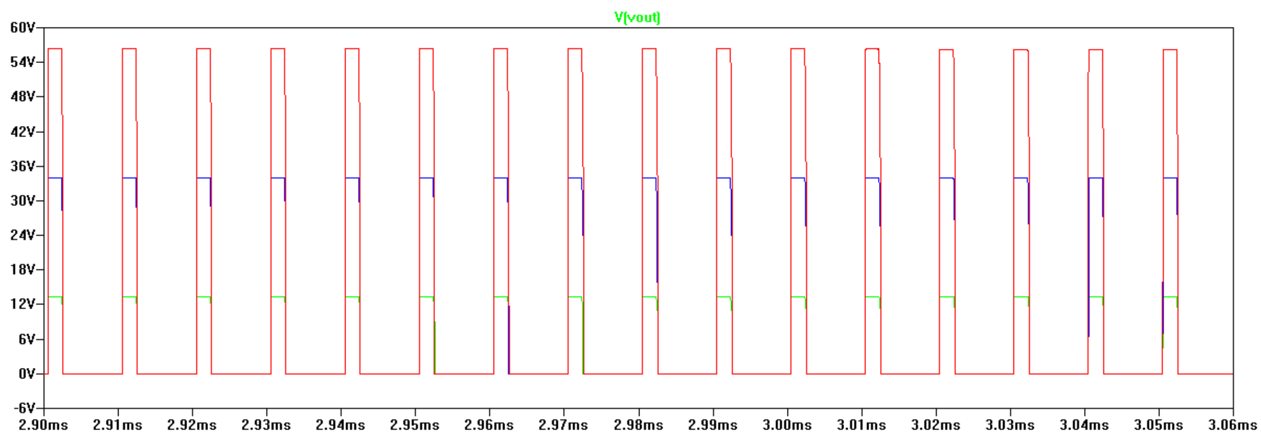

Figure 4-19: Output Pulse @100k Hz, 20% Duty Cycle

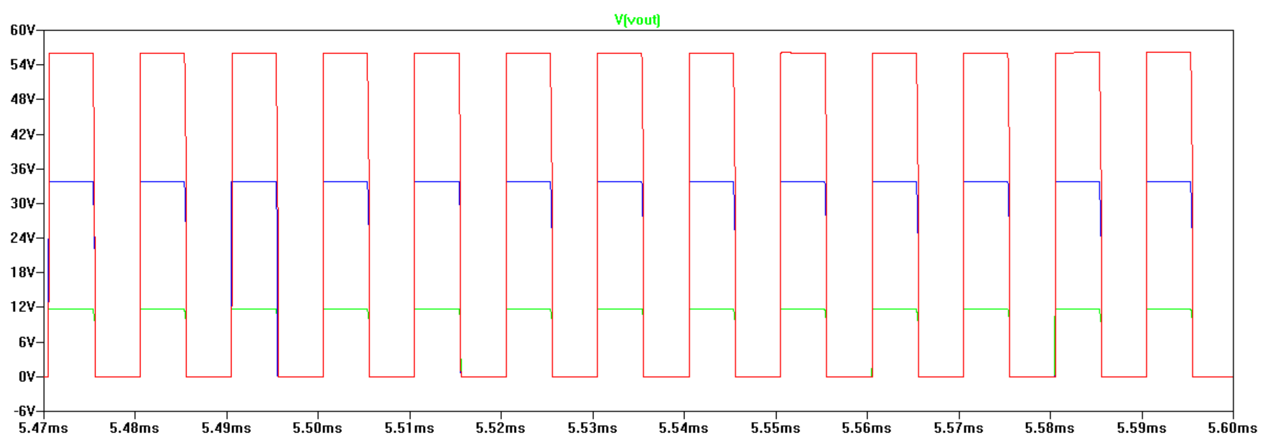

Figure 4-20: Output Pulse @100k Hz, 50% Duty Cycle

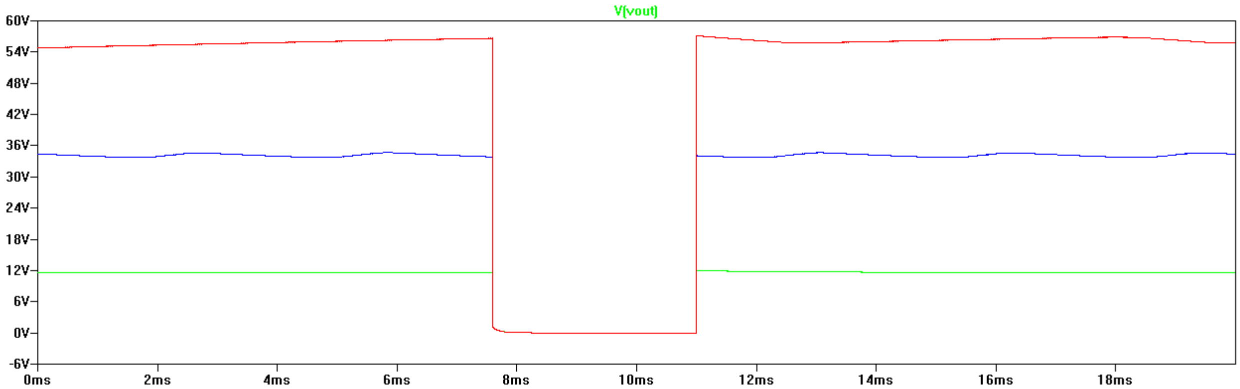

Figure 4-21: Output Pulse @ 60 Hz, 20% Duty Cycle

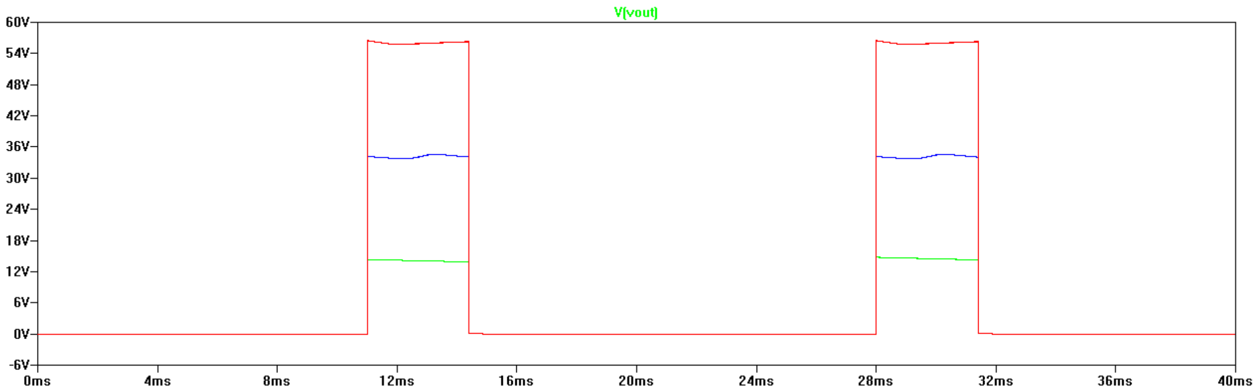

Figure 4-22: Output Pulse @ 60 Hz, 80% Duty Cycle

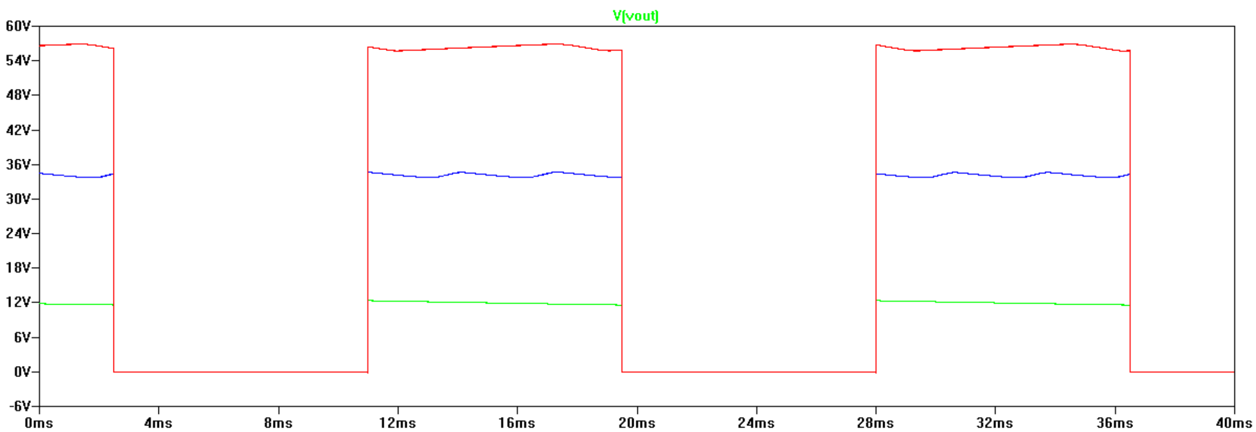

Figure 4-23: Output Pulse @ 60 Hz, 50% Duty Cycle

V. Hardware Test Plan and Results

Input Rectifier Test Plan

The input rectifier was tested with the schematic in Figure 5-1. The input rectifier takes the stepped down AC voltage and rectifies it to a DC voltage for the flyback converter. An AC power outlet will provide the 120V AC for the input rectifier. A multimeter will measure the average voltage on the output.

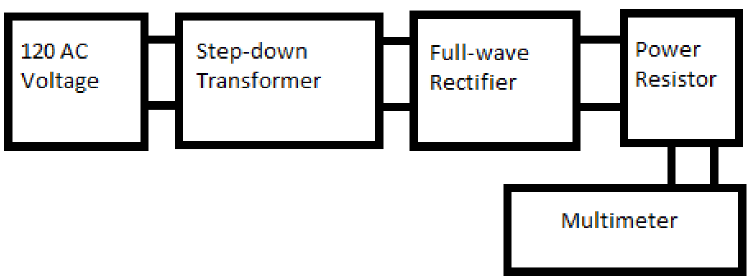

Figure 5-1: Input Rectifier Test Schematics

The following lists the equipment used for testing.

Equipment List

- Clarostat Mfg. Co. Inc. 240-C Power Resistor Decade Box
- BK Precision 5491A 50000 Count Multimeter
- Agilent Technologies U3401A 4 ½ Digit Dual Display Multimeter

Input Rectifier Test Results

Figure 5-2 illustrates the actual lab measurement when the ac voltage was set at 64.29 VAC which yielded an average output voltage of 90.42. Table 5-1 shows results as AC input voltage is varied and how it affects the amount of average output voltage produced by the rectifier.

The input rectifier results are similar to what the nominal DC voltage will be. There is about between a 0.5%-3.5% difference between the actual DC voltage and calculated DC voltage. This can be contributed from the forward voltage drop on each of the diodes used in the rectifier circuit.

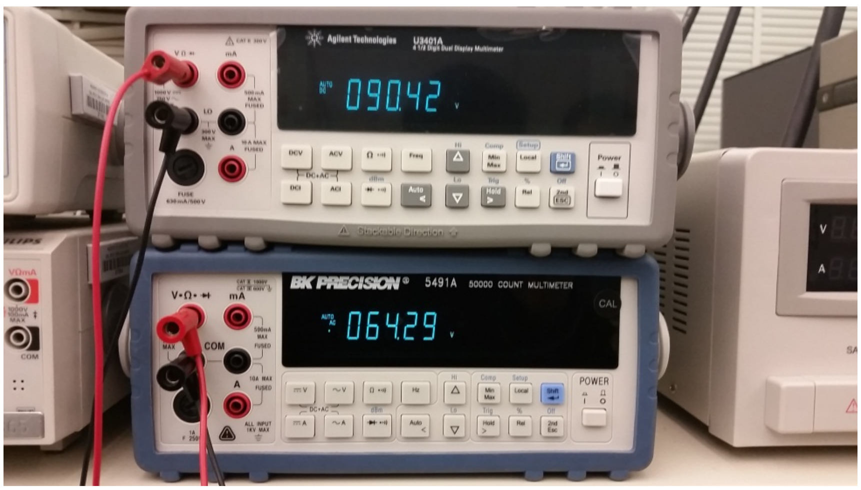

Figure 5-2: Input Rectifier's 90V Output Voltage

Actual Stepped Down AC Voltage	Actual DC Voltage	Calculated DC Voltage	% Difference
15.123 V	20.63 V	21.38 V	3.5 %
29.457 V	40.94 V	41.65 V	1.7 %
43.32 V	60.66 V	61.26 V	0.9 %
