VOLTAGE PROTECTION SYSTEM FOR EHFEM PROJECT

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Abstract

The EHFEM project aims to convert the energy generated by exercise in a gym to electrical power and transport said energy to the grid. At the top level, this project includes several components including: a voltage and current protection system, a DC-DC converter, and an inverter. This project improves upon past voltage protection systems [1] [2]. The DC-DC converter takes the user-generated energy from the elliptical trainer and passes it to the grid. The user can generate voltage spikes upwards of 100V, far above the current DC-DC converter's maximum limit. The voltage protection circuit sits between the energy harvesting machine and the DC-DC converter and limits the voltage allowed across the converter. This ensures voltage spikes cannot overload and damage the energy harvesting mechanism. An inverter designed for solar cells expects current to increase as voltage decreases and places a dangerous demand on the DC-DC converter. [1] The voltage protection circuit works in conjunction with a current protection circuit to stabilize voltage and current outputs to the DC-DC converter and prevent any damage.

In 2014, Byung Yoo and Sheldon Chu designed a DC-DC converter with an operating range of 6 - 51V. At the same time, Cameron Kiddoo and Eric Funsten designed a voltage protection system (VPS) to work within this range. Their design monitored the input voltage and diverted the power to ground when it exceeded 51V using an IGBT. This project proposes a VPS that operates both within the converter's range and improves upon previous VPSs. The VPS regulates the incoming elliptical trainer voltage and passes it through five capacitors to filter out high frequency transients and power supply noises as well as to smooth out sharp spikes to produce a DC signal. When the elliptical voltage exceeds 51V, the output voltage at the source terminal of the transistor also reaches 51V, at which point the transistor stops the voltage from rising further. A high power PMOS and a power resistor ease the power dissipation requirement of the NMOS. Minimizing power loss as well as component count and size allows for an easily assembled system with a payback period of ten years at normal use.

Chapter I.

Introduction

The Energy Harvesting from Exercise Machines (EHFEM) project aims to harness energy generated by exercise equipment, such as elliptical trainers or exercise bikes, convert it to electricity, and deliver that energy to the grid. In total, the EHFEM project consists of three smaller projects: a protection system, a DC-DC converter, and an inverter. Overseen by Dr. Braun, students have worked on many designs in the past [1][2][4][5].

The EHFEM Project utilizes an elliptical trainer and an energy harvesting mechanism to convert the mechanical energy from the movement of the pedals to electrical energy. This harvesting mechanism produces electrical energy in the form of a DC voltage with varying voltage levels. The generated electricity passes through a DC-DC converter to reach a safe and stable output level. At this point, the largest challenge of the EHFEM Project remains sending harvested energy back to the grid.

One major need of this project involves a voltage protection circuit between the output of the elliptical trainer and the input of the DC-DC converter. The output voltage from the elliptical trainer resembles a noisy triangular waveform with spikes reaching above 100V. However, the DC-DC converter only accepts an input voltage between 20-51V, which means some form of voltage limiting must occur between the two devices. A voltage protection circuit would smooth out the input voltage to more closely resemble a DC waveform as well as limit the amplitude to an acceptable value for the DC-DC converter.

This project continues work on the EHFEM Project, with the goal of improving upon the voltage protection system design presented by Cameron Kiddoo and Eric Funsten. Last year, Byung Yoo and Sheldon Chu designed a DC-DC converter with an operating range of 6 - 51V. At the same time, Cameron Kiddoo and Eric Funsten designed a voltage protection system (VPS) to work within this range. Their design monitored the input voltage and diverted the power to ground when it exceeded 51V using an IGBT. This project proposes a VPS that operates both within the converter’s range and improves upon previous voltage protection systems The VPS regulates the incoming elliptical trainer voltage and passes it through five capacitors to filter out high frequency transients and power supply noises as well as to smooth out sharp spikes to produce a DC signal. A voltage boost circuit sets the NMOS’ gate voltage to 52V. When the elliptical voltage exceeds 51V, the output voltage at the source terminal of the transistor also reaches 51V, at which point the transistor stops the voltage from rising further. A high power PMOS and a power resistor ease the power dissipation requirement of the NMOS. Minimizing power loss as

well as component count and size allows for an easily assembled system with a payback period of ten years at normal use.

Our motivation for this project mainly stems from an interest in energy sources and power generation. The EHFEM project relates to this with its focus on generating renewable energy. Many types of renewable energy generation exist, from solar panels used in homes to windmills designed for large scale harvesting. This project focuses on commercial and university gym use, rather than at home use, because of how much use the elliptical trainer must see before breaking even in terms of cost. See the section on Commercial Manufacturing in Appendix A of the report.

Chapter II.

Customer Needs Assessment

The types of customers our project serves include: gyms, citizens, stores, environmental groups, rehabilitation centers, and power companies [3]. From this list of possible customers, we determined the following needs: ease of use, cost effectiveness, generation of clean and renewable power, efficient use of space, safe product operation, reliability, and simple maintenance. This project uses four components to accomplish this: an elliptical trainer, a protection system, a DC-DC Converter, and some Energy Harvesting component. The energy created by the user pedaling the elliptical trainer generates voltage spikes that can exceed one-hundred fifty volts. The harvesting device has an optimum range for the input voltage, which the spikes easily exceed. The DC-DC converter works to bring those high voltages into this "sweet-spot" but can't handle voltages over 51V. Therefore, the customer needs a circuit to protect a DC-DC converter from voltage spikes above 51V [4]. This project targets the DC-DC Converter designed by Sheldon Chu and Byung Yoo. The design of the VPS should use very little space and cost a proportionately small amount compared to the entire exercise bike project. It must perform reliably during its lifespan and not need extra maintenance. The input must handle all voltage levels from the energy harvesting mechanism and output a safe voltage to the DC-DC converter. We determined these needs by researching commercial products and considering product usage intensity and duration [5].

Requirements and Specifications

Customer needs determine the marketing requirements. Marketing requirements direct the engineering specifications, which specify how the product meets the requirements. To determine the requirements and specifications we brainstormed the top needs of each possible customer.

This guided the selection of requirements and specifications. Table 1 below lists the requirements and specifications. Gyms, power companies, citizens, stores, and rehabilitation centers have interest in saving money. Reducing the cost of the project meets this need. This means that we must find the balance between high quality components and high cost. The elliptical trainer aims to generate power. By generating power, owners of this bike such as gyms and rehabilitation centers can lower their power bill [6]. Generating power and saving money meets the need for generated power and offsets the need for minimizing the cost of the project. A single person exercising on a machine cannot generate very much power by themselves, which means the device must convert power efficiently [3]. The efficiency of the system contributes to the sustainability of the project. Nobody wants a product that breaks easily. This requires easy maintenance and repairs of the VPS. Making the project durable and sustainable fills this need. Gyms and citizens need to efficiently utilize their limited space. Condensing the bike's and VPS' designs helps them in this regard. In order to create a high quality design with a long lifespan, it must detect and respond to voltages that would damage the DC-DC Converter.

Table 1: Voltage Protection System Requirements and Specifications

Marketing Requirements	**Engineering Specifications**	**Justification**
1	Costs remain under $150.	Passive and active circuit components cost $40, PCB manufacturing cost $50, protection elements for the circuit cost $30, and shipping costs $30.
1, 2, 3, 5	Electrical components require maintenance no more than once every five years.	The device must operate for a minimum of two years without failing or endangering the user. Depending on capacitor type and usage per day, service life varies from two to ten years.
5, 6	Voltage Protection System limits output voltage to 51V.	Voltages in excess of 51V can cause significant damage to DC-DC converter circuitry.

4	Fits within a 4” by 4”by 2” space.	The product design takes up little volume in order to fit within the elliptical trainer enclosure.
3	Powered by electricity generated by the user.	Energy collected by energy harvesting device powers the protection circuit.
5	A enclosure encompasses all electrical components.	Plastic enclosure protects user against accidental electric shock as well as components from sustaining damage.
7	Components tested for functionality and nominal and actual component values match within five percent.	Non-working parts or actual values too far from the nominal values can cause the device to malfunction.
8	System must detect an unsafe voltage and respond within 35μs.	A response time longer than 35μs allows the DC-DC Converter to sustain damage.

Marketing Requirements

1. Low Cost
2. Reliable/Durable
3. Sustainable
4. Space efficient
5. Safe
6. Protects DC-DC Converter
7. High quality
8. Fast Response Time

Table 2: Voltage Protection System Deliverables

Delivery Date	Deliverable Description
11/14/14	Report V1
2/20/15	Design Review
3/17/15	EE 461 report
4/27/15	EE 462 demo
5/25/15	ABET Sr. Project Analysis
5/29/15	Sr. Project Expo Poster
6/10/15	EE 462 Report

Table 2 lists important milestone due dates throughout EE460, EE461, and EE462.

Chapter III.

Functional Decomposition

Figure 1 shows the level zero block diagram, a single block with one input and one output. The voltage protection system tempers the input from the elliptical trainer generator to operational values. At the output, the limited voltage safely feeds into the DC-DC converter [2] [3].

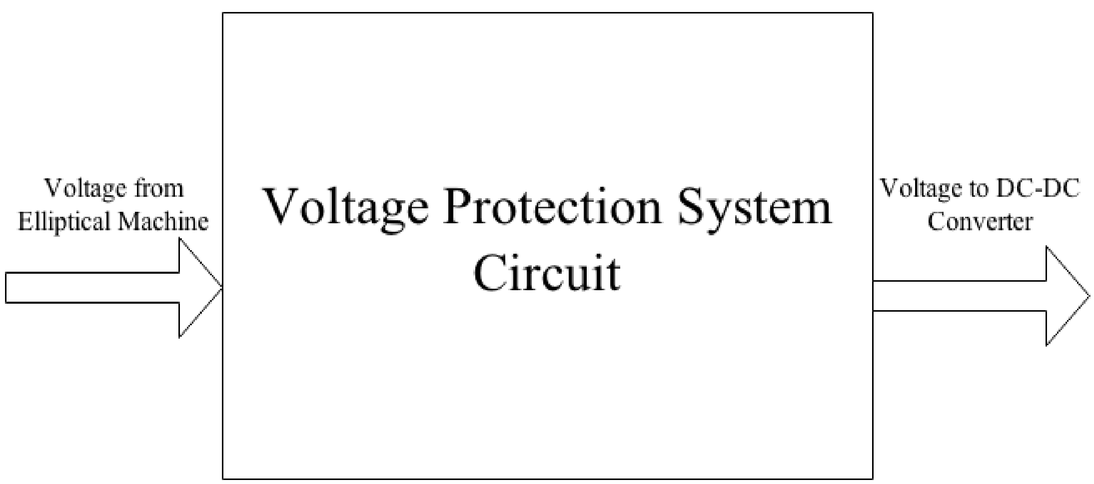

Figure 1: Voltage Protection System Level 0 Block Diagram

Table 3 lists the inputs, outputs, and functions of the voltage protection system. The circuit has one main function: to limit the voltage at the output. The input received from the elliptical trainer varies between 20 and 65 volts with spikes in excess of 100 volts [4]. See tables 5, 6, and 6 as well as figures 3, 4, 5, 6, 7, and 8 for data showing voltage levels and spikes. The Voltage Protection System limits the voltage sent to the DC-DC Converter to less than 51 volts.

Table 3: Voltage Protection System Level 0 I/O and Functions

Module	Voltage Protection System
Inputs	● Input from elliptical trainer generator
Outputs	● Output to DC-DC Converter
Functions	● Input Voltage Protection System limits output maximum voltage to 51V.

Figure 2 shows the level one block diagram. The input remains the same, with 0-150V input from the elliptical trainer, which goes into the capacitive filtering stage [2]. In this stage, a capacitor network filters and smooths the input, removing small voltage spikes and producing a more stable voltage level for the rest of the circuit.

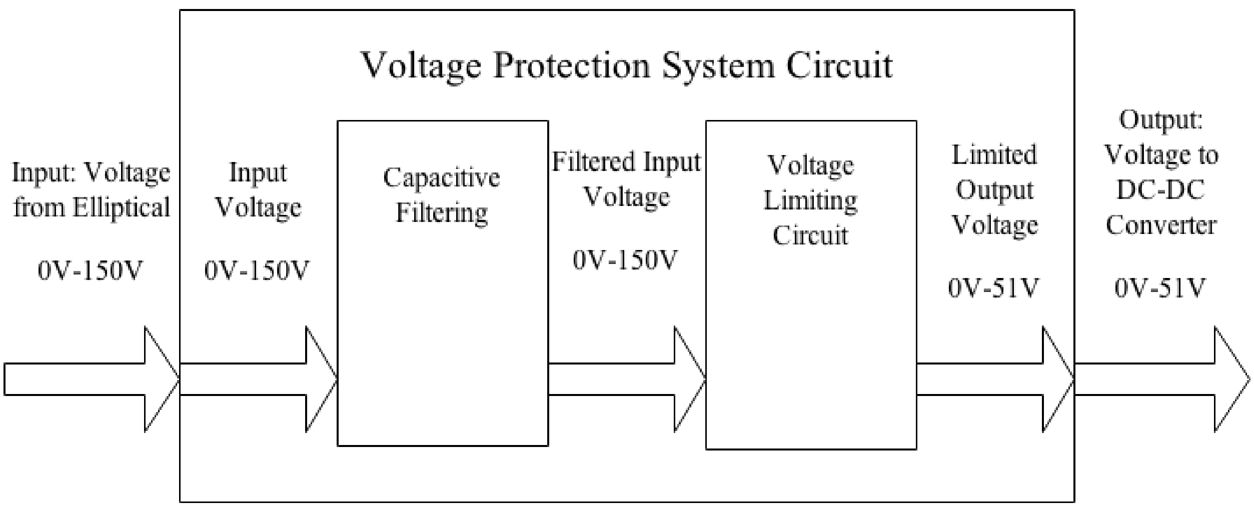

Figure 2: Voltage Protection System Level 1 Block Diagram

Table 4 lists the inputs, outputs, and functions of the Voltage Protection System (VPS), Capacitive Filtering (CF) component, and Voltage Limiting Circuit (VLC) [2]. The VPS has one main function: to limit the voltage sent to the DC-DC Converter. It performs this function through two systems within the circuit. A capacitor network makes up the capacitive filtering

portion, taking in a raw input voltage from the elliptical trainer and filtering it to remove smaller spikes from the voltage waveform and result in a smoother filtered input voltage. This filtered voltage passes to the next system, the voltage limiting circuit. The VLC performs one main function of limiting the output to 51V and below, in order to protect the DC-DC converter from harm [3]. It uses a transistor in the output path, with a 52V gate voltage provided by a boost converter circuit, to control the allowable output voltage. Once the output rises close to the gate voltage, the transistor prevents the output from rising further, and keeps the voltage steady. An additional transistor provides a path to another resistor to dissipate excess power.

Table 4: Voltage Protection System Level 1 I/O and Functions

Module	**Capacitive Filtering**
Inputs	● Input voltage from elliptical trainer generator. (0 - 150V)
Outputs	● Filtered Input Signal. (0 - 150V; a cleaned up version of the elliptical trainer input signal.)
Functions	● Capacitor network smooths out input voltage to a more stable voltage level and removes most small spikes.
Module	**Voltage Scaling Circuit**
Input	● Filtered Input Signal (0 - 150V; a cleaned up version of the elliptical trainer input signal.)
Outputs	● Scaled Output Voltage (0 - 51V; Safe voltage levels for the DC-DC Converter.)
Functions	● Filtered Input Signal passes to the VSC to either proceed to the DC-DC Converter or scale down to an allowable level.

Chapter IV.

Elliptical Characterization

Table 5: Elliptical Trainer Data - 100 Strides per Minute (SPM)

Res. Level	$V_{OUT,AVG}$ [V]	$V_{OUT,MAX}$ [V]	$I_{OUT,AVG}$ [A]	$I_{OUT,MAX}$ [A]	$P_{OUT,AVG}$ [W]	$P_{O,MAX}$ [W]
2.000	7.000	28.300	0.700	2.830	4.900	80.089
4.000	11.000	55.200	1.100	5.520	12.100	304.704
6.000	15.300	31.200	1.530	3.120	23.409	97.344
8.000	19.300	40.800	1.930	4.080	37.249	166.464
10.000	24.300	53.600	2.430	5.360	59.049	287.296
12.000	27.800	54.000	2.780	5.400	77.284	291.600
14.000	29.900	64.000	2.990	6.400	89.401	409.600
16.000	34.300	60.800	3.430	6.080	117.649	369.664
18.000	34.000	47.600	3.400	4.760	115.600	226.576
20.000	33.000	50.400	3.300	5.040	108.900	254.016

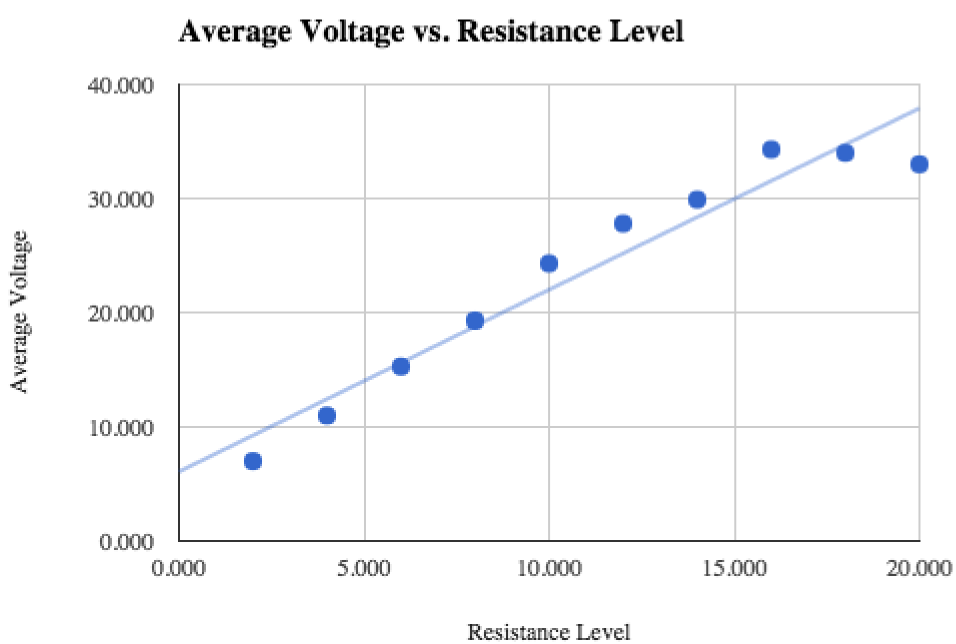

Figure 3: Average Elliptical Trainer Output Voltage vs. Resistance Level - 100 SPM

Table 5, above shows recorded elliptical trainer output data for varied resistance levels at one hundred strides per minute. Figure 3 plots average elliptical trainer output voltage versus resistance level for the same data set.