57.09 V	80.28 V	80.73 V	0.5 %
64.29 V	90.42 V	90.91 V	0.5 %

Table 5-1: Rectifier Output Voltage Test Results

Flyback Converter Test Plan

Figure 5-3 was built to test the flyback converter circuit to verify that it can achieve the desired DC output voltage for the next stage (two-switch network). The DC power supply is hooked up to the input Vin to power the LT3748 in order to operate the flyback converter. The multimeter measures the DC output voltage from the power resistor. To start testing the circuit, power resistor of 100 ohms was used. Then the DC power supply was set to 22.5V, which was just enough voltage to turn on the chip. The output voltage was then read from the multimeter and recorded in Table 5-2. Once completed, the DC power supply was turned off to power down the circuit.

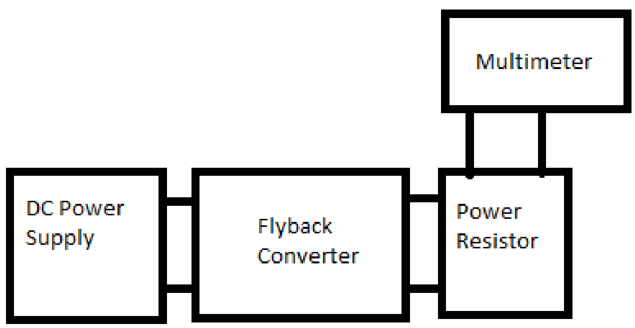

Figure 5-3: Flyback Converter Test Schematics

The following lists the equipment used for testing.

<u>Equipment List</u>

- GwInstek GPM-8212 Multimeter
- Maja 9313-PS DC Regulated Power Supply
- Clarostat Mfg. Co. Inc. 240-C Power Resistor Decade Box
- Agilent Technologies U3401A 4 ½ Digit Dual Display Multimeter

Flyback Converter Test Results

Figure 5-4 shows the flyback circuit setup for the lab test measurements. As shown, the Flyback circuit was built on a protoboard. However, since the controller used is a surface mount component, a surface mount to thru-hole adapter was being used. Figures 5-5 to 5-7 as well as Table 5-2 show how average output voltage of the flyback varies with different values of the feedback resistor.

The results from the flyback converter testing agree with the simulations results. However, since the maximum voltage the flyback transformer can handle is 66.66V, therefore additional testing with highest feedback resistor was not tested due to circuit safety concerns. Additionally, a lower resistance was not tested as the output voltage seems to be going very close to its minimum voltage that it can produce which correlates with the simulation results.