Table 6: Elliptical Trainer Data - 150 SPM

Res. Level	$V_{OUT,AVG}$ [V]	$V_{OUT,MAX}$ [V]	$I_{OUT,AVG}$ [A]	$I_{OUT,MAX}$ [A]	$P_{OUT,AVG}$ [W]	$P_{OUT,MAX}$ [W]
2.000	7.000	28.300	0.700	2.830	4.900	80.089
4.000	11.000	55.200	1.100	5.520	12.100	304.704
6.000	15.300	31.200	1.530	3.120	23.409	97.344
8.000	19.300	40.800	1.930	4.080	37.249	166.464
10.000	24.300	53.600	2.430	5.360	59.049	287.296
12.000	27.800	54.000	2.780	5.400	77.284	291.600
14.000	29.900	64.000	2.990	6.400	89.401	409.600
16.000	34.300	60.800	3.430	6.080	117.649	369.664
18.000	34.000	47.600	3.400	4.760	115.600	226.576
20.000	33.000	50.400	3.300	5.040	108.900	254.016

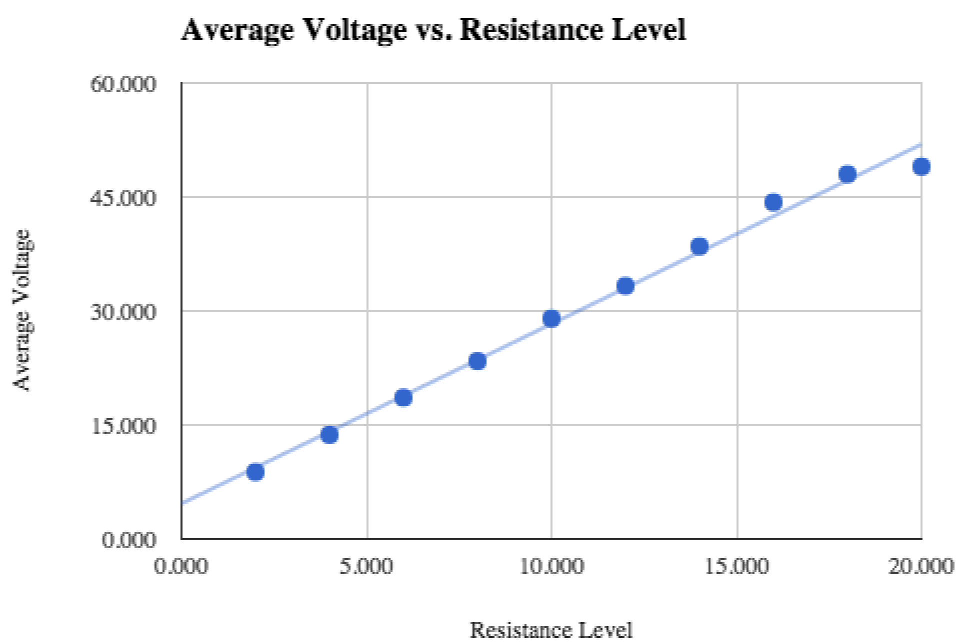

Figure 4: Average Elliptical Trainer Output Voltage vs. Resistance Level - 150 SPM

Table 6 above shows recorded elliptical trainer output data for varied resistance levels at one hundred-fifty strides per minute. Figure 4 plots average elliptical trainer output voltage versus resistance level for the same data set.

Table 7: Elliptical Trainer Data - Sprint (SPM > 200)

Res. Level	$V_{OUT,AVG}$ [V]	$V_{OUT,MAX}$ [V]	$I_{OUT,AVG}$ [A]	$I_{OUT,MAX}$ [A]	$P_{OUT,AVG}$ [W]	$P_{OUT,MAX}$ [W]
2	12.000	88.000	1.200	8.800	14.400	774.400
4	16.700	100.000	1.670	10.000	27.889	1000.000
6	23.000	94.400	2.300	9.440	52.900	891.136
8	28.500	96.800	2.850	9.680	81.225	937.024
10	35.000	103.200	3.500	10.320	122.500	1065.024
12	40.600	98.000	4.060	9.800	164.836	960.400
14	46.040	100.000	4.604	10.000	211.968	1000.000
16	53.400	97.600	5.340	9.760	285.156	952.576
18	55.600	92.000	5.560	9.200	309.136	846.400
20	65.000	132.000	6.500	13.200	422.500	1742.400

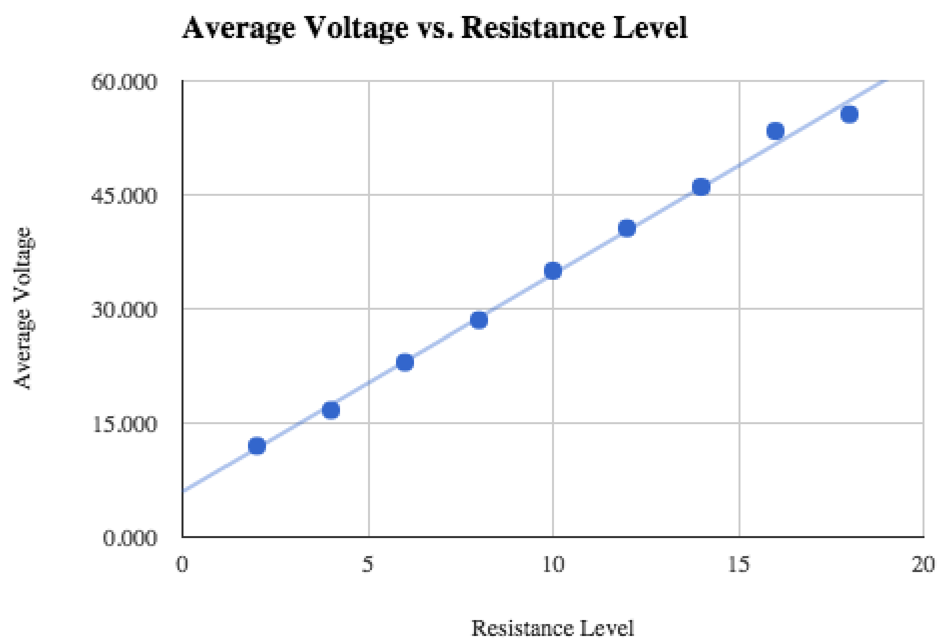

Figure 5: Average Elliptical Trainer Output Voltage vs. Resistance Level - Sprint (SPM>200)

Table 7 above shows recorded elliptical trainer output data for varied resistance levels at over two hundred strides per minute. Figure 5 shows the average elliptical trainer output voltage versus resistance level for the same data set.

Figure 6, Figure 7, and Figure 8 below show oscilloscope measurements of elliptical trainer output voltage at resistance level ten and paces of 100 SPM, 150 SPM, and sprinting (SPM>200).

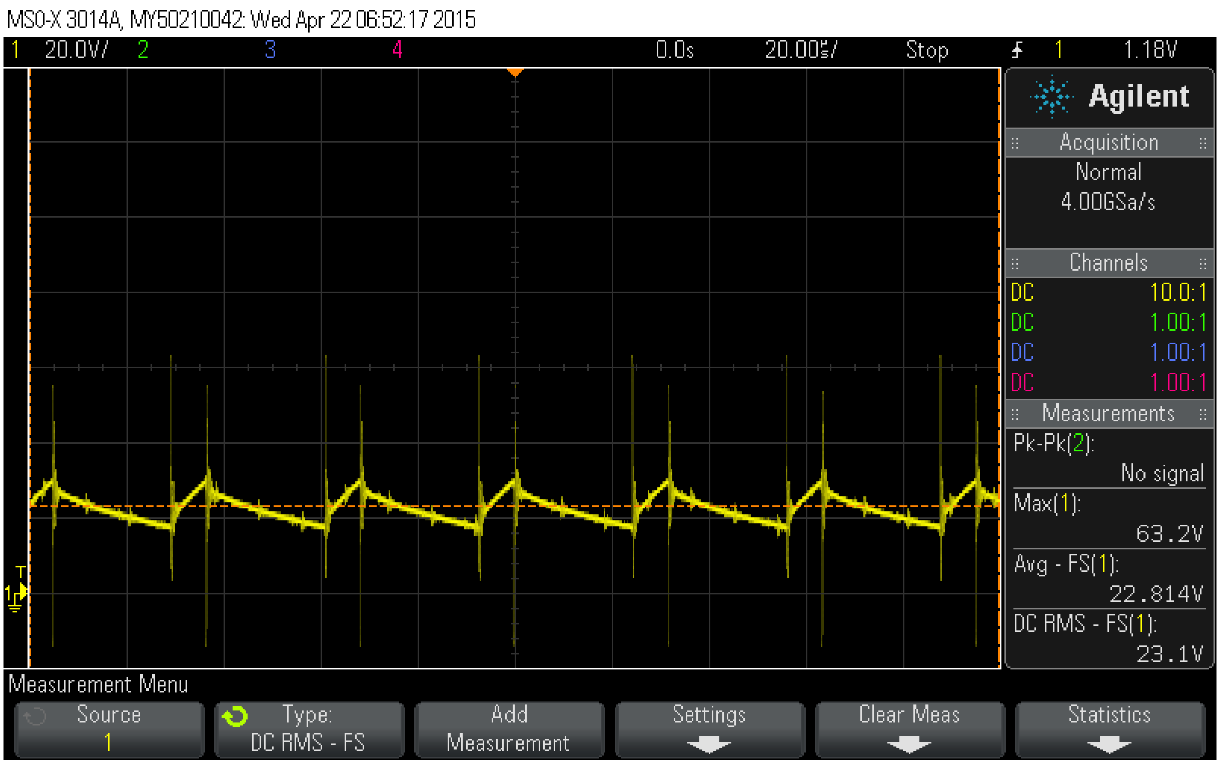

Figure 6: Oscilloscope Capture - Resistance 10, 100 SPM

Figure 7: Oscilloscope Capture - Resistance 10, 150 SPM

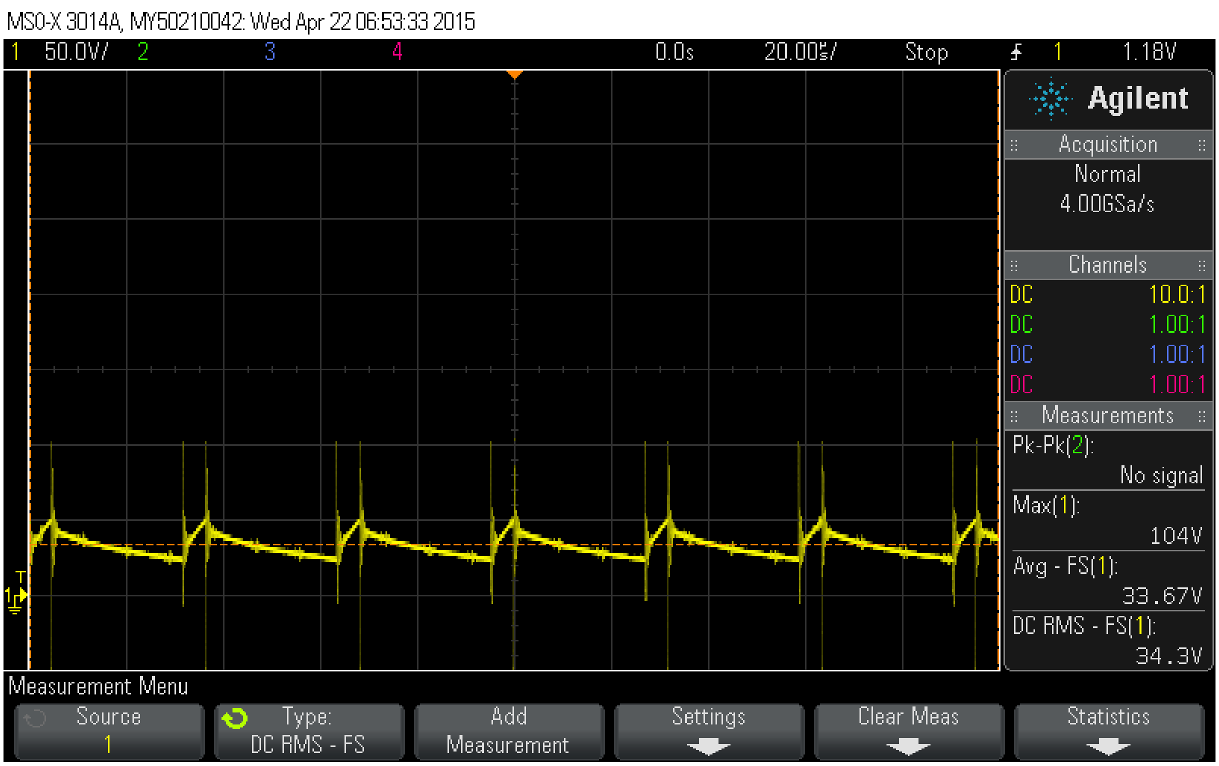

Figure 8: Oscilloscope Capture - Resistance 10, SPM > 200

Chapter V.

Voltage Protection System Design Iterations

The voltage protection circuit limits voltage generated by the elliptical machine to 50V. Voltages under 50V follow the input while voltages above 51V clip at that point. Figure 9 shows the ideal operation of the circuit, where the output to the DC-DC converter rises to 50V and stops. We chose to stop at a value of 50V in order to have a margin of error with component tolerances.

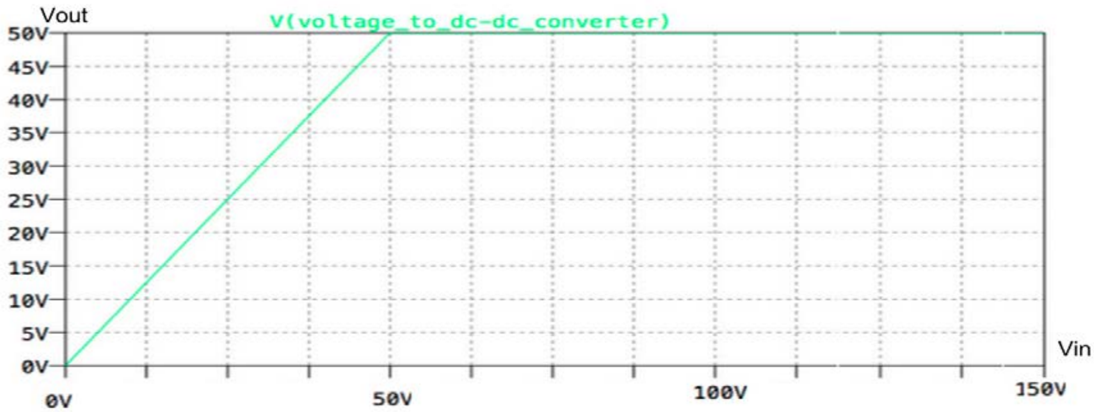

Figure 9: Ideal Operation of Protection Circuit

Design Attempt 1

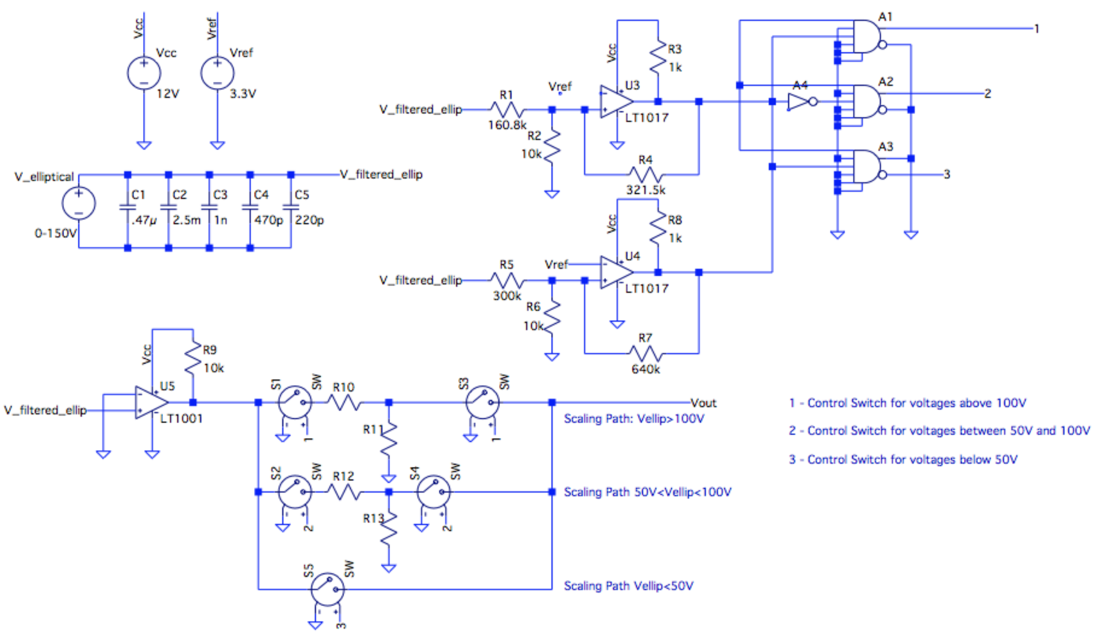

Figure 10: Design Attempt 1

The first design attempt shown in Figure 10 borrows heavily from both the Turner/Weiler [1] and Kiddoo/Funsten [2] designs. The capacitors, C1 - C5, filter the voltage received from the elliptical trainer, removing both low frequency power supply noise and higher frequencies, as well as eliminating most voltage spikes, resulting in a steady DC voltage. One branch of this voltage goes to a pair of resistor voltage divider network, lowering the voltage before passing to the comparators, which compare it to a 3.3V reference voltage by the comparators. The comparator U3 outputs high when the input voltage reaches higher than 50V, while the comparator U4 outputs high when the input voltage reaches higher than 100V. Following them, the behavioral AND gates control switches based on the combination of outputs from the comparators. Depending on the control signals, elliptical trainer voltages under 50V pass through unchanged and voltages higher than 50V become halved by the resistor dividers.

The issues in this design came from a lack of completely thinking through the capabilities of each component. The unity gain op-amp intended to buffer the input cannot handle the current that would need to flow from the input to the output. Using multiple comparators in addition to all the AND gates and switches causes unstable hysteretic behavior around the switching points of 50V and 100V. We moved away from this design due to these issues and the cost of components needed to fix these issues.