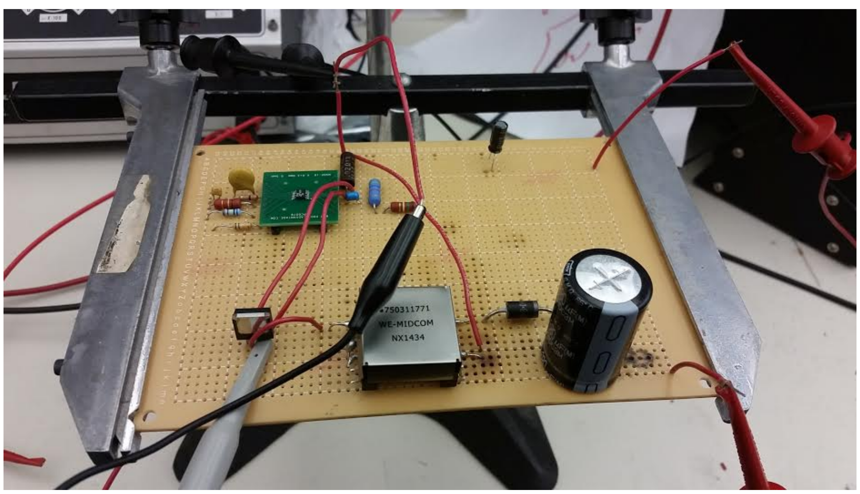

Figure 5-4: Flyback Converter Circuit

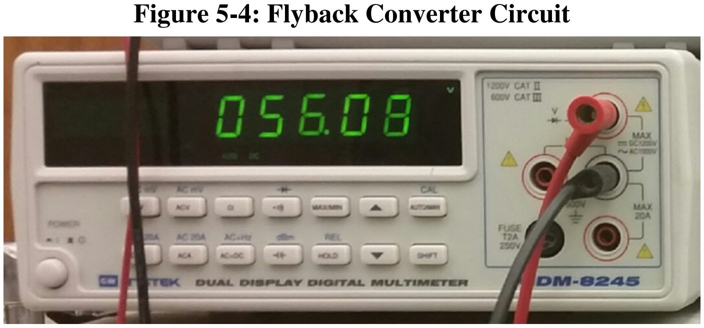

Figure 5-5: Output Voltage @ 760k ohm feedback resistor

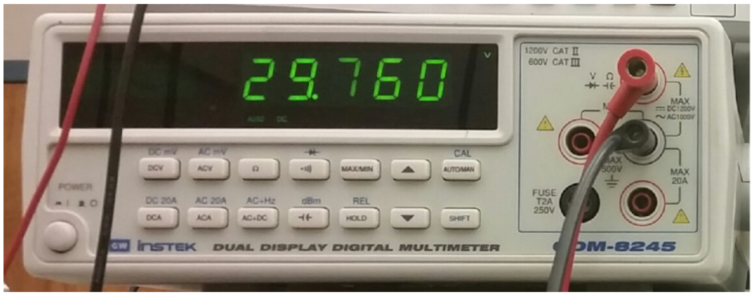

Figure 5-6: Output Voltage @ 330k ohm feedback resistor

Figure 5-7: Output Voltage @ 110k ohm feedback resistor

Feedback Resistance(ohms)	Output Voltage(V)
110k	11.29 V
330k	29.76 V
490k	36.76 V
680k	51.24 V
760k	56.08 V

Table 5-2: Flyback Converter Output Voltage Test Results

Two Port Switch Network Test Plan

The two port switch network was tested with the schematic in Figure 5-8. The two port switch network uses an FG Chip to control the top pulse and an inverter which controls the bottom pulse. This will ensure that there will never be any overlapping for the output pulse. A DC power supply will provide the 12V input for the two port switch network to output. An oscilloscope was used to probe the FG chip output, the inverter output and the two port switch network output to ensure that the signals were correct.

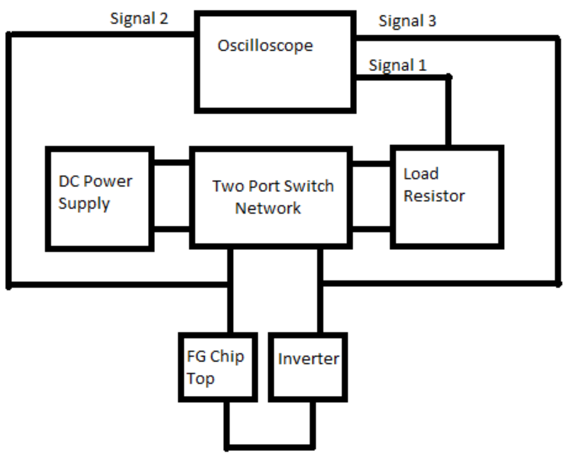

Figure 5-8: Two Port Switch Network Test Schematics

The following lists the equipment used for testing.

<u>Equipment List</u>

- GwInstek GDS-2204 Digital Storage Oscilloscope
- Maja 9313-PS DC Regulated Power Supply
- Extech Instruments 380400 Resistance Decade Box

Two Port Switch Network Test Results

The test result shows that the two port switch network can reach a maximum of 66.66 kHz at 50% duty cycle as shown in Figure 5-9. Figures 5-10 and 5-11 show the maximum frequency at both 20% and 80% duty cycle. Finally, in Figures 5-12 and 5-13 show that the network can reach the 60 Hz at both 20% and 80% duty cycle. Table 5-3 further illustrates the timing resistor values used to achieve both the maximum and minimum frequency and duty cycles.

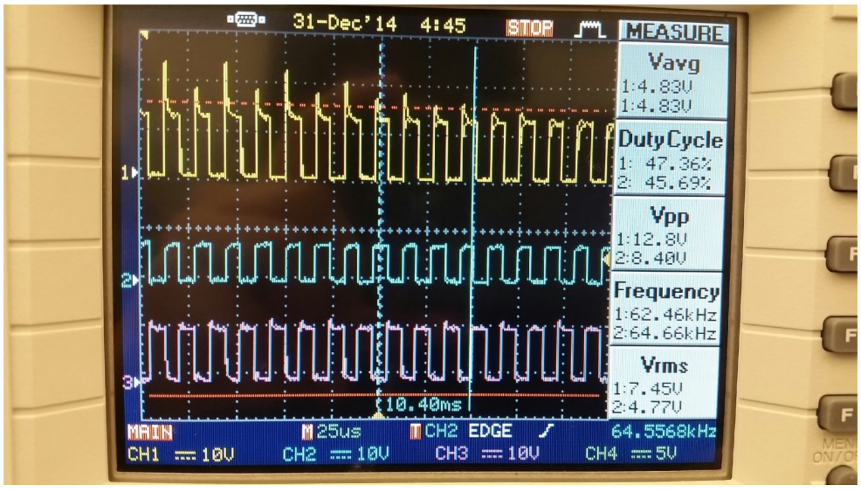

Figure 5-9: 66.66 kHz @ 50% Duty Cycle

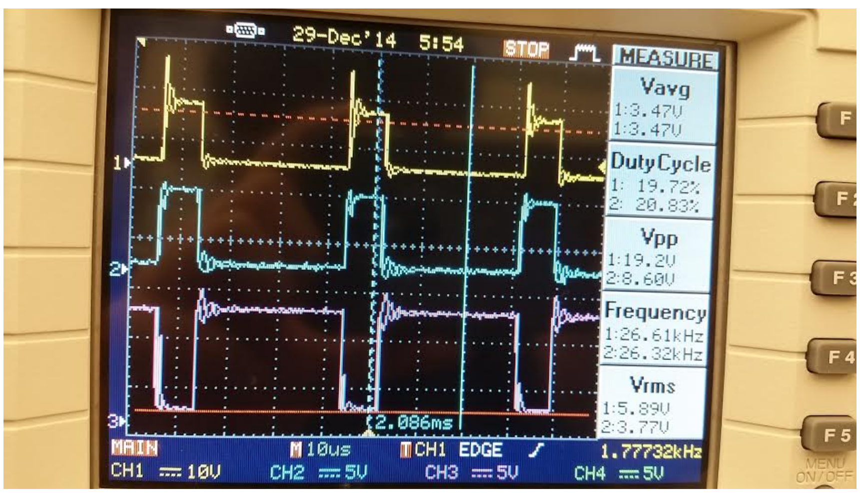

Figure 5-10: 26.66 kHz @ 20% Duty Cycle

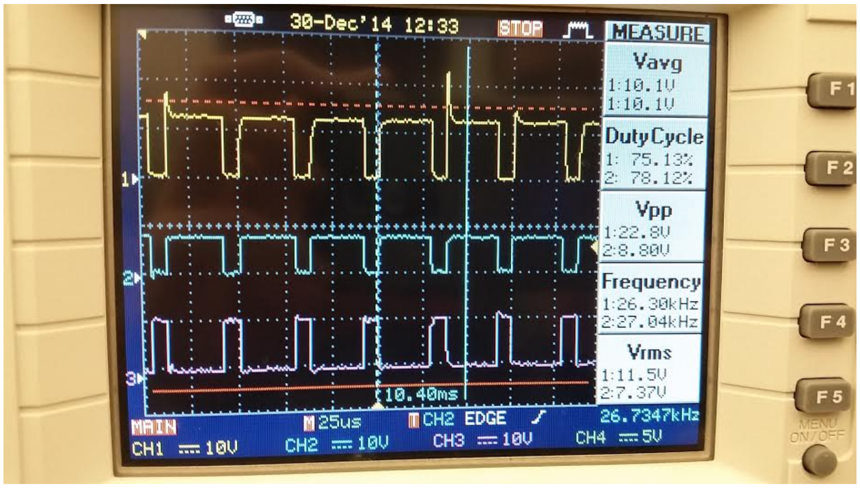

Figure 5-11: 26.66 kHz @ 80% Duty Cycle

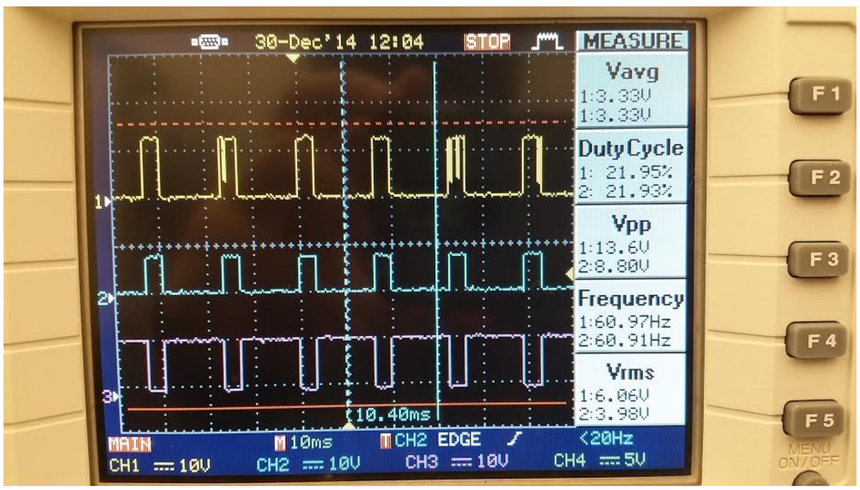

Figure 5-12: 60 Hz @ 20% Duty Cycle

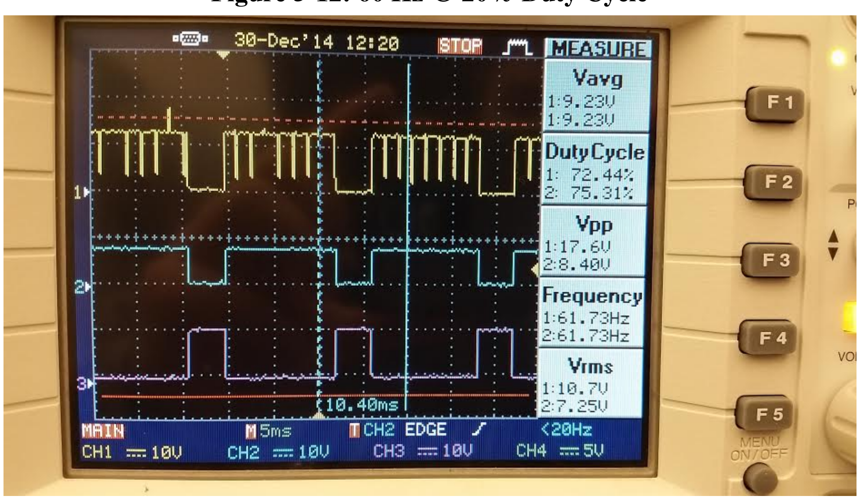

Figure 5-13: 60 Hz @ 80% Duty Cycle

R1 and R2 Values		Duty Cycles		
		20%	50%	80%
	60	R2 2000000 R1 500000		R2 500000 R1 2000000
Frequency (Hz)	26.66k	R2 4000 R1 1000		R2 1000 R1 4000
	66.66k		R2 1000 R1 1000	

Table 5-3 : Timing Resistor Values of Function Generator

Overall System Test Plan

The overall system was tested using the schematic in Figure 5-14. Note that the rectifier stage was not included to ensure that the input voltage of the Flyback converter is stable and does not depend on the loading of the two port network. In addition, since the control parameters are incorporated into just the Flyback and the two-switch network, it is therefore not necessary to demonstrate the overall system functionalities with the input rectifier. The flyback converter output voltage will then feed into the two port network to set the amplitude of the pulse. An oscilloscope will measure the output of the two port network to confirm the pulses. A multimeter is placed at the output of the flyback converter to confirm the output voltage.

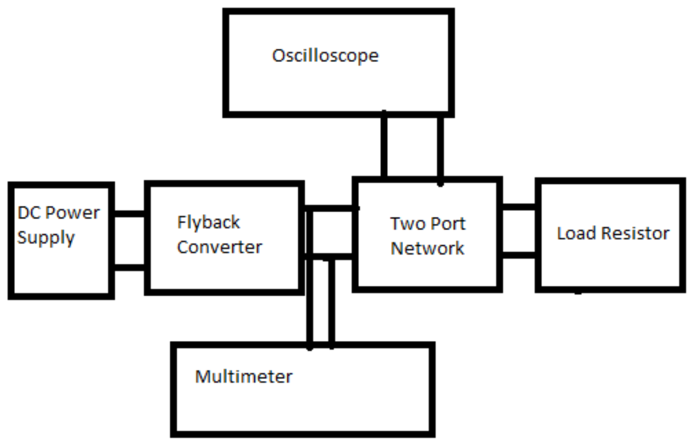

Figure 5-14: Overall System Test Plan Schematics

The following lists the equipment used for testing.

<u>Equipment List</u>

- Clarostat Mfg. Co. Inc. 240-C Power Resistor Decade Box
- Agilent Technologies U3401A 4 ½ Digit Dual Display Multimeter
- GwInstek GDS-2204 Digital Storage Oscilloscope

Overall System Test Results

Figures 5-16 and 5-17 show the output pulse of 8.8V with an output voltage of 8.5V from the Flyback converter. These numbers are different from the simulation output voltage is 11.6V. The difference can be contributed from the lack of regulation in the Flyback converter which is further caused by noise in the gate signal of the MOSFET used in the Flyback.

During prior overall system testing, the two port switch network was tested using a DC Power Supply acting as the flyback converter. Test results showed that the pulse would become unstable at 25V. This caused to abandon any further testing with the flyback above 25V due to the concern of circuit damage above that point. Figures 5-18, 5-19, 5-20, and 5-21 show the oscilloscope displays of the pulses produced by the two port network, but with a DC Power Supply acting as the output of the flyback.