Design Attempt 2

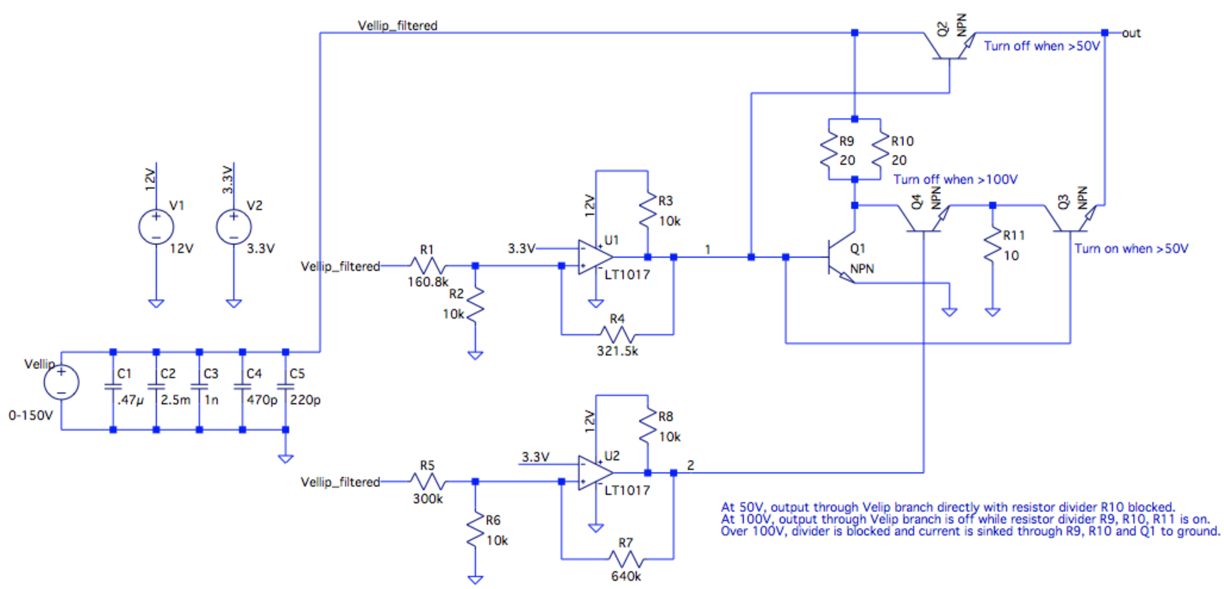

Figure 11: Design Attempt 2

The second design, shown in Figure 11, simplifies things by minimizing the amount of power dissipated by the protection circuit. Similar to Design 1, capacitors C1-C5 filter the input voltage, and resistors R1, R2, R5, and R6 scale the voltage down for the comparator input. Comparator U1 outputs low when the elliptical trainer voltage rises above 50V. This switches off Q2 and diverts the power flow through R9, R10, and R11 and through Q4 and Q3 resulting in an output voltage of half the magnitude of the input. Comparator U2 outputs low when the input rises above 100V and therefore keeps Q4 off and sends the power to ground. The difference between Design 1 and 2 comes in the usage of the BJTs as switches and the elimination of scaling voltages above 100V through the utilization of power resistors to dissipate excess power.

The main issue with this design comes from the comparator's inability to properly switch the transistor Q2 on or off. In order to turn on a BJT, the base-emitter voltage must exceed the BJT's turn-on voltage - typically ~0.7V. In our case, the output of the comparators can reach a maximum of 12 V. An elliptical trainer user rarely generates a voltage so low and the output exceeds this easily. Since we desire output much greater than 12V from the VPS, Q2 cannot turn on. Q2 and Q3 use the same comparator signal, but turn on and off different branches depending on the voltage at the output. Q3 blocks off R11 for voltages under 50V while Q2 blocks off the direct path for voltages above 50V.

Design Attempt 3

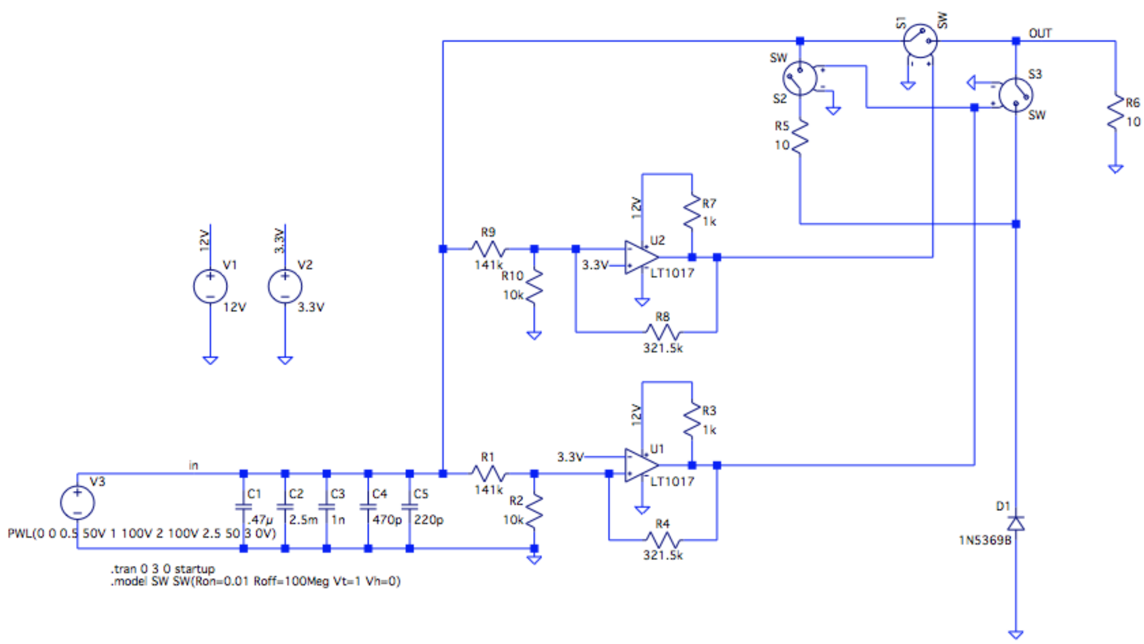

Figure 12: Design Attempt 3

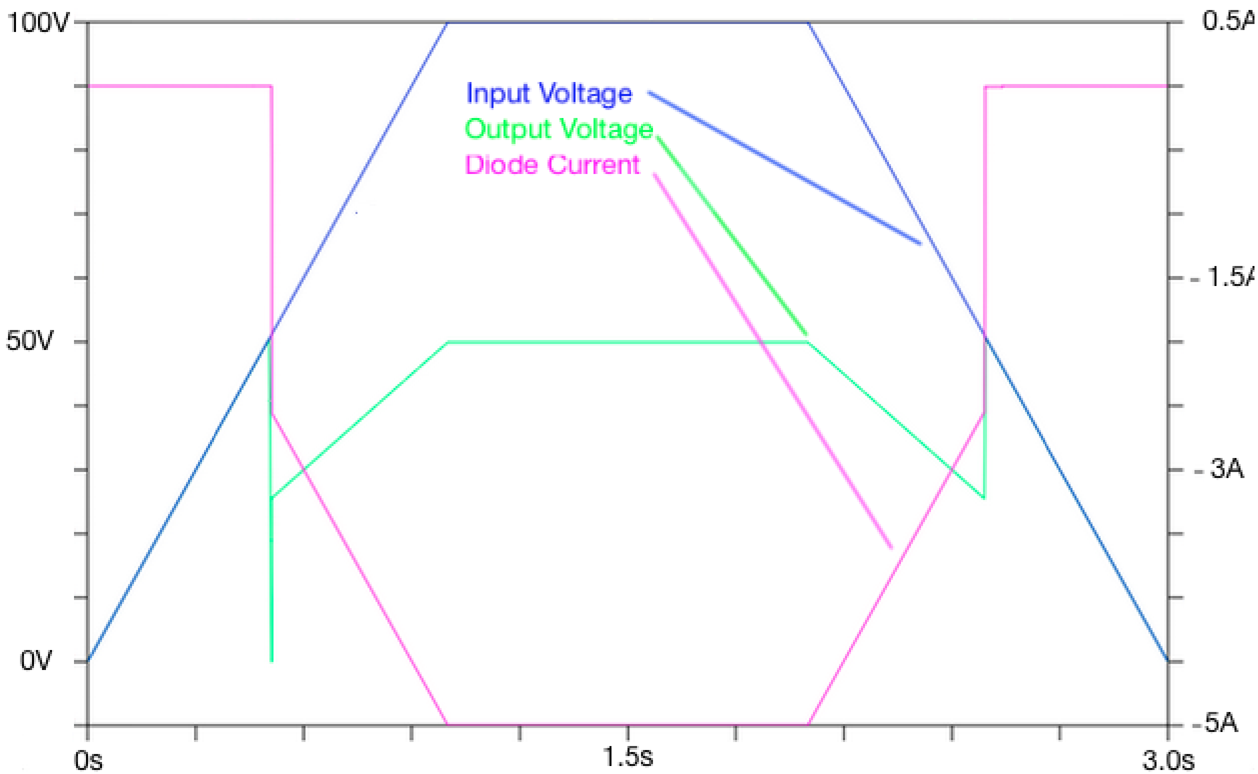

Figure 13: Operation of Design Attempt 3

The third design shown in Figure 12 attempts to further simplify the circuit and reduce the number of components. Input voltages below 50V pass through to the output uninterrupted since the switch S1 turns on and the zener diode becomes decoupled from the output by switches S2 and S3. The switch S1 turns off while S2 and S3 turn on with input voltages above 100V. This allows the zener diode to set the output at its zener voltage, in this case 51V, which prevents the output from rising any higher. Figure 13 shows the behavior of this circuit.

The problems we encountered with this design came from power dissipation issues in the zener diode. With potentially up to 5A of current flowing through the diode, it would need to dissipate as much as 250W. Diodes that can handle even 50W already cost as much as $28 [24]; spending $150 on diodes did not fit within our budget. Another issue involved the output voltage drop when switching the comparators on and off at 50V. The very large impedance of the switches most likely caused this dip since, at the moment they all turn off, the output becomes cut off from the input.

Design Attempt 4

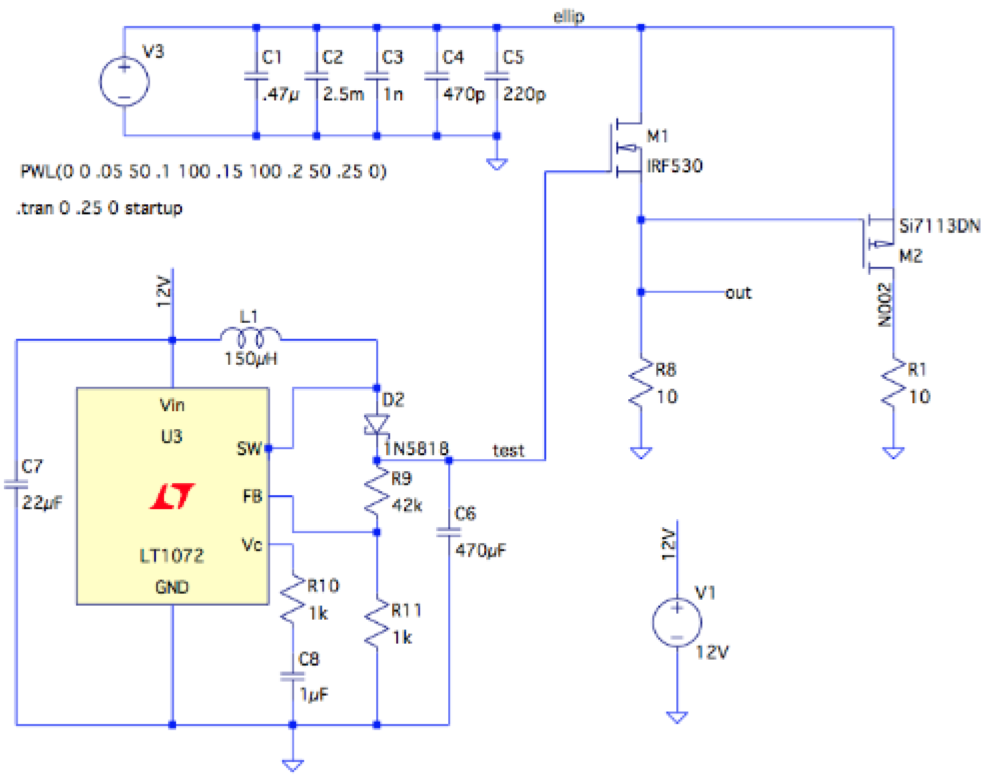

Figure 14: Design Attempt 4

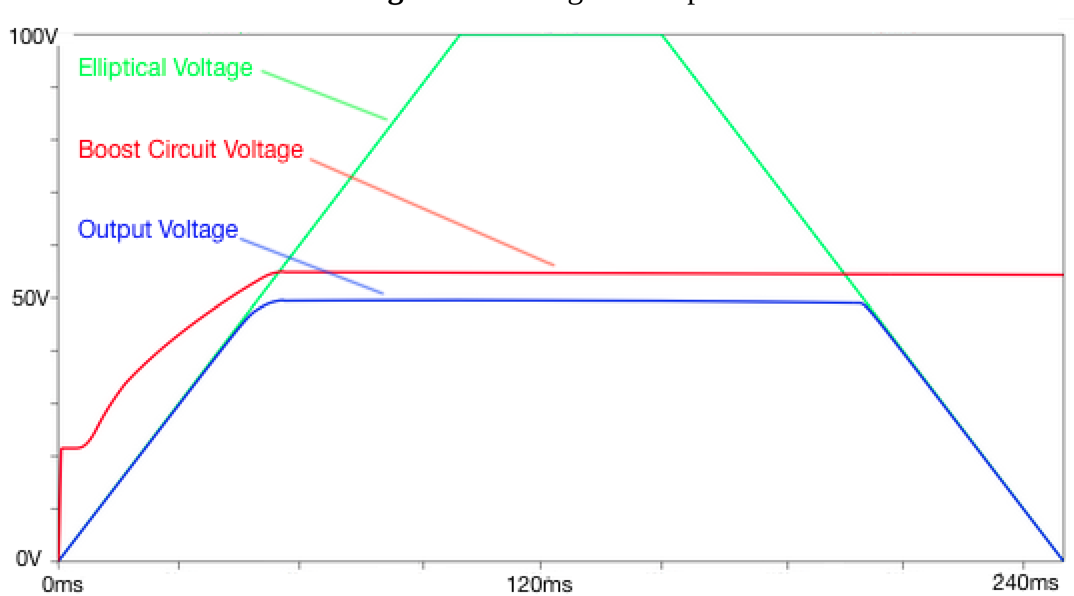

Figure 15: Operation of Design Attempt 4

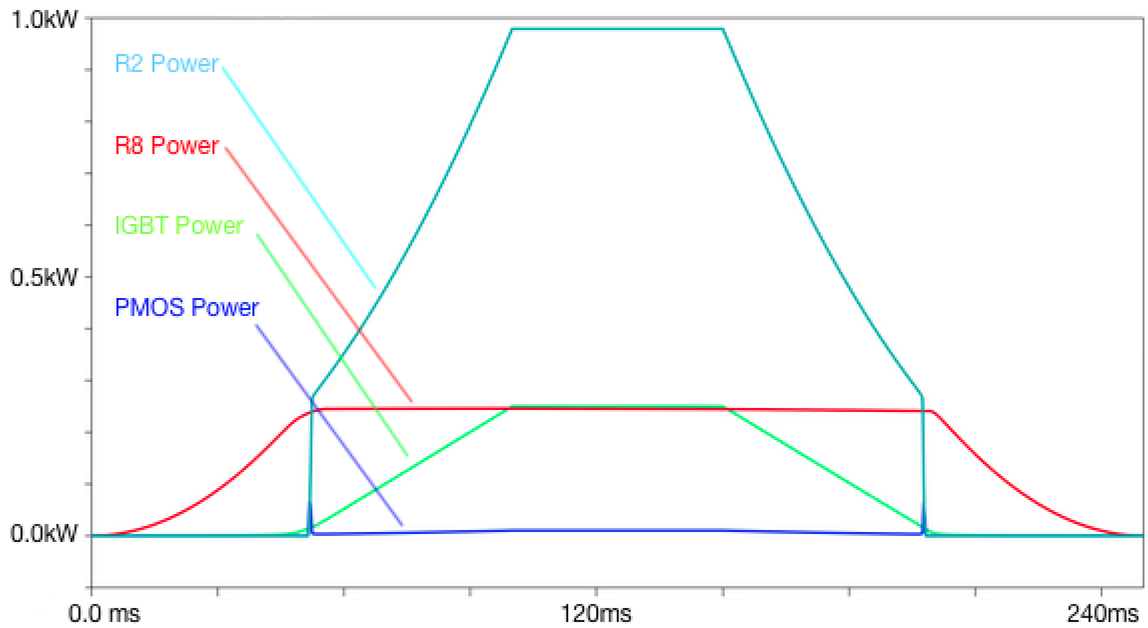

Figure 16: Power Dissipation of Transistors and Load Resistors Design 4

The fourth design attempt, shown in Figure 14, removes many of the components found in the third design since we discovered they did not impact the performance of the circuit. Instead of switches, we use an NMOS transistor M1, controlled by a gate voltage of 52V from a boost converter circuit [23]. The output voltage still follows the input voltage until approximately 48V, at which point it stops rising. This happens because the output voltage rises close to the gate voltage and essentially cuts off any additional rise in voltage. An additional PMOS transistor M2 with a resistor R1, connected in parallel with M1, aid in power dissipation by providing another path for excess current flow. Figure 15 shows the circuit's operation.

The largest problem, which we did not notice at first, involves the gate-to-source voltage of the transistor M1. With a gate voltage of 52V at all times, the Vgs exceeds the rating of many transistors that only handle 20V or 30V. Power dissipation also becomes a problem at high voltages, as the transistor can see up to 50V and 5A, resulting in needing a way to dissipate 250W of power. Figure 16 plots these problematic powers.

Design Attempt 5

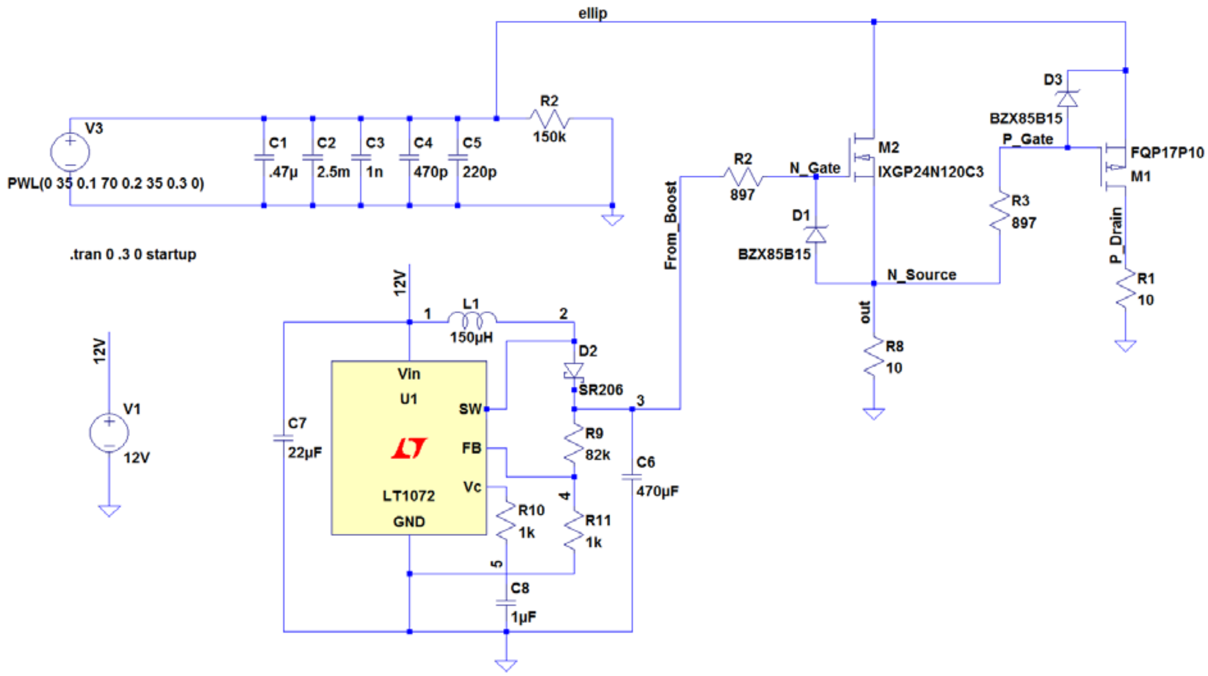

Figure 17: Design Attempt 5

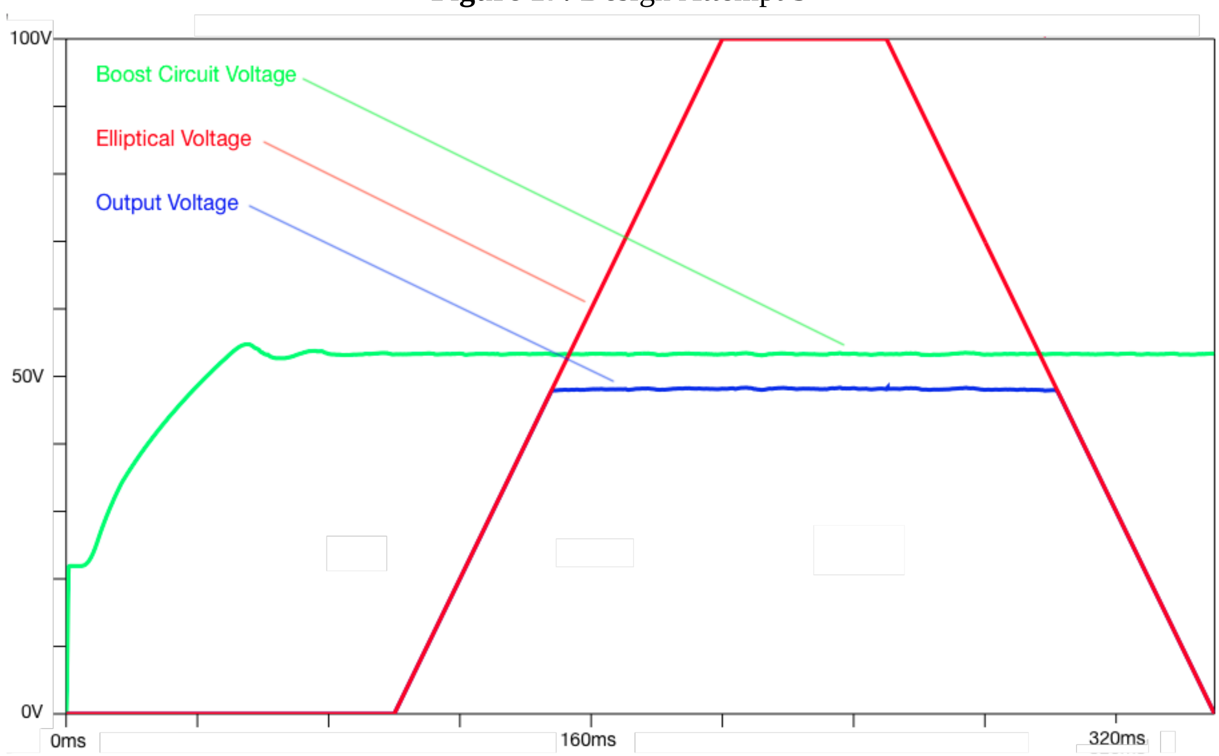

Figure 18: Operation of Design Attempt 5

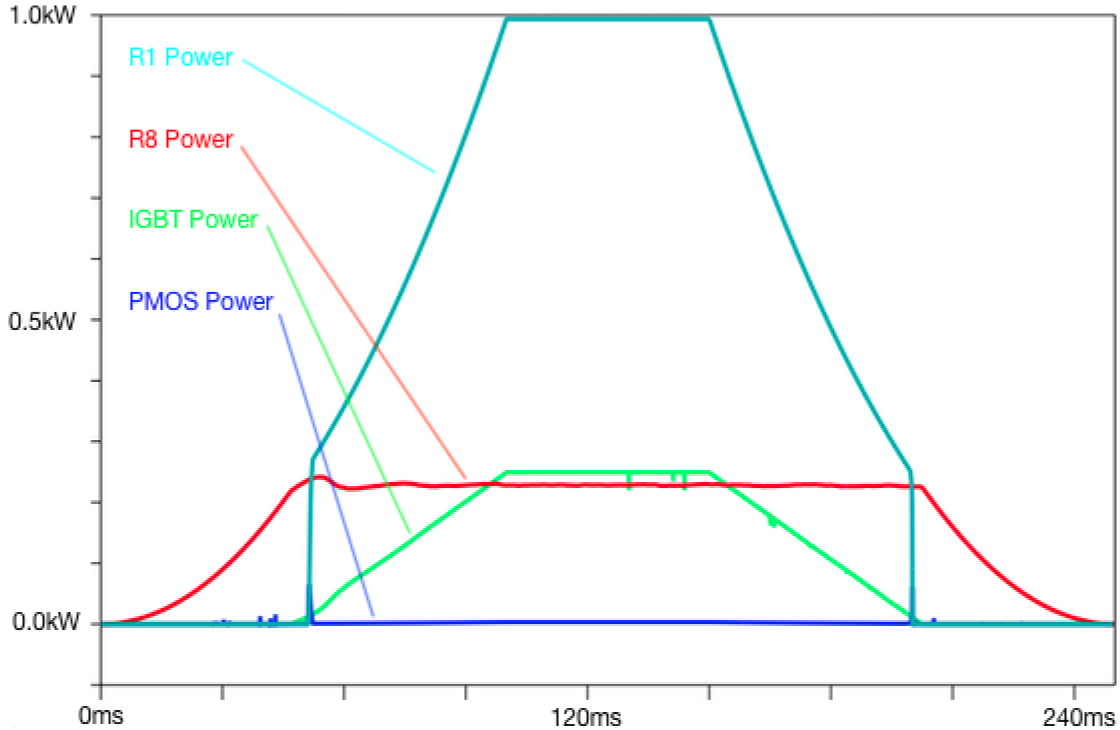

Figure 19: Power Dissipation of Transistors and Load Resistors Design 5

The design shown in Figure 17 solves the problem with the gate-to-source voltages of the IGBT and PMOS transistors. A 15V zener diode placed between the gate and source keeps the voltage difference at 15V, lower than the IGBT and PMOS rated maximums of +/-20V and +/-30V. Adding the two 5kΩ resistors between the boost circuit and the IGBT and between the IGBT and the PMOS directs the current through the 10Ω resistors. Design 5 operates identically to Design 4, with its operation shown in Figure 18.

While the figures above show that the design performs as desired, in the real world we encountered a few issues that did not appear in simulation. After solving the problem with the gate-source voltage, the diodes present a new one. With the boost circuit providing 50V to the gate of the IGBT, the 15V zener diode holds the output at a constant 35V. This prevents current from flowing to the output for input voltages lower than 35V, and therefore no power flows. Since the current cannot leave through the 10Ω resistors, the transistors involuntarily dissipate the applied power. Once the input rises above 35V, the circuit operates as expected. The addition of a 1-10nF capacitor in parallel with R11 helps to eliminate noise entering the feedback pin of the LT1072. Figure 19 graphs the power dissipation of the transistors and power resistors.

Chapter VI.

Testing

Table 8: Testing Equipment

Low Voltage/Current Testing	High Voltage/Current Testing	Cables
Agilent E3646A Dual Output DC Power Supply	BK Precision 9153 60V/9A 540W Programmable DC Power Supplyy	6x Banana-Grabber Leads
Agilent 54622A Oscilloscope	Agilent E3640A Triple Output Power Supply	12x Banana-Banana Leads
Agilent 34401A Digital Multimeter	Agilent U3606A Multimeter	12x Alligator Clips
	Fluke Handheld Multimeter	2x Oscilloscope Probes

Boost Circuit Testing

Using the circuit shown in Figure 20, along with the pin connections listed in Table 9, we first test the boost circuit design. We did this by setting the Agilent E3646A Dual Output DC Power Supply to 12VDC and connecting it to Vin on the breadboard via banana to grabber cables attached to short wires. Table 8 above lists the necessary equipment for testing. Then we check that Node 3 outputs approximately 52V using the Agilent 54622A Oscilloscope. We can adjust resistor R9 to increase or decrease the output voltage.

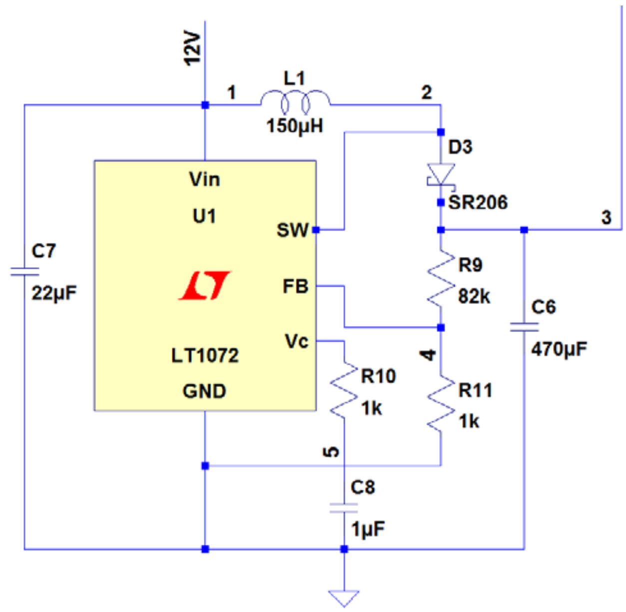

Figure 20: Boost Circuit

Table 9: Connections for Boost Circuit

Component	Measured Value	From Node	To Node
12V DC Source	12V	GND	1, V_{IN}
L1 = 150 µH	147.8 µH	1	2, SW
C7 = 25 µF	20.7 µF	1	GND
R10 = 1 kΩ	993 Ω	Vc	5
C8 = 1 µF	0.891 µF	5	GND
D2 = MBRS130L	-	2, SW	3
R9 = 82 kΩ	82.0	3	4
R11 = 1 kΩ	995 Ω	4, FB	GND
C6 = 470 µF	399 µF	3	GND

Protection Circuit Testing

Testing the circuit shown in Figure 21 for functionality uses the BK Precision 9153 60V/9A 540W Programmable DC Power Supply in place of the elliptical trainer and the Agilent E3630A Triple Output Power Supply in place of the elliptical trainer battery. We measure and record the voltage, current, and power of both the input and output while changing the input voltage of the BK Precision 9153 60V/9A 540W Programmable DC Power Supply in increments of 5V. The

the Agilent 54622A Oscilloscope measures the Boost Circuit output. Table 10 shows the pin connections for this circuit.

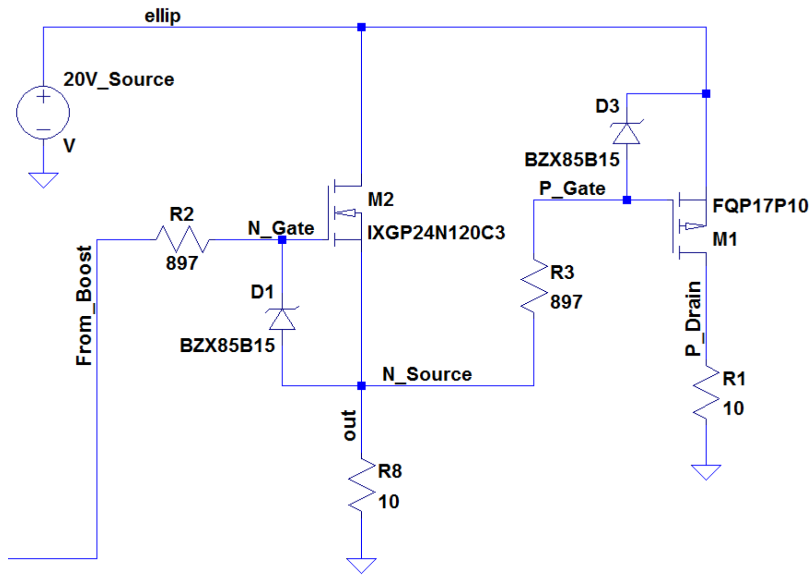

Figure 21: Voltage Limiting Circuit

Table 10: Connections for Voltage Limiting Circuit

Component	From	To
20V Source	Ground	Ellip
R2 = 5.6 kΩ	From_Boost	N_Gate
R3 = 5.6 kΩ	N_Source	P_Gate
R8 = 10 Ω	N_Source	Ground
R11 = 10 Ω	P_Drain	Ground
D1	N_Source	N_Gate
D3	P_Gate	Ellip
M1	[Gate, Drain, Source]	[N_Gate, Ellip, N_Source]
M2	[Gate, Drain, Source]	[P_Gate, P_Drain, Ellip]

Issues and Observations

Table 11: Measured Boost Circuit Output Voltage vs. Input & Gain Resistor

Input Voltage [V]: R9(kΩ)/Measured	Output Voltage [V]
12V : R9 = 47 / 46.9	40.5
12V : R9 = 68 / 68.3	46
12V : R9 = 82 / 82.03	48.7

Initial low-voltage testing of the Boost Circuit showed that theoretical calculations based on information from Linear Technologies Application Note 19 did not produce desired results. As shown in Table 11 above, a 47kΩ resistance produced a boost circuit output voltage of 40.5V. We increased the resistance to 82kΩ, which settled at an output voltage of 48.7V. This lower voltage results in limiting the output earlier than at 51V, the maximum voltage Sheldon Chu and Byung Yoo's DC-DC converter can handle.

Upon finishing testing of the boost circuit and determining its output voltage, we connected the entire circuit together. At this point, we discovered a problem involving the boost circuit output dropping to 18V when connected without an applied input. Applying an input test voltage raised the boost circuit output voltage. Increasing the input voltage also increased the Boost Circuit output until it reached a maximum of 49V, slightly above our set output voltage. We do not have an explanation for why this happened, but it does not affect the operation of the voltage protection circuit because the circuit still prevents the output from rising above the voltage set by the Boost Circuit.

Table 12: Boost Circuit Output Current vs. Interfacing Resistance

R2 (kΩ) / Measured Value	R2 Current (mA)
5 / 4.95	3.6
3.3 / 3.4	5
2.2 / 2.17	7
1 / .985	13.6
1.8‖1.8 / 1.798‖1.79 = 897	15.003

We then found another problem with the zener diodes not breaking down properly. Checking the datasheet for the zener diodes revealed that they needed a minimum current of 15mA, while our initial design with 5kΩ interfacing resistors limited current to 3.6 mA. Table 12 shows the various resistances we tested with to reach 15mA. We decreased the resistance to 897Ω in order to achieve the needed current. We used two 1.8kΩ resistors in parallel to accomplish this with the additional benefit of extra power dissipation as the available resistors have power ratings of 250mW each, for a total of 500mW.