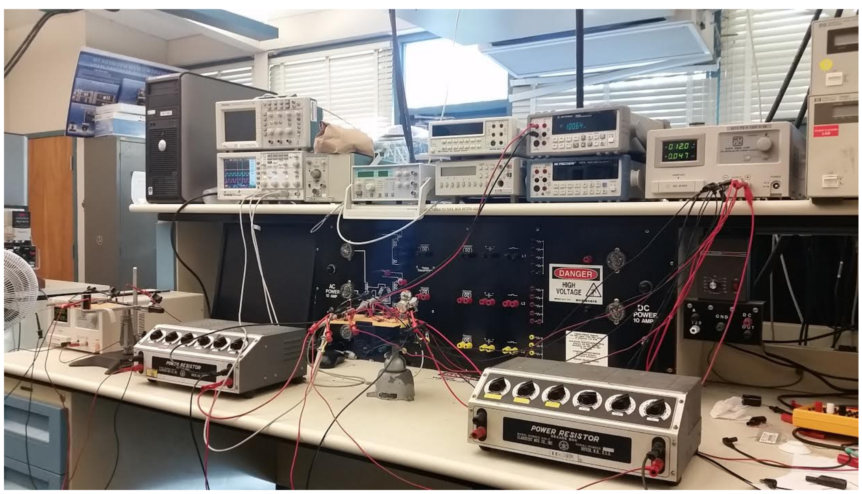

Figure 5-15: Overall System Test Setup

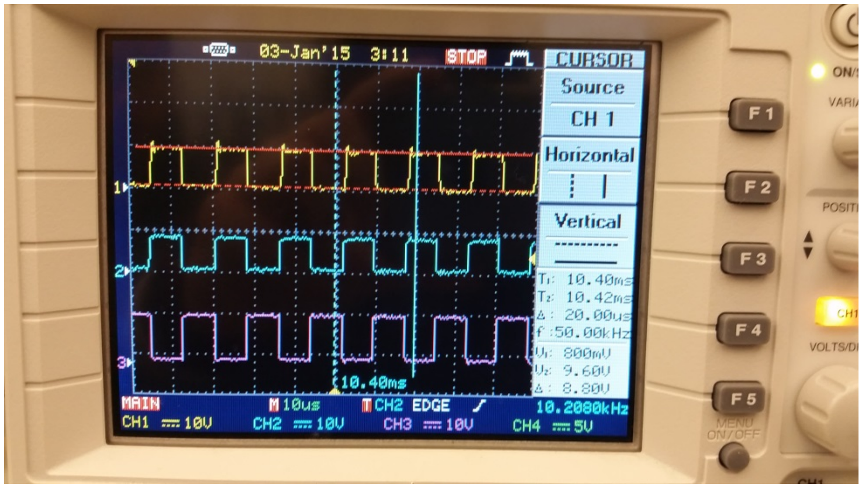

Figure 5-16: Output Pulse @ 110k ohm feedback resistance

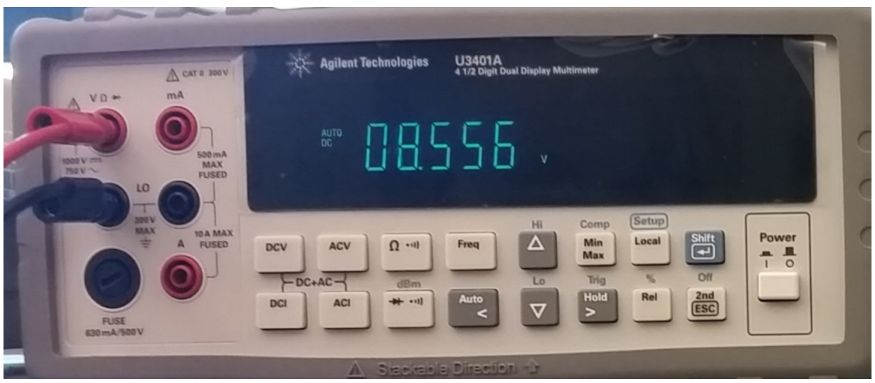

Figure 5-17: Output Voltage @ 110k ohm feedback resistance

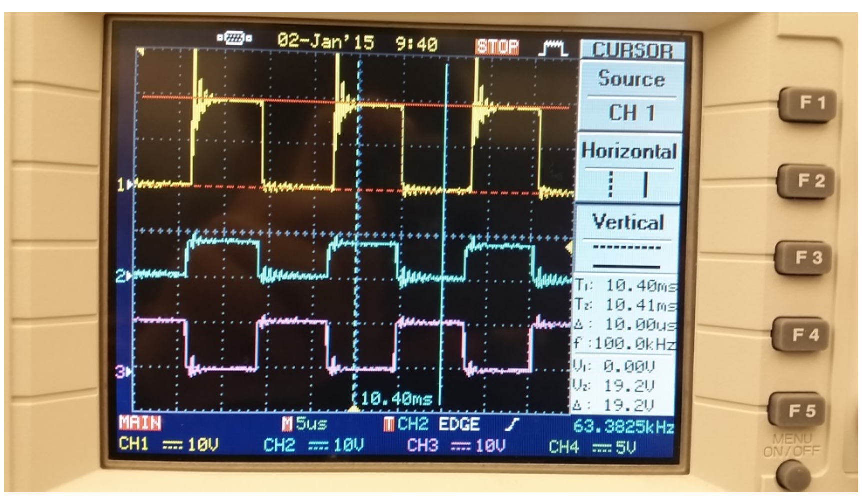

Figure 5-18: Output Pulse @ 19V as Flyback Voltage

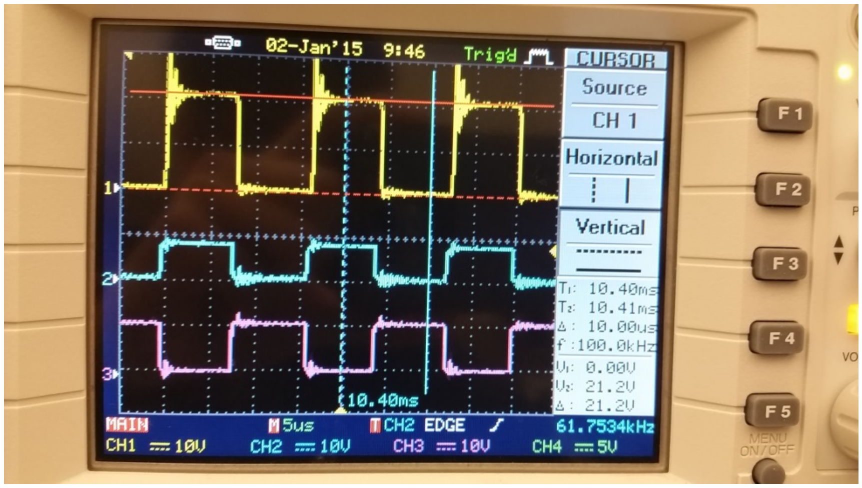

Figure 5-19: Output Pulse @ 21V as Flyback Voltage

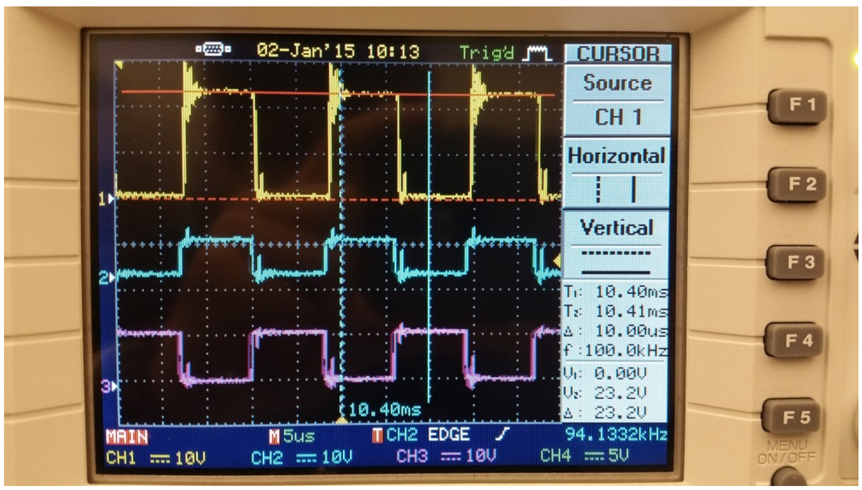

Figure 5-20: Output Pulse @ 23V as Flyback Voltage

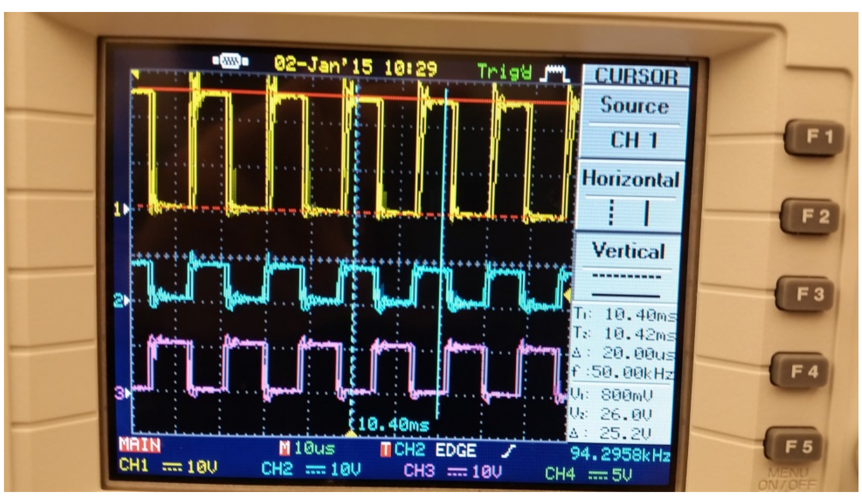

Figure 5-21: Output Pulse @ 25V as Flyback Voltage

VI. Conclusion

This project aims to demonstrate the capability of the portable cascaded high voltage converter with variable control. The project showed pulse width generation with variable voltage, frequency, and duty cycle can be done with individual circuits. However, when all three circuits were combined, the desired range of outputs could not be met.

When tested by itself, the input rectifier works as intended. The AC input is rectified into a DC output which is recorded in Table 5-1. The flyback converter also when tested by itself operates like the simulation results. In particular, the output voltage recorded from the flyback converter using a multimeter is approximately the same as those obtained from the simulation results. However, there are some fluctuation and discrepancy in the output voltage, so an improvement to fix the voltage ripple can be done using an RC snubber to dampen the ringing. In addition, the wire that connects the output pin of the controller to the gate of the MOSFET should be made as short as possible. One challenge of the flyback converter is trying to find a flyback transformer that meets the requirements of high voltage while staying within the requirements for the primary inductance set by the flyback controller.

The two port switch network by itself correctly outputs a pulsed signal with varied frequency and duty cycle by altering the two timing resistors on the function generator chip at pins 7 and 8. However, when combined with the other two circuits it is difficult to get the desired range of outputs since the desired output pushes the resistor values to the limit. A limitation in two port switch network was the use of function generator chips. The function generator chips allow for the elimination of the function generator, which made the circuit more portable. However, the two function generator chips outputted noisy signals at certain frequencies. The use of potentiometers was implemented to make the circuit more portable, however after testing the circuit, the potentiometers were found to be inaccurate and difficult to precisely adjust the resistance resulting in a smaller output range. Adjusting four potentiometers without knowing the resistance values sometime causes the signals to overlap and become distorted. Dedicated resistors are needed to vary the entire range of frequency and duty cycle. To get a better signal, the CD4007UB CMOS chip is used as an inverter to invert the signal outputted from the function generator chip. This allows the function generator chip to always give a pulse output independent from the resistance values and the signals will never overlap. An additional resistance of 1kohms is added in series with each of the potentiometer to become the minimal resistance so the circuit never goes to 0 ohms and cause the circuit to fail. After testing the limits of the two port switch network, the results show that the output becomes distorted at 25+V to the drain of the top MOSFET. At this 25+V, the current rises exponentially, thus testing the circuit ended to avoid damage to the circuit. A problem found after looking at the original proposal for the two port switch network and comparing it to the data sheet, it was discovered that the LT1160 chip can only take up to 60V as opposed to the initial requirement of 80V.