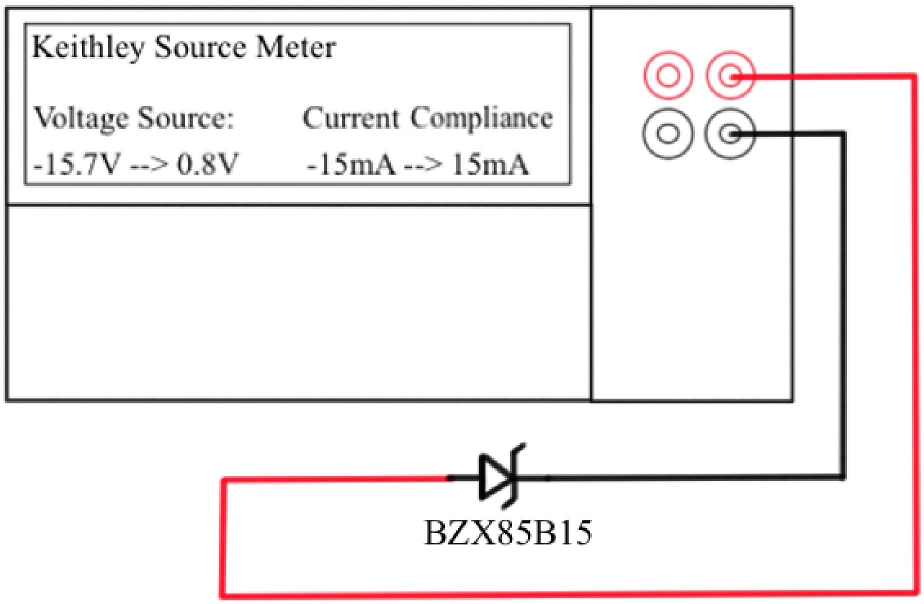

Figure 22: Zener Diode Characterization Test Setup

Table 13: Zener Diode I-V Characteristic

Diode Voltage [V]	Diode Current [mA]
-15.7	-20.4
-15.6	-17.6
-15.5	-16.8
-15.4	-13.7
-15.3	-11
-15.2	-8.5
-15.1	-6.7
-15	-4.6
-14.9	-2.7
-14.8	-0.002
-14.7	0
-14.6	0
-14.5	0
-12	0
-8	0
-4	0
0	0
0.1	0
0.2	0
0.3	0
0.4	0.001
0.5	0.009
0.6	0.104
0.64	0.297
0.68	0.876
0.7	1.489
0.725	2.816
0.75	5.15
0.775	9.22
0.79	12.81
0.8	15.5

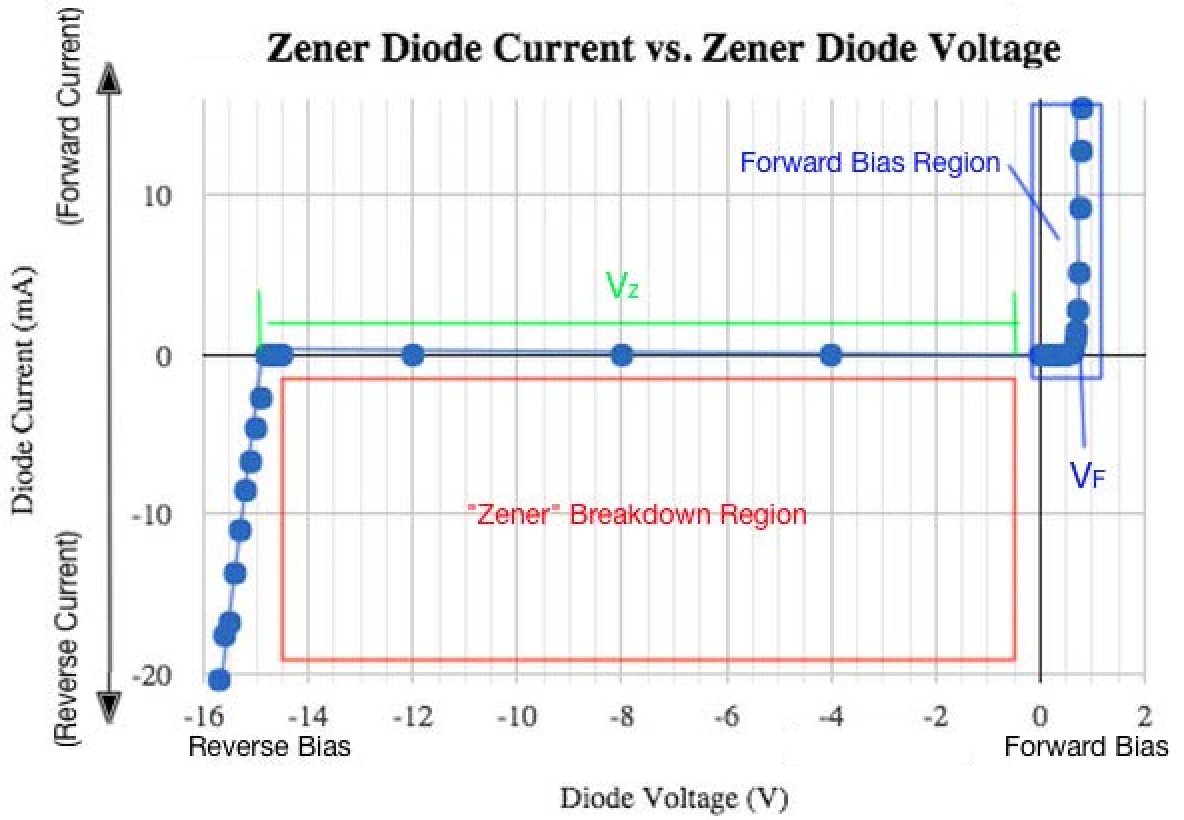

Figure 23: BZX85B15 Zener Diode I-V Characteristics

Figure 22 shows the simple test setup we used to characterize the zener diode. Table 13 and Figure 23 display the results of our test, with the zener diode breaking down at 15V while having a forward on voltage of 0.8V. These values match the values given in the datasheet [26].

Data

Table 14 contains data measured and collected from the Boost Circuit and Voltage Protection Circuit connected using the equipment detailed in the Protection Circuit Testing section.

Table 14: Input & Output Voltages, Currents, & Powers & System Efficiency

Input Voltage [V]	Input Current [A]	Input Power [W]	Output Current [A]	Output Voltage [V]	Output Power [W]	Efficiency [%]
20	1.6380	32.7600	1.6370	16.1600	26.5000	80.8913
25	2.1000	52.5000	2.1010	20.7200	43.5600	82.9714
30	2.6300	78.9000	2.6290	25.9000	68.1000	86.3118
35	3.1260	109.4100	3.1290	30.8000	96.4000	88.1089
40	3.6240	144.9600	3.6300	35.7300	129.8000	89.5419
45	4.1080	184.8600	4.1200	40.5100	166.8000	90.2304
50	4.3156	215.7800	4.3200	42.5800	183.9000	85.2257
55	4.3400	238.7000	4.3500	42.8500	186.1000	77.9640
60	4.3730	262.3800	4.3800	43.1500	189.0000	72.0329

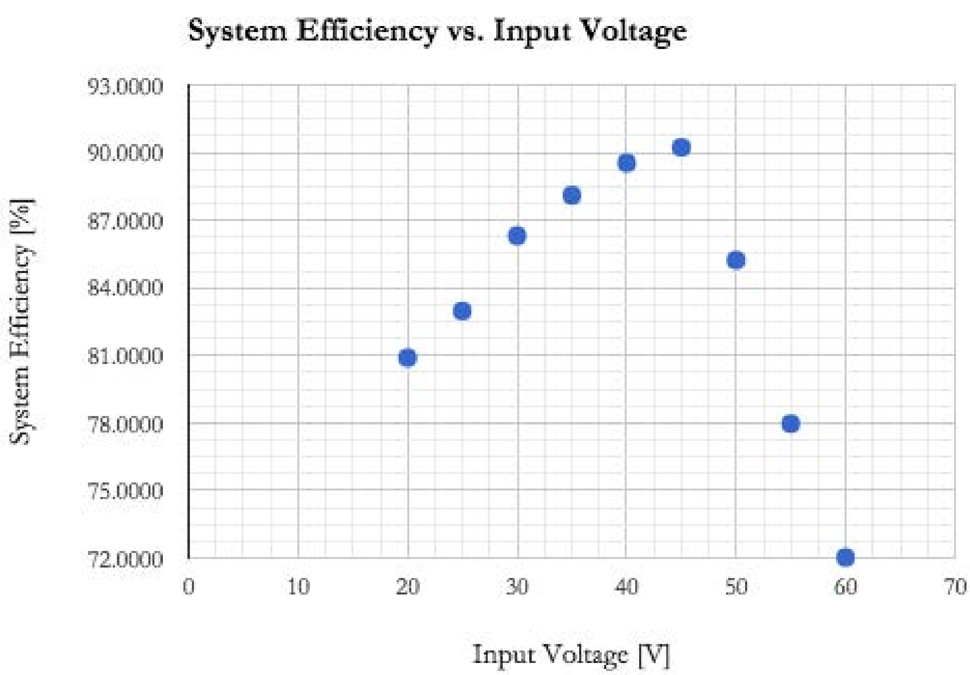

Figure 24: System Efficiency vs. Input Voltage

Table 14 lays out the input and output voltages, currents and powers as input voltage increases from 20V to 60V in 5V increments. We calculate overall efficiency of the system by dividing the output voltage by the input voltage and then multiplying by 100 to give us a percentage. For input voltages of 50V, 55V, and 65V, the system incurs extra losses since the VPS limits output voltages to below 44V. We did not reach the design goal of limiting the voltage at 51V with the current revision of the design, but simply adjusting the boost circuit resistor R9 to a higher value should cause limiting to occur at a higher voltage. Figure 24 plots the efficiency of the system versus input voltage. The efficiency of the system dips dramatically for input voltages higher than 51V. Because the system design prohibits voltages higher than 51V from reaching the DC-DC converter, the VPS must dissipate the excess power.

Ideally, the system should operate above 95% efficiency for input voltages below 50V. Since it did not operate so efficiently, we needed to investigate where additional power loss occurred; Table 15 and Table 16 show parts of that investigation. Table 15 displays the voltage, current, and power dissipation of the IGBT as well as the power resistor below it, which simulates the load placed upon the protection system. Table 16 contains the same data as Table 15, but for the PMOS and the power resistor below it.

Table 15: IGBT and Output Power Resistor Voltages, Currents, & Powers

Input	IGBT			R8 (IGBT)		
V [V]	**Vce [V]**	**I [A]**	**P [W]**	**V [V]**	**I [A]**	**P [W]**
20	3.27	1.637	5.353	16.08	1.608	25.856
25	3.56	2.101	7.480	20.62	2.062	42.518
30	3.08	2.629	8.097	25.89	2.589	67.029
35	2.98	3.129	9.324	30.79	3.079	94.802
40	2.89	3.63	10.491	35.68	3.568	127.306
45	2.91	4.12	11.989	40.44	4.044	163.539
50	5.84	4.32	25.229	42.3	4.23	178.929
55	10.6	4.35	46.110	42.4	4.24	179.776
60	15.38	4.38	67.364	42.5	4.25	180.625

Table 16: PMOS and Overvoltage Power Resistor Voltages, Currents, & Powers

Input	PMOS VS-D			R1 (PMOS)		
V [V]	V [V]	I [A]	P [W]	V [V]	I [A]	P [W]
20	19.75	0	0	0	0	0
25	24.68	0	0	0	0	0
30	29.6	0	0	0	0	0
35	34.52	0	0	0	0	0
40	39.44	0	0	0	0	0
45	44.4	0	0	0	0	0
50	49.3	0	0	0	0	0
55	54.3	0	0	0	0	0
60	59.3	0	0	0	0	0

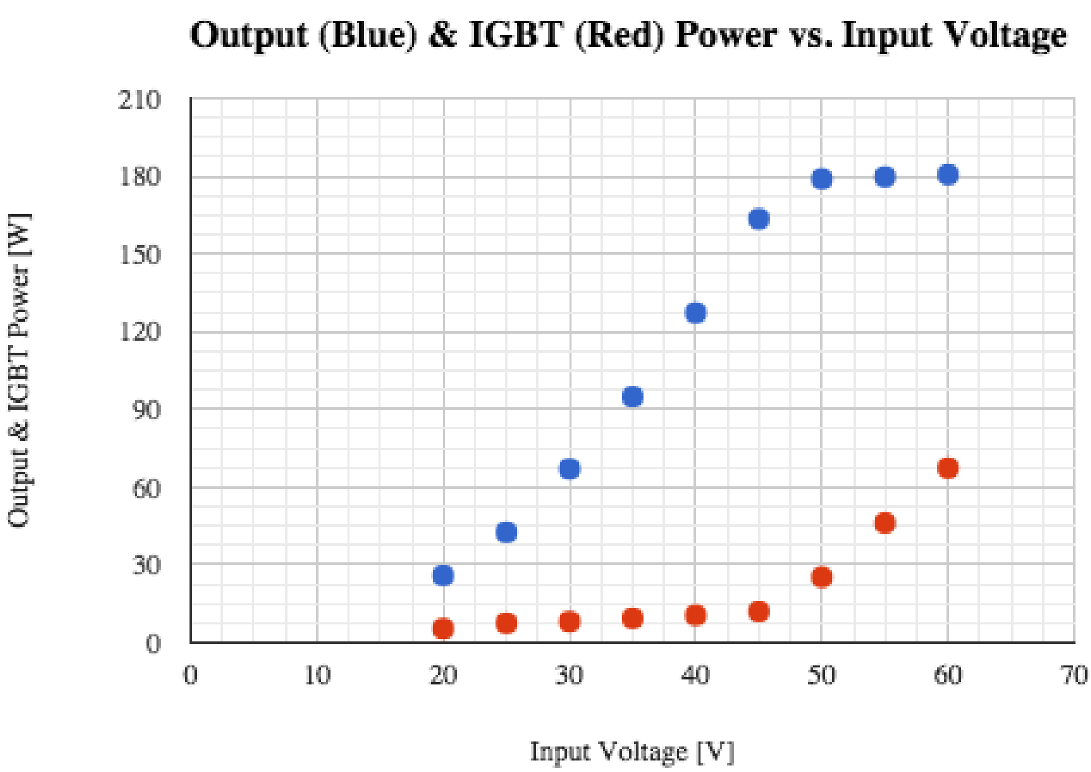

Figure 25: Output and IGBT Power vs. Input Voltage

Figure 25 plots the output power and power dissipated by the IGBT. As expected, we reach maximum power output, about 180W, at 50V. Once the input voltage exceeds that, the power remains relatively constant. At the same time, the dissipated power in the IGBT increases as the input voltage approaches the voltage limit. The IGBT dissipates little power below input voltages of 45V, at which point power dissipation increases substantially. As seen in Table 16, even though the source-to-drain voltage of the PMOS very nearly matches the input, no current flows to the power resistor below it. Table 17 shows data regarding operation of the PMOS.

Table 17: PMOS Operation Investigation

Input	PMOS S-G	PMOS G-GND	R3 (+ at IGBT Emitter, - at PMOS Gate)		
V [V]	**V [V]**	**V [V]**	**V [V]**	**I [A]**	**|P| [W]**
20	0.63	19.12	-2.64	0.00293	0.00774
25	0.67	24.01	-2.88	0.00320	0.00922
30	0.614	28.99	-2.53	0.00281	0.00711
35	0.603	33.92	-2.46	0.00273	0.00672
40	0.593	38.86	-2.41	0.00268	0.00645
45	0.601	43.8	-2.46	0.00273	0.00672
50	0.959	48.4	-5.05	0.00561	0.02834
55	1.387	53	-9.36	0.01040	0.09734
60	1.72	57.6	-13.7	0.01522	0.20854

The datasheet for the FQP17P10 shows that the PMOS used in our design has a 2.0V gate threshold voltage. As shown in the table above, V_{SG} does not exceed that and therefore the transistor does not turn on. This explains why the PMOS and its power resistor do not conduct current or assist in dissipating excess power. Two possible options exist to remedy this problem: 1) Choose a different PMOS with a lower threshold voltage or 2) Find a way to create over 2V for the appropriate voltages. We discuss the first option directly below, and discuss the second option in the System Troubleshooting section further down.

Because of the low measured V_{SG}, the NMOS must dissipate the majority of the excess power instead of dumping some of the work on the PMOS. In order to turn on the PMOS, we need to either use input voltages greater than 60V or find a replacement. Explore this option only after you have exhausted the second. See discussion in the system troubleshooting section.

A replacement PMOS must have at least the following requirements:

- ❑ Maximum Power Dissipation: (P_D) > 100W
- ❑ Case-to-Sink Thermal Resistance: ($R_{\theta CS}$) ~ 0.5 $^oC/W$
- ❑ Gate-to-Source Voltage: (V_{GSS}) >= +/- 20V
- ❑ Gate Threshold Voltage: 0.8V < ($V_{GS(TH)}$) < 1.0V
- ❑

For more guidelines for component selection, see the FQP17P10 datasheet [25].

Table 18: System Loss

Input Voltage [V]	Total Power Loss [W]	IGBT Power Loss [W]	Difference [W]
20	6.260	5.353	0.907
25	8.940	7.480	1.460
30	10.800	8.097	2.703
35	13.010	9.324	3.686
40	15.160	10.491	4.669
45	18.060	11.989	6.071
50	31.880	25.229	6.651
55	52.600	46.110	6.490
60	73.380	67.364	6.016

Table 18 shows total system power loss as input voltage increases. We calculate total power loss by subtracting the output power from the input power and calculate the power loss in the IGBT from current and voltage measurements in Table 15. IGBT power loss constitutes the vast majority of the power dissipation in the system. The system has relatively low power loss for input voltages below 45, with a sharp increase as input voltage reaches 50V. This occurs because as the voltage becomes limited, less of the input flows to the output, with the difference dissipated as heat throughout the circuit. The IGBT dissipates the majority of the power due to the PMOS not turning on below 60V. The remaining power loss not in the IGBT comes from the various resistors in circuit as well as the diodes. Table 17 shows the power dissipation in resistor R3, which while not very high, could exceed the tolerances of a single ¼ W resistor at higher voltages, thus requiring two resistors in parallel. The remaining difference comes from power loss in the diodes.

One other issue we measured involved the time it took for the boost circuit to charge up to its maximum output voltage with an elliptical voltage applied. Table 19 and Figure 26 below list the amount of time it took for each voltage step we tested it, with 20V only taking 4 seconds while

45V and above took around 40 seconds to reach the final voltage. This charge time, while lengthy, does not affect the performance of the protection circuit as the output still follows the limit set by the boost circuit. The System Troubleshooting section below delves into this problem in greater detail.

Table 19: Boost Circuit Charge Times

Input Voltage [V]	Charge Time [seconds]	Final Voltage [V]
20	4	33
25	6.2	38
30	11	42
35	22	47
40	37.5	49
45	40	49
50	41	49
55	39	49.5
60	40	49.5

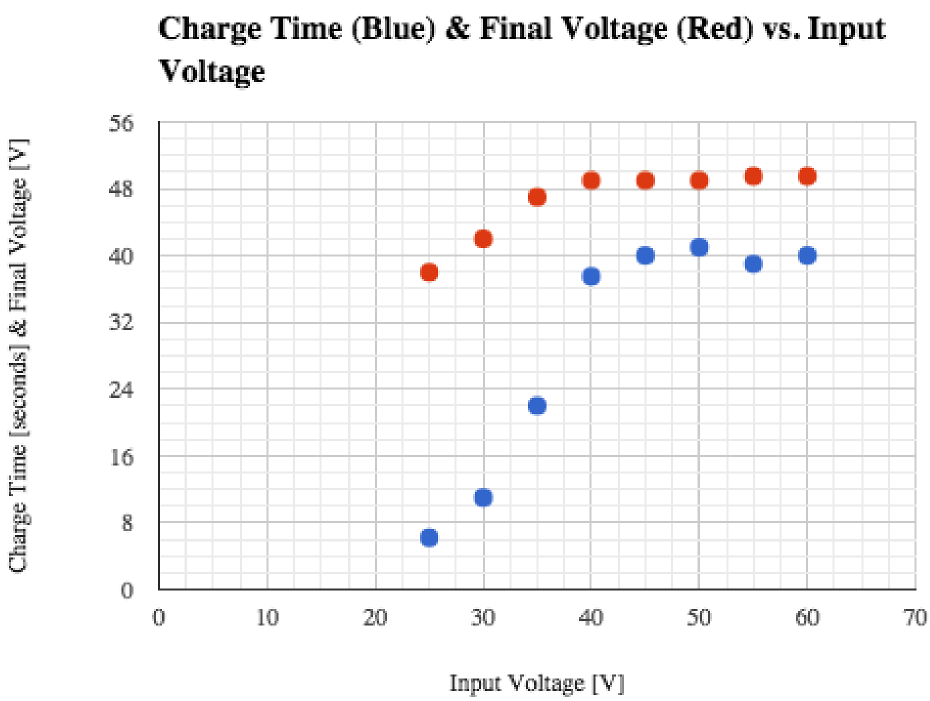

Figure 26: Boost Circuit Charge Times and Final Voltages vs. Input Voltage

System Troubleshooting

Boost Circuit:
As seen in Table 19 above, the Boost Circuit takes too long to charge up to its final value of 50V. This necessitates the troubleshooting of the Boost Circuit. The two figures below, Figure 27 and Figure 28, show the expected values at each node of the Boost Circuit while connected to the Voltage Limiting Circuit with applied input voltages from 20V up to 60V. Each input voltage gave the same values at each node in simulation so only one plot shown.

Troubleshooting testing utilizes the same equipment as initial low voltage, low current testing of the Boost Circuit. For a list of required equipment, connection diagrams, and tables refer to Figure 20, Table 8, and Table 9.

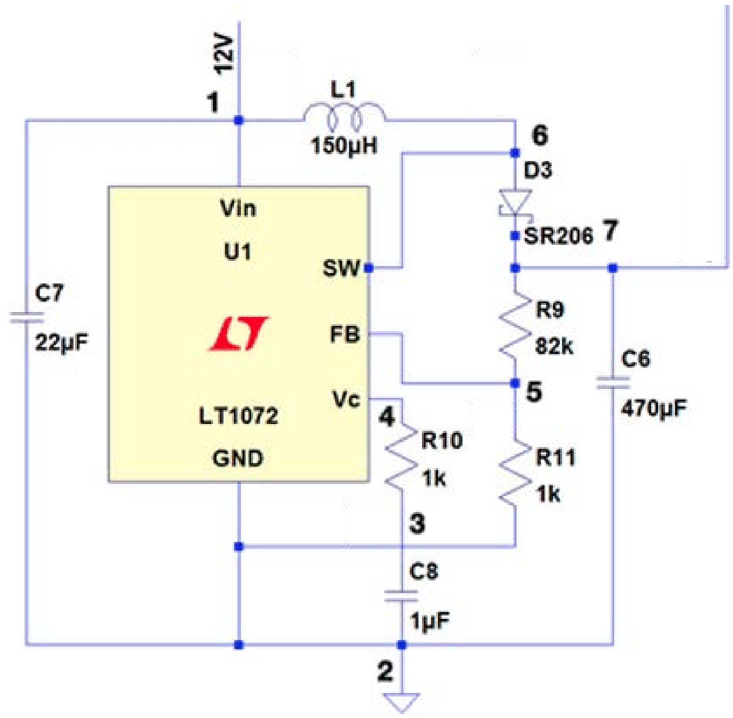

Figure 27: Boost Circuit Troubleshooting Measurement Locations

Figure 28 does not include Node 2 because it simply measures ground, which measures zero volts in all test cases. Similarly, Node 4 displays the same value as Node 3 on the plot.

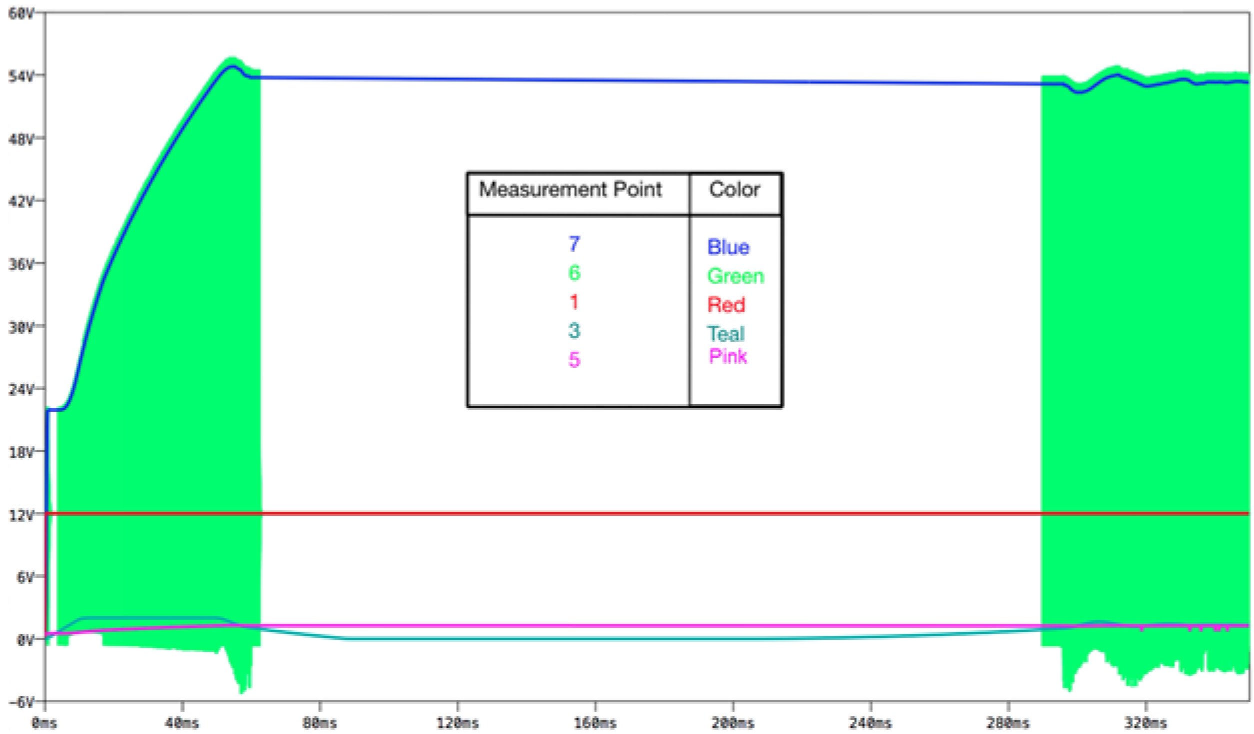

Figure 28: Expected Values from Simulation

The teal and pink lines reach steady state at about 1.5V. The green trace dips to 12V while the blue trace remains constant in the middle portion. Table 20 lays out the measured values of each of the nodes in the Boost Circuit by input voltage.

Table 20: Boost Circuit Measured Values - 20V to 60V

Input Voltage	Measurement Locations						
	1 [V]	2 [mV]	3 [V]	4 [V]	5 [V]	6 [V]	7 [V]
20	11.996	0.076	1.832	1.829	0.4	11.994	32.02
25	11.993	0.05	1.829	1.829	0.439	11.989	36.9
30	11.987	0.009	1.92	1.92	0.495	11.987	41.7
35	11.987	0.122	1.92	1.92	0.55	11.986	46.6
40	11.987	0.08	1.928	1.918	0.56	11.987	48.5
45	11.985	0.002	1.919	1.919	0.57	11.985	48.8
50	11.98	0.007	1.92	1.92	0.55	11.98	48.8
55	11.986	0.001	1.92	1.92	0.57	11.986	48.8
60	11.987	0.0007	1.92	1.919	0.58	11.986	48.8

Examination of Figure 28 and Table 20 shows that each node in the Boost Circuit performs as expected with the only difference being explained by slight modifications made in the physical circuit from the simulated. We increased R9 to achieve an output voltage of 48V as the original value of 42kΩ only produced 31V on the output of the physical circuit. From the voltages in Table 20, we calculated the Boost Circuit resistor currents to check them against simulation. Comparison of the currents revealed that they matched with the exception of R9, which had almost double the resistance as in the simulation. It should be noted that some entries in Table 21 cannot actually be zero, but have such small values the multimeter cannot accurately measure them.

Table 21: Boost Circuit Resistor Currents

Currents	I(R10) [A]	I(R9) [A]	I(R11) [A]
Input Voltage			
20	-0.000003	0.000385	0.000324
25	0	0.000444	0.000389
30	0	0.000503	0.000486
35	0	0.000562	0.000428
40	-0.00001	0.000585	0.00048
45	0	0.000588	0.000568
50	0	0.000588	0.000543
55	0	0.000588	0.000569
60	-0.000001	0.000588	0.000579

Since the measured data from the physical circuit matched the expected results from simulation we concluded that the issue does not lie with the components external to the LT1172 Switching Regulator [27]. After discussion with Dr. Braun, it seems either a thermal or soft start protection most likely cause the prolonged charge times. We ruled out thermal protection as the LT1172 never showed any signs in terms of temperature change, but remained cool and not warm. The datasheet for the LT1172 mentions soft-starting as one of the functions of the V_C pin and a product of the capacitor coupled external clamp. This leads us to believe that the limitations due to soft-starting cause the boost circuit output to take so long to reach its final value.

Voltage Limiting Circuit

The data presented in the Data section above shows that the PMOS does not turn on when expected. Dr Braun noted that a value of 897Ω for the interfacing resistors may allow too much current to flow through the zener diode. However, after increasing the value of that resistor to reduce the current through the diode we obtained the same results as before; the PMOS still did not turn on. Table 22 below displays the results for the various test cases.

Table 22: PMOS Source-Gate Voltage with varying Interfacing Resistors

Input Voltage [V]	V_{SG} [V]: R3 = 897Ω	V_{SG} [V]: R3 = 2.17kΩ	V_{SG} [V]: R3 = 4.7kΩ
20	0.63	0.478	0.274
25	0.67	0.51	0.3
30	0.614	0.472	0.27
35	0.603	0.46	0.261
40	0.593	0.454	0.26
45	0.601	0.455	0.259
50	0.959	0.735	0.449
55	1.387	1.07	0.695
60	1.72	1.35	0.887

As shown in Table 17, and again in Table 23, the current in R3 flows from the PMOS gate to the IGBT emitter for all input voltages. Table 23 reports the measured voltages with the (+) at the IGBT emitter and the (-) at the PMOS base. Simulation showed that no current should flow through R3 until V_{SG} of the PMOS exceeds 15V, the breakdown voltage of the zener diode. By the same token, R3 should have no voltage drop across it; Figure 28 and Figure 29 show this. Increasing R3 only diminished the current.

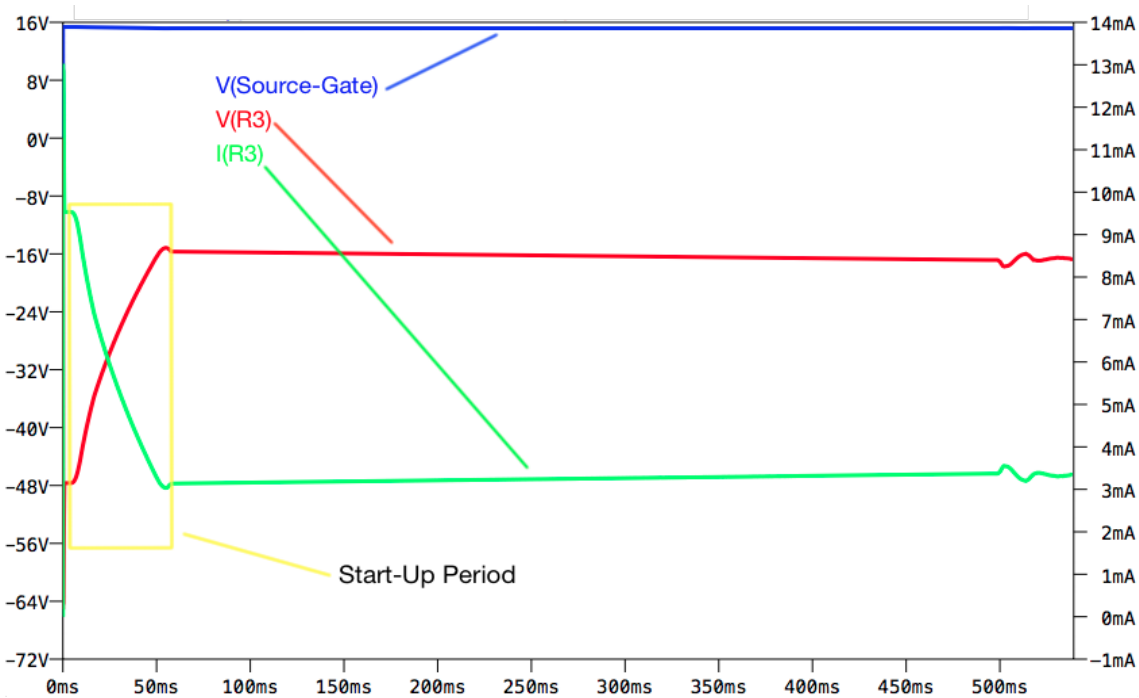

Figure 29: Expected PMOS Behavior and R_3 Voltage and Current - 80V Input

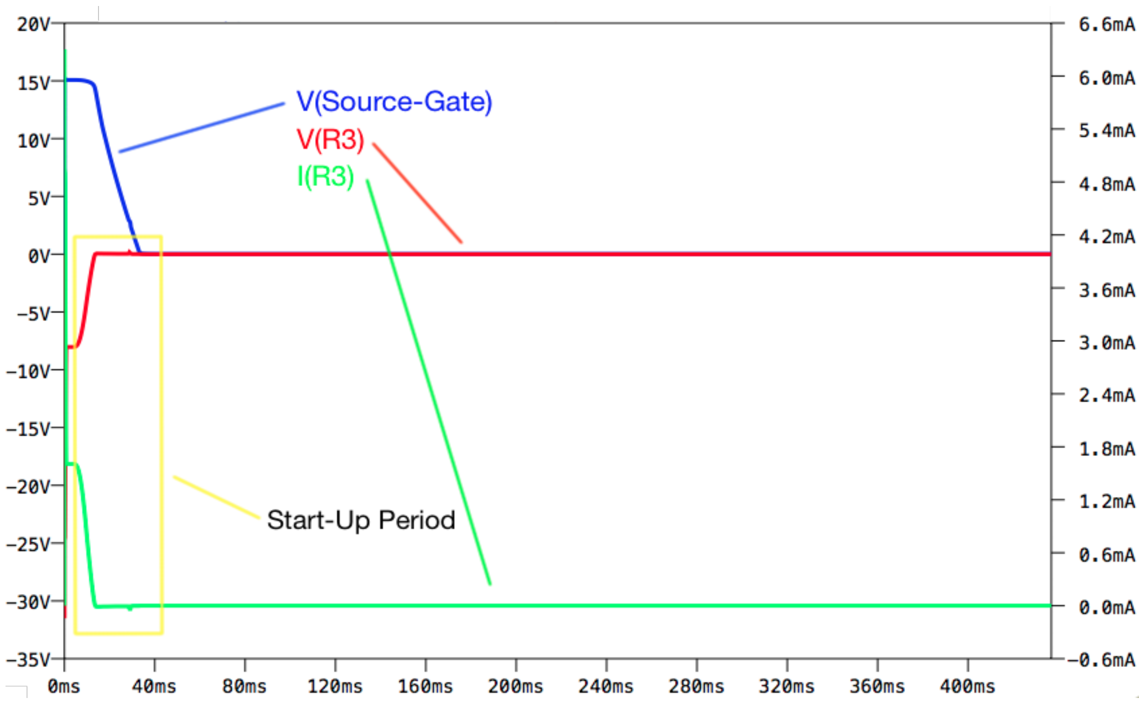

Figure 30: Expected PMOS Behavior and R_3 Voltage and Current - 40V Input

The BZX85B15 zener diode datasheet lists the reverse leakage current as less than 0.5 μA under 15V. Table 23 below indicates that the diode does not operate correctly because we see between 3 mA and 15 mA of current, even with voltages under 15V, through the resistor R3, which equals the current through the diode. Simulation, as shown above, reports no current flowing until V_{SG} rises higher than 15V.

Table 23: Reverse Diode Current

Input Voltage [V]	R3 = 897Ω		R3 = 4.7kΩ	
	V [V]	I [A]	V [V]	I [A]
20	-2.64	0.00293	-2.76	0.00059
25	-2.88	0.00320	-3.03	0.00064
30	-2.53	0.00281	-2.69	0.00057
35	-2.46	0.00273	-2.61	0.00056
40	-2.41	0.00268	-2.58	0.00055
45	-2.46	0.00273	-2.64	0.00056
50	-5.05	0.00561	-4.98	0.00106
55	-9.36	0.01040	-9.41	0.00200
60	-13.7	0.01522	-13.9	0.00296

Table 17 clearly shows that V_{SG} does not even reach the turn on voltage of the PMOS. After this troubleshooting, it appears that the zener diode on the PMOS no longer functions correctly and needs replacing before testing can continue.

Conclusion

Overall, our system succeeded at limiting the elliptical voltage to approximately four volts below the set Boost Circuit output voltage. The voltage seen on the output of the Voltage Limiting Circuit can safely pass to a DC-DC Converter that accepts voltages of 44V and above. Changing the limiting threshold only requires adjusting resistor R9 in the Boost Circuit for a higher boost output. Through many design iterations, our final design attempt proved the most robust, though it does have its own flaws. The charge up time of the Boost Circuit results in inefficiencies for the first forty seconds when attempting to limit an input voltage. The PMOS not turning on represents another flaw. If retesting with a fresh Zener diode on the PMOS does not fix the issue, a different component with a lower turn on voltage may better fit our design. In the end, we reached most of our goals from the beginning of the project of designing a protection circuit to limit input voltage and create a stable output voltage.

Chapter VII.

References

[1] R. Turner and Z. Weiler, "DC-DC Converter Input Protection System", EE Dept., San Luis Obispo, CA, 2013. Available: http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1226&context=eesp

[2] E. Funsten, C. Kiddoo, "Protection System for the Energy Harvesting from Exercise Machines Project", EE Dept., San Luis Obispo, 2014. Available: http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1275&context=eesp

[3] T. Gibson,"These Exercise Machines Turn Your Sweat Into Electricity" IEEE Spectrum, Jun. 21, 2011. [Online]. Available: http://spectrum.ieee.org/green-tech/conservation/these-exercise-machines-turn-your-sweat-into-electricity. [Accessed: Oct. 19, 2014].

[4] M. Wong, "Energy Harvesting From Exercise Machines - DC-DC Buck Boost Converter (LT3791)", Dept. Elect. Eng., California Polytechnic State Univ., 2014. Available: http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1273&context=eesp

[5] M. Lum, J. Yuen, "Energy Harvesting from Elliptical Machines: DC Converter Troubleshooting" EE Dept., San Luis Obispo, 2009. Available: http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1015&context=eesp

[6] K. Tang. "Exercise Machines That Power Your Home", Apr. 10, 2014. [Online]. Available: http://www.livestrong.com/article/418932-exercise-machines-that-power-your-home. [Accessed: Nov. 15, 2014].