The overall system results confirmed that both the flyback circuit and two port switch network can support pulses with varying frequency, pulse-width, and amplitude. Since the flyback converter outputs about 10-60V and the two port switch network can theoretically take up to 60V and 25V during testing, the testing was done using ~12V outputted from the flyback converter. Our initial design had flaws such as a poorly sized transformer and components. This delayed the building and testing phases. An improvement would be to plan out the schedule more carefully to avoid any problems in future projects. Another improvement for this circuit is to use a dedicated PCB instead of a protoboard since this circuit is very sensitive to noise. The noise may cause the signals to be mixed up and result in incorrect outputs. Another improvement is to utilize a microcontroller for the two port network to give the user more flexibility to control the input signals. The last improvement is to find better function generator chips that have a wider range of outputs and less sensitive to noise. Overall, the project was a great learning and challenging experience.

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Appendix A
Senior Project Analysis

Project Title: High Voltage Pulse-Width Generator for the Algae Biofuel Project

Student's Name: Philip Yu & Stephen Leung

Student's Signature:

Advisor's Name: Taufik

Advisor's Initials:

Date: 3-01-14

1. Summary of Functional Requirements
The high voltage pulse width generator for the Algae Biofuel Project uses a cascaded high voltage converter with variable control creating a pulsed electric field to lyse algae cells for biofuel. The output ranges from 10V-80V for the peak voltage, 60Hz-100 kHz for the frequency, 17ms to 10us for the pulse width, and 20%-80% duty cycle.

2. Primary Constraints
The size of the pulse width generator proves as the main constraint in this project. The project requires the size pulse width generator to be portable but ensure enough space to contain the circuit and other electrical components. This poses another problem; the amount of heat allowed inside the enclosure. The inside of the pulse width generator needs a way to dissipate the heat and allow for airflow so it does not overheat.

Refer to Table A-1 for requirements and specification and Table A-2 for deliverables.

3. Economic
The human capital includes researchers that use the high voltage pulse width generator to lyse algae cells and harvest the biofuel inside.

The financial capital includes test equipment such as power supply, meters, and oscilloscope, as well as simulation software. The cost of components also factor in the financial capital.

The manufactured capital includes the generator constructed manually, so workers benefit from labor costs. Manufacturers benefit from the purchasing of components and shipping costs.

The natural capital includes the metals and minerals to make the components used in this project such as silicon, copper, aluminum.

This project sponsored by Boeing should not exceed $5,000. This includes the parts required to build the generator and labor costs. This project should last until the availability of a better pulse width generator with a higher variable range. The maintenance of the generator consists of replacing broken and non-functional parts. After the project ends, researchers use the pulse width generator to experiment with the algae cells. Most of the cost comes from the purchasing components in the building phase.