[7] H. Sheng et al. "A Fault Detection and Protection Scheme for Three-Level DC–DC Converters Based on Monitoring Flying Capacitor Voltage." IEEE Trans. Power Electron., vol. 27, no. 2, pp. 685-697. Jan. 2012. Available: http://static.googleusercontent.com/media/research.google.com/en/us/pubs/archive/39976.pdf. [Accessed: Oct. 18, 2014].

[8] Linear Technology, "High Voltage Surge Stopper", LTC4366 datasheet, Aug 2013. Available: http://cds.linear.com/docs/en/datasheet/436612fd.pdf. [Accessed: Oct. 18, 2014].

[9] A. Mikolajczak, "Integrated Overdrive and Overvoltage Protection Device," 6 064 094, May 16, 2000. Available: http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&p=1&u=%2Fnetahtml%2FPTO%2Fsearch-

bool.html&r=5&f=G&l=50&co1=AND&d=PTXT&s1=Mikolajczak&OS=Mikolajczak&RS=Mikolajczak. [Accessed: Oct. 19, 2014].

[10] I. Myong, W. T. Presley, “Electrical Protection Systems,” 6 356 424, Mar., 19, 1999. Available: http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&u=%2Fnetahtml%2FPTO%2Fsearch-adv.htm&r=7&f=G&l=50&d=PTXT&p=1&S1=6356424&OS=6356424&RS=6356424. [Accessed: Oct. 19, 2014].

[11] P. M. Anderson, “Protection Measurements and Controls” in Power System Protection, New York: IEEE Press, 1998, Ch. 2, pp. 17 - 42.

[12] C. Christopoulos, A. Wright, “Overcurrent and Earth Fault Protection” in Electrical Power System Protection, Dordrecht, The Netherlands: Kluwer Academics Publisher, 1998, Ch. 4, pp. 103 – 144.

[13] Linear Technology, “LTC4362-1/LTC4362 – 1.2A Overvoltage/Overcurrent Protector,” LTC4362 Datasheet, 2010. Available: http://cds.linear.com/docs/en/datasheet/436212fa.pdf. [Accessed: Oct. 20, 2014].

[14] E. Dallago et. al. “An Interface Circuit for Low-Voltage Low-Current Energy Harvesting Systems.” IEEE Transactions on Power Electronics, 30, pp. 1411–1420, May 7, 2014.

[15] K.M. Tham. “Transient current and voltage protection of a voltage regulator.” U.S. Patent 6 246 555. September 6, 2000. Available: http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&p=2&u=%2Fnetahtml%2FPTO%2Fsearch-bool.html&r=55&f=G&l=50&co1=AND&d=PTXT&s1=6246555&OS=6246555&RS=6246555. [Accessed: Oct. 20, 2014].

[16] R. Jaeger and T. Blalock. Microelectronic Circuit Design, 4th ed. New York: McGraw-Hill, 2011.

[17] H. Al-Nasseri et al. “A voltage based protection for micro-grids containing power electronic converters,” in Power Engineering Society General Meeting. Montreal, Quebec, 2006, pp. 0-7.

[18] U.S. Energy Information Administration, *How much carbon dioxide is produced per kilowatt-hour when generating electricity with fossil fuels?*, Apr. 17, 2014. [Online]. Available: http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11. [Accessed: Nov. 23, 2014].

[19] Environmental Transport Association. (2011, December 13). CO_2 Emissions from Cycling Revealed. [Web]. Available: https://www.eta.co.uk/2011/12/13/co2-emissions-from-cycling-revealed. [Accessed: Nov. 23, 2014].

[20] “ReRev, A Renewable Energy Revolution,” *rerev.com*, 2011. [Online]. Available: http://rerev.com/default.html. [Accessed: Nov. 12, 2014].

[21] Nichicon, “General Description of Aluminum Electrolytic Capacitors,” Aluminum Electrolytic Capacitors. Available: http://www.nichicon-us.com/english/products/pdf/aluminum.pdf. [Accessed: Dec. 05, 2014].

[22] UL, “Guide Information for Electrical Equipment The White Book,” *UL.com*, 2014. Available: http://ul.com/wp-content/uploads/2014/09/UL-White-Book.pdf?utm_source=multiple&utm_medium=vanity&utm_campaign=codeauthorities whitebook. [Accessed: Dec. 05, 2014].

[23] Linear Technology, “LT1070 Design Note”, Application Note 19, Jun 1986. Available: http://cds.linear.com/docs/en/application-note/an19fc.pdf. [Accessed: Feb. 22, 2015].

[24] Newark, “NTE ELECTRONICS NTE5275A Zener Diode”, 2014. [Web]. Available: http://www.newark.com/nte-electronics/nte5275a/zener-diode-single-two-terminal/dp/31C4654. [Accessed: Feb. 22, 2015].

[25] Fairchild, “FQP17P10 P-Channel QFET® MOSFET - 100 V, - 16.5 A, 190 m”, 2013. [Web]. Available: http://www.mouser.com/ds/2/149/FQP17P10-244266.pdf

[26] Vishay, “BZX85-Series”, 2014. [Web]. Available: http://www.vishay.com/docs/85607/bzx85.pdf

[27] Linear Technology, “LT1170/LT1171/LT1172 - 100kHz, 5A, 2.5A and 1.25A High Efficiency Switching Regulators”, Datasheet, [Web]. Available: http://cds.linear.com/docs/en/datasheet/117012fg.pdf

Appendix A – Analysis of Senior Project Design

I. Summary of Functional Requirements

This project involves a voltage protection circuit as a part of the energy harvesting from exercise machines project. The energy harvester outputs voltage spikes as high as 150V [1] or more while the DC-DC converter has a max input voltage of approximately 51V. A voltage protection mechanism placed in front of the input of the DC-DC converter limits the input voltage to safe levels.

II. Primary Constraints

The challenges we anticipate encountering include: component compliance, handling high voltages, and high currents that the elliptical trainer user can generate. Component tolerances can create problems, when the ordered parts arrive and do not work or actual and nominal values range too far to work effectively in the voltage protection system design. Handling high voltages with low voltage components such as a differentiator or comparator can also prove challenging. Improperly tempered voltages can damage the VPS and therefore endanger the rest of the energy harvesting system. High currents present the same threat, and the solution works alongside voltage regulation. Another challenge in designing the voltage protection circuit comes from the need for a quick response time of 35 µs or less. Previous designs successfully accomplished the voltage protection section, but did not respond quickly enough to completely protect the DC-DC converter [2]. In addition, the design needs high power efficiency so that we do not waste power coming from the energy harvesting device.

III. Economic

Several areas of economic impact that this project has on the world consist of: human capital, financial capital, manufactured or real capital, and natural capital. This project has both positive and negative effects depending on which stakeholders' point of view you take.

Human Capital: What people do

The human capital that this project could generate includes: improvement in physical, mental, and emotional health, education of the public to the generation of electricity, public contributions to the renewable energy movement, and increased motivation to exercise.

Science has linked improvements in overall health to exercise. This project, although not explicitly an exercise device, involved in the generation of electric power via exercise equipment. Exercise releases endorphins and allows people a chance to relieve some of the stress of life in addition to the benefits of better cardiovascular and muscular health.

People do not always agree when it comes to sustainable energy. The production of this project would provide a very visible and tangible platform to inform the general populace about the generation of electric power. Creating this project would allow individuals, as well as corporations, to generate clean power on their own and contribute the effort to reduce our dependence on nonrenewable forms of energy.

This project would provide a simple way for people to create clean power at the same time as improving their health, both of which have gained significant traction with the current culture [3]. Simplifying the way people can get involved in the generation of sustainable energy increases their motivation to actually do something about the problems facing us as depletion of other sources of energy continues.

Manufactured Capital: Made by people and their tools

The “positive” capital generated by this product consists of the jobs created to design, manufacture, and assemble the components, the marketing and selling, the shipping and distribution of the completed product, and most importantly, the power generated by the user.

The “negative” capital includes potential job loss for those in the business of generating nonrenewable energy.

Financial Capital: Monetary instruments

The financial capital this project could generate consists of: conservation of natural resources, improvement of human life, and the incremental decline in the production of nonrenewable energy based equipment.

This product helps reduce the volume of natural resources used every year by decreasing the need for devices used to create nonrenewable energy and thereby their production.

Human life would benefit from this by allowing people a chance to generate their own power and sell it to power companies or to power their own appliances in their homes. This, in turn, would reduce people’s electric bill and free them to spend and invest their money elsewhere.

Natural Capital: The Earth’s resource and bio-capacity

This product aims to produce renewable electric energy and therefore yield natural capital in the forms of reduction in the usage of and dependence on nonrenewable natural resources, and improvements in air quality. Although this project cannot completely squelch our dependence on unsustainable energy, such as oil, it can help assuage the intensity of our reliance on it by creating another outlet to obtain clean energy.

Besides the emissions produced by the user, this project has zero emissions once built. However, the manufacturing unavoidably contributes to degrading air quality. Generating energy by non-renewable resources results in significantly greater emissions of carbon dioxide compared to this project. According to the U.S. Energy Information Administration [18], generating 1 kilowatt hour of energy using natural gas produces 22 pounds of CO_2. The European Cyclist Federation [19] reports that the average car produces one 271 grams (about one pound) of CO_2 per mile, while riding a bicycle for a mile produces only 34 grams. Clearly, this project contributes far less to emissions than aforementioned methods of energy generation.

Project Lifecycle Costs and Benefits:

A large part of the project’s cost comes from the time spent in design and development in the early part of its lifecycle. Designing, testing, and prototyping the product requires qualified people and their services come at a price. The next portion of the product’s cost comes from production: purchasing and assembling the components. Any real benefit comes when selling the finished product starts. The voltage protection system costs about $9,250 to design and test and $150 per unit for components and assembly.

The VPS costs $196.25, a 30.8% markup from the cost to manufacture. The design engineers and the companies supplying components benefit from this. The customers who buy the product benefit both physically and financially. Environmental groups benefit, as this presents them with another platform to advance their message of conservation. The environment benefits since the project aims to create clean, sustainable energy.

The product becomes available to buyers June 2015. The voltage protection system has a forty year lifetime. Repairs to the voltage protection system vary based on case, with a maximum cost of $180. A test of all components to determine the issue costs $30. The product goes on the market after the project ends. The Gantt Chart below shows the expected development time. See the commercial manufacturing section below for a full cost analysis and breakdown.

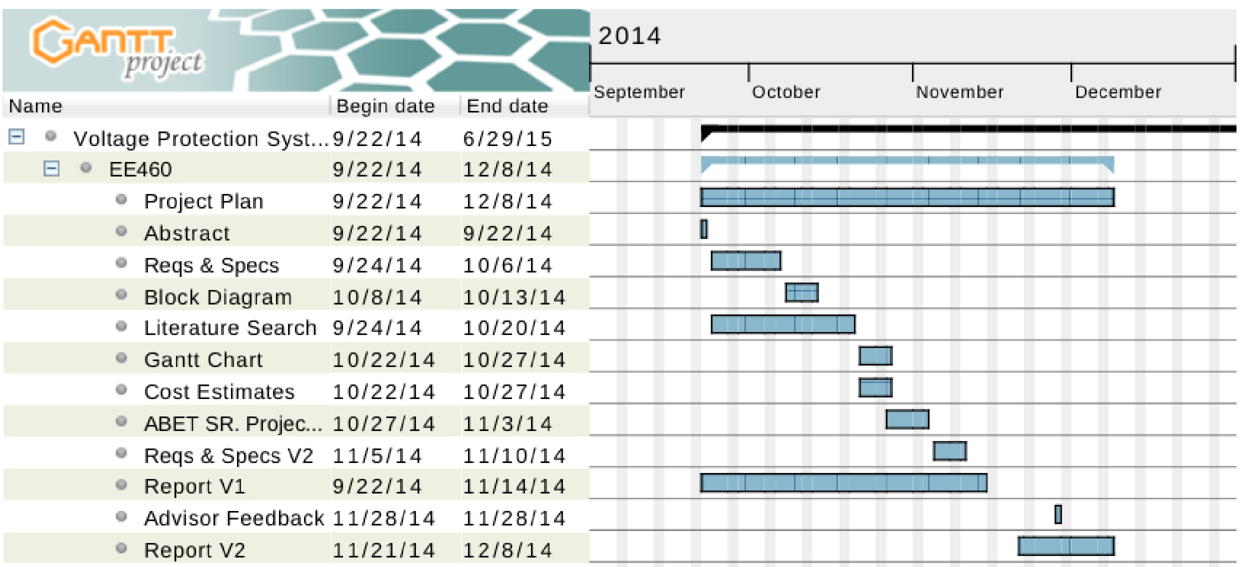

Figure 31: EE460 Gantt Chart

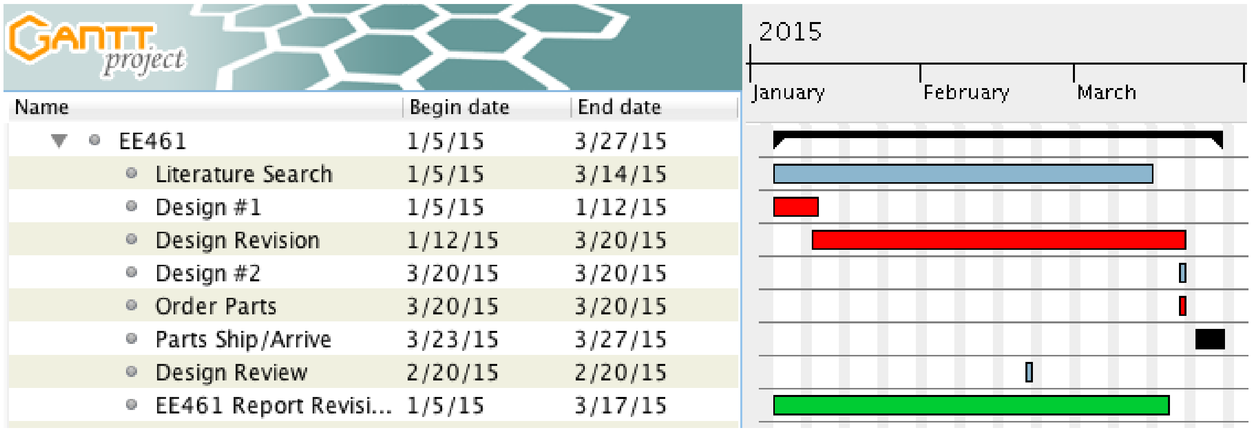

Figure 32: EE461 Gantt Chart

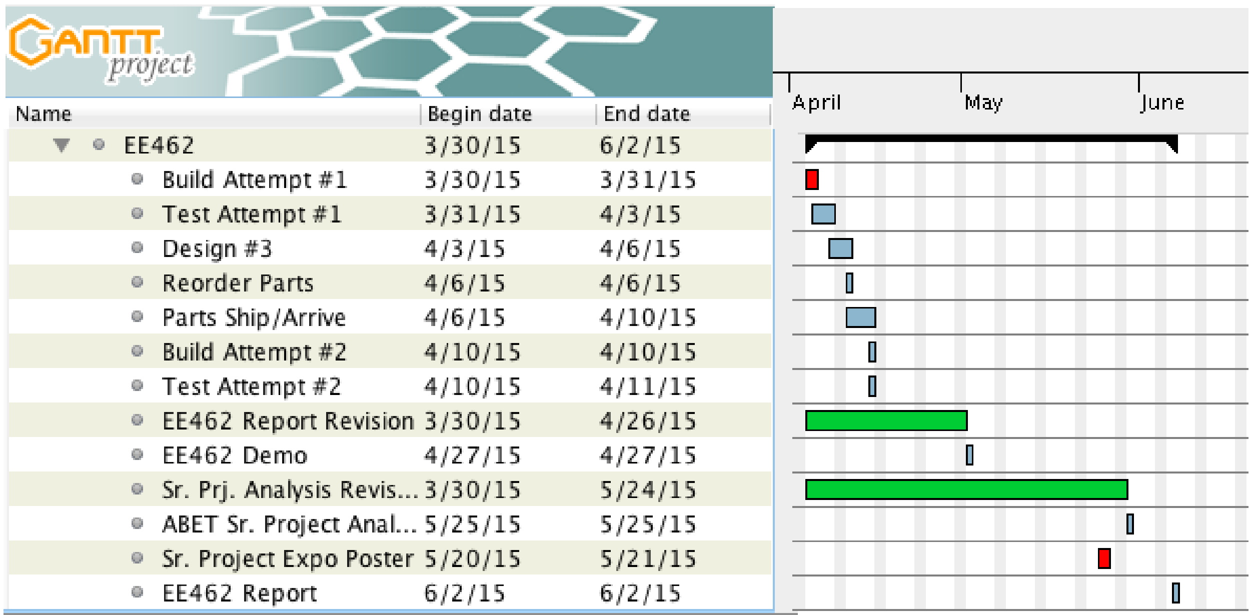

Figure 33: EE462 Gantt Chart

The tasks detailed in the Gantt Charts above (Figure 27, Figure 28, and Figure 29) required teamwork to accomplish. Calvin Xu took leadership duties with tasks colored red, while Calvin Abshier took leadership duties under green colored tasks. Blue colored tasks involved both partners equally and black indicates no necessary person specific management.

IV. Commercial Manufacturing

The initial project costs $9,250 for design and testing, and $150 for purchasing components and assembly. Design and testing costs come from labor, where if we use the PERT formula with a base cost of $30/hour, and a best case work time of 250 hours, estimated work time of 300 hours, and a worst case work time of 400 hours, labor costs $9,250. Circuit components cost $40, PCB manufacturing another $50, shipping costs $30, and assembly costs another $30. We anticipate selling between 50-100 units each year [20]. Table 20 and Table 21 give initial and adjusted cost estimates for the project with a breakdown of needed components. Producing 100 units at $150/unit and adding on the design costs of $9,250 results in a base cost of $24,250. The break-even point within a year requires 100 units to sell at $242.50/unit; break even within two years requires 200 units to sell at $196.25/unit. After that point, all sales result in net profit of $92.50/unit at the one year price or $46.25/unit at the two year price. Eventually, the total system cost of the EHFEM project must drop below $50-100.

Tables 10 and 11 include information about calculations and projections of profits. Figure 30 plots profit versus number of units sold. Taking into account current PG&E rates of $0.17/kWh, and assuming a single machine can harvest 100Wh an hour for 12 hours a day, the machine begins making a profit for the buyer in four years. Since the machine operates on generated power and the battery in the exercise machine, it should not cost the user any money to operate, outside of maintenance every five years.