Table A-1: Parts Cost Estimate

Parts	Cost	Justification
PCB	$100	The PCB makes the pulse generator look clean and safe
Resistor x8 Capacitor x7 Inductor x1 Diode x6 Mosfet x3 Transformer x 1 Flyback Controller x1 Mosfet driver x1	$5 $5 $1 $5 $3 $15 $6 $5	The components needed to create the circuit needed for the pulse generator to create the following circuits: Full wave rectifier Flyback Converter 2 switch network
Casing	$100	The case makes the system safe and portable
External (LEDs, knobs, buttons), 3-prong plug	$40	These components turn the pulse generator on/off and display values
Temperature Module	$50	The temperature module keeps the pulse width generator cool so overheating does not occur
Total Cost	$380	

Table A-2: Labor Cost

Labor Breakdown	**Cost**
Validate Original Thesis	**20**
• Review Thesis	20
Research/Design Improvement Phase 1	**35**
• Review on suggested improvement from thesis	5
• Brainstorm Improvements	4
• Conduct simulations on proposed improvements	17
• Integrate simulations from proposed design	7
Research/Design Improvement Phase 2	**50**
• Revision on proposed design	15
• Integrate simulations for final design	11
• Finalize final design	9

• Send out design for fabrication for PCB	7
• Purchase parts for hardware	10
Build/Implement Hardware	**39**
• Build Pulse Generator	14
• Hardware testing	19
• Hardware final Product	7
Total Cost ($30/hr)	**$4320**

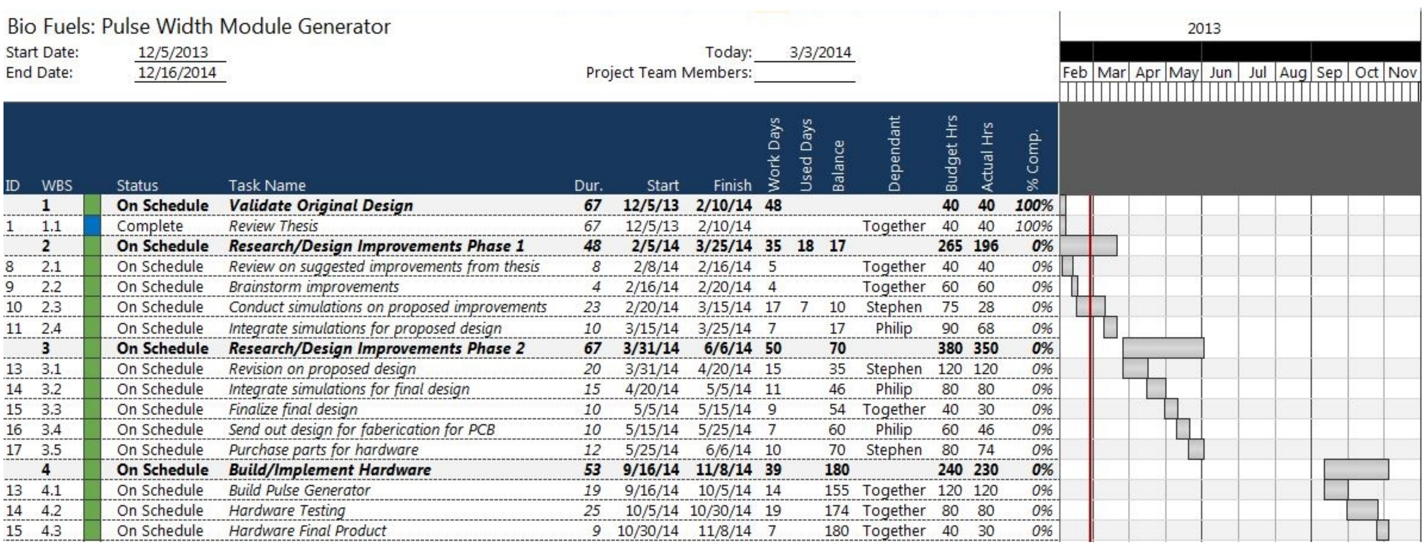
Table A-3: Labor Cost Estimates

Optimistic Hours	200
Pessimistic Hours	250
Realistic Hours	225

Break Even Analysis Equation

$t_e = (t_a + 4t_m + t_b)/6 = 255$ Hours

@$30/hr wage, Total cost: $6,750



Bio Fuels: Pulse Width Module Generator

Start Date: 12/5/2013
End Date: 12/16/2014
Today: 3/3/2014
Project Team Members:

ID	WBS	Status	Task Name	Dur.	Start	Finish	Work Days	Used Days	Balance	Dependant	Budget Hrs	Actual Hrs	% Comp.
	1	**On Schedule**	***Validate Original Design***	**67**	**12/5/13**	**2/10/14**	**48**				**40**	**40**	**100%**
1	1.1	Complete	*Review Thesis*	67	12/5/13	2/10/14				Together	40	40	100%
	2	**On Schedule**	***Research/Design Improvements Phase 1***	**48**	**2/5/14**	**3/25/14**	**35**	**18**	**17**		**265**	**196**	**0%**
8	2.1	On Schedule	*Review on suggested improvements from thesis*	8	2/8/14	2/16/14	5			Together	40	40	0%
9	2.2	On Schedule	*Brainstorm improvements*	4	2/16/14	2/20/14	4			Together	60	60	0%
10	2.3	On Schedule	*Conduct simulations on proposed improvements*	23	2/20/14	3/15/14	17	7	10	Stephen	75	28	0%
11	2.4	On Schedule	*Integrate simulations for proposed design*	10	3/15/14	3/25/14	7		17	Philip	90	68	0%
	3	**On Schedule**	***Research/Design Improvements Phase 2***	**67**	**3/31/14**	**6/6/14**	**50**		**70**		**380**	**350**	**0%**
13	3.1	On Schedule	*Revision on proposed design*	20	3/31/14	4/20/14	15		35	Stephen	120	120	0%
14	3.2	On Schedule	*Integrate simulations for final design*	15	4/20/14	5/5/14	11		46	Philip	80	80	0%
15	3.3	On Schedule	*Finalize final design*	10	5/5/14	5/15/14	9		54	Together	40	30	0%
16	3.4	On Schedule	*Send out design for faberication for PCB*	10	5/15/14	5/25/14	7		60	Philip	60	46	0%
17	3.5	On Schedule	*Purchase parts for hardware*	12	5/25/14	6/6/14	10		70	Stephen	80	74	0%
	4	**On Schedule**	***Build/Implement Hardware***	**53**	**9/16/14**	**11/8/14**	**39**		**180**		**240**	**230**	**0%**
13	4.1	On Schedule	*Build Pulse Generator*	19	9/16/14	10/5/14	14		155	Together	120	120	0%
14	4.2	On Schedule	*Hardware Testing*	25	10/5/14	10/30/14	19		174	Together	80	80	0%
15	4.3	On Schedule	*Hardware Final Product*	9	10/30/14	11/8/14	7		180	Together	40	30	0%

Figure A-1: Gantt Chart

4. If manufactured on a commercial basis

The estimated number of devices sold per year approximately in the hundreds since researchers and universities may want to use it for researching purposes. The cost of manufacturing the generator approximately ~$400 and sold for $600 each. The profit yields $200 per unit and $100,000 per year if 500 sells. The cost for users to operate the device should be minuscule since the generator designed for simplistic use.

5. Environmental

The majority of the environmental impact associated with this project occurs when natural resources are used to make the specific parts such as integrated circuits, PCB board, and the aluminum enclosure used. During the lifetime of the pulse width generator, electricity powers the device resulting in some degree of pollution. Our finished project does not directly harm the ecosystem but rather indirectly benefit the ecosystem and natural resources. The pulse width generator lyses algae cells to harvest the oil lipids inside and use as biofuel. Thus, by using biofuel for vehicles rather than fossil fuels, fossil fuel usage reduces and the air becomes less polluted. Overall, this project intends to secure a way to help the environment by consuming less fossil and converting to biofuel.

6. Manufacturability

The main challenge of this senior project comprise of finding a way to fabricate an enclosure to house the circuit and other components. as of now, we have no means of fabricating one specifically for our project. We plan to use the machine shop at California Polytechnic State University San Luis Obispo to fabricate an enclosure unique to this project ourselves.

7. Sustainability

The goal of this project is simplicity; since, non-engineers plan to operate the pulse width generator to lyse algae cells. The proposed project uses 120V source [5] from the wall so the sustainability of resources does not factor in this project. A possible upgrade for this project can include a wider range for the variables including voltage, duty cycle, and frequency. The challenge in terms of upgrading this project requires basic electronics skills which not all people know.

Our project deals with the overall society's well-being since it relates to one of the biggest resource we currently use. We always put safety, health, and welfare of the users as one of our main priority. Our goal of this project to construct a pulse generator better in all aspects from the previous prototype including controls, efficiently, and safety.

8. Ethical

One of the main concerns of this project includes safety. Since different people use the pulse width generator, the safety of it concerns us. Thus, the first rule of the IEEE code of ethics should hold true, *"to accept responsibility in making engineering decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment"*. Since the pulse width generator deals with high voltage, users with malicious intents pose a problem, thus safety precautions implemented prevents this. Thus, the ninth rule of the IEEE code of ethics should hold true, *"to avoid injuring others, their property, reputation, or employment by false or malicious action"*. This project does not require maximum efficiency, thus the responsibility does not fall upon us. However, given more time to change the design, making the pulse width generator more efficient becomes possible. Based on the conditional rule-based ethic, if given more time, then implementing more possibilities allows results in lower costs.

9. Health and Safety

Since researchers use this pulse generator to lyse algae, they may touch and experiment with different control combinations on the generator. Since the pulse width generator uses high voltage, touching a loose wire outputting high voltage may cause hazardous situations. Thus, the generator needs becomes safe to use and easy to operate without any dangerous wires sticking out.

10. Social and Political

The use of the pulse generator impact social issues such as global warming and the reduction emission since biofuels only provides one answer for fossil fuels. The direct stakeholders include the researchers, Dr. Taufik, Dr. Arakaki, Boeing, and this project team consisting of Philip and Stephen. The indirect stakeholders include everyone else in the world as the consumption of fossil fuel and emission concerns every living thing in the world. It benefits the stakeholders since as it pushes towards a common goal of providing a clean way to sustain our current standard of living but minimizing the impact on the environment. in our project, which concerns the environment and its whole, it benefits everyone equally as we all live in the same environment.

11. Development

Linear Technology provides the software, LTspice, for the majority of the simulation done in this project; a new technique learned in LTspice is creating a transformer by using two inductors. The literature search provides a vast amount of information as well by looking in the library. We learned how to find reliable sources by using scholar.google.com to find if the writer has trustworthy information and checking how many times they cite information and other people cited them. Also, just because patents become published does not necessarily give it authority as a reliable source, thus by checking the use of the patent asserts the patent's authority as a source.

Appendix B

Literature Search

[1] Taufik, Introduction to power electronics, San Luis Obispo: Taufik, 2013.

Dr. Taufik's book provides us basic knowledge of power electronics essential in this project. Dr. Taufik, a Senior Member of IEEE recognized by the power electronics world with numerous conferences preceding, Journal articles, and magazine articles wrote the book together with Dale Dolan. He received recognition from several professional organizations including IEEE USA.

[2] Taufik, Advanced power electronics, San Luis Obispo: Taufik, 2013.

Dr. Taufik's book provides us basic knowledge of power electronics essential in this project. Dr. Taufik, a Senior Member of IEEE recognized by the power electronics world with numerous conferences preceding, Journal articles, and magazine articles wrote the book together with Dale Dolan. He received recognition from several professional organizations including IEEE USA.

[3] I. Takuya and M. Tatsuo, "Fly back converter switching power supply device". US Patent 5,146,394, 8 9 1992.

The first stage of the three stages in our pulse generator consists of a Flyback converter. Understanding the invention of the Flyback and fully understanding the fly back converter provides us the background knowledge for this project. Matsushita Electric Industrial Co, now Panasonic Corporation, founded in 1918; now one of the largest Japanese electronics producers, obtained this patent.

[4] N. S. NAHMAN, "Reference Pulse Generators:Theory,Applications, and Status of Development," *IEEE Transaction on instruments and measurments,* vol. 38, no. 2, p. 442, 1989.

A pulse generator provides the basis of this project, this Journal Article talks about the theory behind a pulse generator and its application. This provides useful background information and helps us better understand how a pulse generator works. This article, published under IEEE, a professional organization for electrical engineering, provides credible source as many people read and cite it.

[5] E. Loza, *CASCADED HIGH VOLTAGE CONVERTER with VARIABLE CONTROL,* San Luis Obispo: California Polytechnic State University, 2012.

Emmanuel Loza's thesis on CASCADED HIGH VOLTAGE CONVERTER with VARIABLE CONTROL for PULSED ELECTRIC FIELD APPLICATIONS provides the basis of our senior project. Emmanuel Loza received his master's degree in electrical engineering from California Polytechnic State University in 2012.

[6] R. Biswas, R. Agarwal, A. Goswami and V. Mansingh, "Evaluation of Airflow Prediction Methods in Compact Electronic Enclosures," in *Semiconductor Thermal Measurement and Management Symposium*, San Diego , 1999.

Airflow in our generator concerns us as the researchers use the device frequently. Keeping the airflow inside the enclosure relatively good protects the components inside from overheating. The article, presented at the 15th annual IEEE conference for semiconductor thermal measurements and management symposium, provides good authority for this source.

[7] Wikipedia, "Two-port network," Wikipedia, 12 1 2014. [Online]. Available: http://en.wikipedia.org/w/index.php?title=Two-port_network&action=history. [Accessed 1 2 2014].

The second stage of the three stages in our pulse generator consists of the two port networks. Understanding how a two port network works provides us knowledge for this project. The Wikipedia article references 9 published books from multiple well-known authors in the industry.

[8] Linear Technology Corporation, "LT3748 100V Isolated Flyback Controller," 2010. [Online]. Available: http://cds.linear.com/docs/en/datasheet/3748fa.pdf. [Accessed 1 2 2014].

LT 3748, a 100V Isolated Fly back Converter controller, used in Emmanuel Loza's thesis design, which provides the basis of our senior project. Linear Technology designs high performance analog integrated circuits which sells various parts for circuits. LT has over 7500 products that range from digital converters to power management.

[9] Linear Technology Corporation, "LT1160/LT1162 -Half-/Full-Bridge N-Channel Power MOSFET Drivers," 1995. [Online]. Available: http://cds.linear.com/docs/en/datasheet/11602fb.pdf. [Accessed 1 2 2014].

LT 1160, a half-/full-bridge N-channel power MOSFET driver, used in Emmanuel Loza's thesis design which provides the basis of our senior project. Linear Technology designs high performance analog integrated circuits which sells various parts for circuits. LT has over 7500 products that range from digital converters to power management.

[10] International Electrotechnical Commission, "IEC- World Plugs: Plug Type B," International Electrotechnical Commission, [Online]. Available: http://www.iec.ch/worldplugs/typeB.htm. [Accessed 26 January 2014].

This reference informs us the standard wall voltage in the US which we use to power the pulse width generator. IEC, composed of members called national committees, represents the nation's electro technical interests in IEC. American National Standards Institute represents the US in IEC which represents 125,000 companies and 3.5 million professionals.