We allotted $150.00 for the total assembly and component cost of the device, $20.00 for assembly, and $130.00 for components including shipping. The components required include PCBs, active and passive circuit components, and heat sinks. The cost for assembly comes from needing to solder all circuit components to the PCB and attach the heatsinks. Table 20 displays the cost estimates for the project. See Table 22 for a cost analysis and Figure 30 and Table 23 for a profitability analysis of the VPS.

Table 24: Initial Voltage Protection System Cost Estimate

Item	Cost [$]
PCB	$50.00
Resistors	$10.00
Capacitors	$10.00
Transistors	$10.00
Op-amps	$10.00
Heat sinks	$10.00
Shipping	$30.00

Table 25: Adjusted Voltage Protection Cost Analysis

Project Component	Quantity	Unit Price ($USD)	Item
Voltage Limiting Circuit	2	0.10	BZX85B15 - Zener Diode
	-	5.00	Shipping & Tax - Order # 233127431
	2	2.07	FA-T220-64E Heatsink
	1	1.13	FQP17P10 P - Channel QFET
	-	8.25	Shipping & Tax - Order # 233391371
	1	5.60	IXGP24N120C3 - IGBT
	1	2.07	FQP17P10 P - Channel QFET
	-	8.70	Shipping & Tax - Order # 2333124112
	1	-5.60	IXGP24N120C3 - IGBT Cancellation
	1	5.82	IXGP24N120C3 - IGBT
	-	11.99	Shipping & Tax Order #42709637
Boost Circuit	1	4.72	LT1072 Switching Regulator
	1	0.44	SR206 Schottky Diode
	1	2.49	811-1342-ND 150 µH Inductor
	1	0.32	445-8614-ND 1 µF Capacitor
	1	0.74	445-8455-ND 22 µF Capacitor

	1	1.45	493-1682-ND 470 µF Capacitor
	1	0.10	82 kΩ Resistor
	2	0.10	1kΩ Resistor
	-	5.86	Shipping & Tax Order #423352306
Total	**-**	**63.62**	-

Table 26: Voltage Protection Cost Analysis

Item	**Cost [$]**		**p*x=v*x+FC**	
Design and Testing	$9,250.00		p - price per unit	$196.25
Assembly	$20.00		x - number of units	200
Components	$130.00		v - variable cost	$150.00
Selling Price	$196.25		FC - fixed costs	$9,250.00

The equation in column four calculates profitability of the product based on number of sold units.

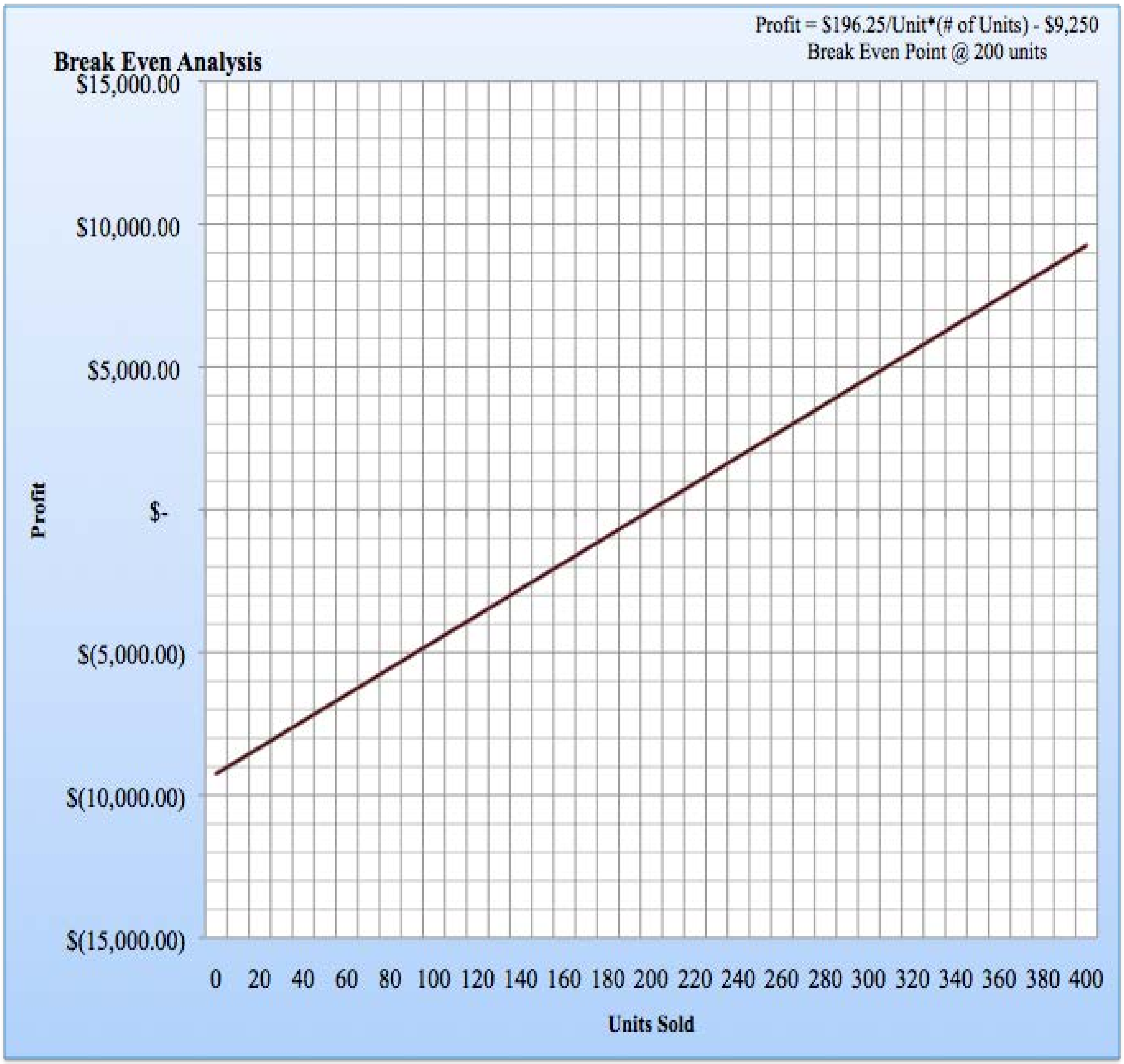

Figure 34: Voltage Protection System Profitability

Table 27: Voltage Protection System Profitability

Number of Units	Profit ($)	Number of Units	Profit ($)	Number of Units	Profit ($)	Number of Units	Profit ($)
0	9,250.00	110	4,162.50	210	462.50	310	5,087.50
10	8,787.50	120	3,700.00	220	925.00	320	5,550.00
20	8,325.00	130	3,237.50	230	1,387.50	330	6,012.50
30	7,862.50	140	2,775.00	240	1,850.00	340	6,475.00
40	7,400.00	150	2,312.50	250	2,312.50	350	6,937.50
50	6,937.50	160	1,850.00	260	2,775.00	360	7,400.00
60	6,475.00	170	1,387.50	270	3,237.50	370	7,862.50
70	6,012.50	180	925.00	280	3,700.00	380	8,325.00
80	5,550.00	190	462.50	290	4,162.50	390	8,787.50
90	5,087.50	200	0.00	300	4,625.00	400	9,250.00
100	4,625.00						

V. Environmental

This project has a direct environmental impact in helping generate renewable energy and reducing use of non-renewable energy sources. An average person generates about 100Wh per hour on a single machine, not a significant amount, but when combined with dozens of other machines, produces a significant benefit [3]. It improves the state of coal and gas usage as more energy generated from the machine means less of these resources burned. That also improves air quality and general health as fewer pollutants enter the environment. Improved air quality in general helps all species live longer and healthier and less drilling for oil helps avoid killing off wildlife.

In addition, the project directly uses natural resources such as silicon and plastics in the electrical components and indirectly other natural resources in the equipment used to build the device. People must harvest materials for the components, sometimes in manners harmful to the environment, while also reducing the total amount available on the planet. The equipment used to turn these materials into actual electrical components for us to use also require resources to design and build.

VI. Manufacturability

The largest problem with manufacturing the product itself comes from producing a large number of these devices. The PCB requires an external contractor to build but producing a single protection circuit only requires soldering components to a circuit board which takes time and effort but does not require very much skill. For larger scale orders, we can contract the building of the circuit to a manufacturer who specializes in building custom circuits. However, for small orders, we can feasibly produce the finished boards by hand.

Quality assurance presents another manufacturing challenge. A single non-functioning component can render the device useless or even cause damage to other components. Since taking the time to inspect each individual component costs more in time than the device costs monetarily, we must test the finished product for functionality. The low volume, high cost nature of the project means we cannot have a high failure rate.

VII. Sustainability

The VPS itself does not need any maintenance except for the electrolytic capacitors which degrade under use [21]. This ensures the device maintains maximum ability to generate power and feed that power back to the grid which helps conserve the planet’s natural resources. Upgrades to improve the design involve testing with more op amps with different characteristics and further tweaking the resistor and capacitor values.

However, repairing the VPS becomes challenging for somebody without substantial education of its internal workings. This requires the owner of the device to send it back to the manufacturer for repairing. The transportation back and forth of the device between the owner and manufacturer involves the usage of automobiles, trains, or planes, all of which use gasoline or other forms of non-renewable power. This impacts the sustainable use of resources.

The VPS benefits from the addition of a back-up protection system in case of unanticipated system failure. The back-up would prevent damage to the rest of the system if the VPS sustains damage and fails to safely limit the voltage sourced from the exercise equipment. This upgrade has similar associated issues as those faced by the VPS: component compliance, and dealing with high voltages and currents with low voltage and current devices.

VIII. Ethical

The ethical implications relating to the design, manufacturing, and use or misuse of this project includes: honest presentation of calculations in design, environmentally responsible attainment of materials, and indication of potential hazards associated with operation of the product.

From the ethical framework of The Golden Rule, honesty in the calculations of the design means not doctoring results to indicate perfect performance and citing references when necessary. To not abide by the guidelines set by The Golden Rule hurts both those involved with project and those who purchase and use the product. Those involved with designing it would lose credit as an engineer by skewing findings for the sake of presentation rather than honestly portraying data.

This dishonesty could damage possible future career opportunities. Glossing over design calculation errors puts those who purchase and use the equipment in danger because the VPS could not work properly and damage the exercise equipment and result in overheating. Keeping The Golden Rule in mind prevents designers from unnecessarily putting customers, as well as themselves, in danger by seeing things from their perspective.

Other ethical considerations to take into account include who performs the manufacturing process and how much should the design borrow from past projects. Ideally, paid workers should perform the labor in the manufacturing process under fair working conditions, a principle found in John Rawl's Contractarianism which states each person has rights to the most basic liberties. This also follows the IEEE Code of Ethics guideline of making decisions in favor of safety and welfare of the public and treating all persons fairly. Another ethical problem arises from using too many design elements from the previous projects. Using as much of the previous design as possible helps out our project but relying too much on previous projects' results in our project steals from the individuality of ours. The IEEE Code of Ethics advises to properly credit all contributions so we need to make sure to only use parts of the design and state which persons designed them.

IX. Health and Safety

Safety problems always exist with manufacturing, from large accidents with heavy machinery to smaller scale accidents such as touching a hot soldering iron. Soldering components also releases hazardous fumes into the air which can impact the health of people nearby. The people testing the equipment may come into contact with the high voltages generated by the device. Unfortunately, manufacturing concerns exist outside our sphere of influence and the best we can do involves actively paying attention to our work. However, protecting consumers from the end product only requires separating them from the electrical components [22], a task easily done by placing the components inside an enclosure. For most people, no safety concerns exist with using the final product as long as they do not disassemble the protective enclosure. Other injuries could occur from incorrect dismounts from the elliptical trainer or loss of footing while operating the product.

X. Social and Political

The social and political issues associated with the design, assembly, and use of this project consist of: the quality of compensation for those involved in each step of the process to create the product, method employed to obtain materials, and the creation of clean, renewable energy.

This project impacts the user, owner, the president of Cal Poly (President Armstrong), the EE department chair (Dennis Derickson), our senior project advisor (David Braun), Calvin Abshier, Calvin Xu, those involved in the construction and shipment of the components used in the design and their families, environmental groups, and those invested in the advancement of the production of nonrenewable energy.

This project impacts the user physically, emotionally and mentally, and financially. Physically, the user elevates his or her heart rate and conditions their muscular system. This physical exertion releases endorphins and absolves stress and boosts their emotional state and enhances their mental acuity. Financially, this project allows the user to generate power and sell it to power utilities and decrease their electric bill. In the same way, the owner of a gym with this equipment can benefit from the production of renewable energy through monetary savings.

This project impacts President Armstrong because the success or failure of this project paints a picture of the quality of education Cal Poly offers. A successful project improves Cal Poly's reputation.

Professor Derickson has stake in this because the outcome of this project reflects on his decisions to shape the EE curriculum.

David Braun has stake in this project due to the fact that he agreed to assist in its development and as an advisor he has responsibility for anything issues related to it.

This project impacts Calvin Xu and Calvin Abshier because we directly choose the path the project takes. We make decisions in regards to component tolerances, which standards to submit our project to, and honesty in the presentation of our work. The success of this project affects our professional reputations.

Those involved in the creation and shipment of the components in the project have investment in this project because they depend on the demand of the items they sell to make a living. Because of this dependence, their families also have a share in this project's success.

Environmental groups and groups advocating for the advancement of the generation of nonrenewable energy own a share in this project in distinct ways. Environmental groups would benefit from this project by seeing their goals of reducing the consumption of natural resources and lessening the dependence on oil as an energy source met in part. Conversely, groups involved with oil production would face a diminishing demand for their services due to an increase in electric power availability.

People want and deserve to receive a fair pay for the services they provide so it makes sense for the design engineer to receive greater pay than the person who checks the boards' connections. However, not everyone agrees upon how great to make the difference. Politicians take both sides of this debate and take action to alter or amend perceived inequalities in salary via tax breaks or tax bracketing.

People consider some methods of acquiring materials harmful to the environment. Many organizations proposing that current methodologies of extracting materials like copper and creating plastics and rubber harm our planet while others find no fault in them. That poses this project with the dilemma of choosing how it gets the necessary materials. Use of this product panders to those concerned with generating alternative sources of energy that have minimal negative impact on our world.

An inequity that this project could create relates to the price of the total energy harvesting equipment. This product costs a significant amount of money and therefore put those in lower income households at a disadvantage when it comes to purchasing. This would prevent them from the savings on electricity and the physical, emotional, and physical benefits the product creates.

XI. Development

Previous years' projects designs of the VPS go about protection simply by monitoring the voltage level the exercise equipment sources [1] [2]. We discovered a different approach: monitoring the slope of the input voltage using that to determine the occurrence of a voltage spike. The design employed a differentiator op-amp circuit in conjunction with a comparator. The differentiator would send a voltage signal, proportional to the input voltage's slope, to the comparator, which matched it to a reference voltage. The reference voltage represented an input voltage slope that exceeded a normal rate of oscillation generated by the user. When the differentiator output signal exceeded the reference voltage, the comparator outputted a zero value, indicating a dangerous voltage level.

Designing the circuit did not require very much additional knowledge but did help me refine my knowledge of using SPICE simulations, especially with PSpice software. We did learn new techniques from using Cadence OrCAD PCB Designer for the PCB design as we last used it in a first year manufacturing lab and we did not remember all the required steps. The Monte Carlo analysis of a circuit by changing all variables and component tolerances stood out as a helpful design tool; it took much more work to use than previously expected but did provide a way to figure out the best and worst case scenarios for circuit operation. For more information, see the Literature Search resources below in References.

Appendix B – Invoices:

MOUSER ELECTRONICS

Order Confirmation
Contact Name :**CALVIN ABSHIER**
Purchase Order Number :**8640599**
Order Number :**233127431**
Web Order Number :**8640599**
Customer Number :**1-9307E**

Calvin Abshier,

Thank you for placing your order with Mouser Electronics, Inc. For your reference, a summary of your order is included below.

As soon as your order is shipped, you will receive a Shipment Notification email.

If you have any questions, please reply to this email or call our Customer Service Team at 800-346-6873.

Thank you and we appreciate your business.

Internet Customer Service
Mouser Electronics, Inc.

Sales Rep	Ship Via	Terms	Order Date
Internet Customer Service	Economy Shipping	Prepaid	04/13/15

Bill To: ABSHIER, CALVIN
3797 ROLLAND DRIVE
COTTONWOOD, CALIFORNIA 96022
UNITED STATES

Ship To: CALVIN ABSHIER
256 N CHORRO ST
APT 15
SAN LUIS OBISPO, CALIFORNIA 93405
UNITED STATES

Line No.	Mouser Part Number Customer Part Number Manufacturer Part Number Description		Estimated Shipment Date(s)	Quantity	Unit Price USD	Extended Price USD
1	78-BZX85B15 BZX85B15-TR 15 Volt 1.3 Watt 2%	RoHS 1	04/13/15	1	0.100	0.10

1 RoHS: Compliant through Exemption

Shipping Notes		
	Merchandise Total USD	**$0.10**
	Shipping	**$4.99**
	8% Estimated Tax	**$0.01**

Figure 35: Invoice - 1: Order No. 233127431

MOUSER ELECTRONICS

Order Confirmation
Contact Name :**CALVIN ABSHIER**
Purchase Order Number :**8792164**
Order Number :**233391371**
Web Order Number :**8792164**
Customer Number :**1-9307E**

Calvin Abshier,

Thank you for placing your order with Mouser Electronics, Inc. For your reference, a summary of your order is included below.

As soon as your order is shipped, you will receive a Shipment Notification email.

If you have any questions, please reply to this email or call our Customer Service Team at 800-346-6873.

Thank you and we appreciate your business.

Internet Customer Service
Mouser Electronics, Inc.

Sales Rep	Ship Via	Terms	Order Date
Internet Customer Service	UPS Ground Service	Prepaid	05/19/15

Bill To: ABSHIER, CALVIN
ATTN: CALVIN ABSHIER
3797 ROLLAND DRIVE
COTTONWOOD, CALIFORNIA 96022
UNITED STATES

Ship To: CALVIN ABSHIER
Attn: CALVIN ABSHIER
256 N CHORRO STREET
APT 15
SAN LUIS OBISPO, CALIFORNIA 93405
UNITED STATES

Line No.	Mouser Part Number Customer Part Number Manufacturer Part Number Description		Estimated Shipment Date(s)	Quantity	Unit Price USD	Extended Price USD
1	588-FA-T220-64E FA-T220-64E HEATSINK FOR TO-220	1	05/19/15	1	2.070	2.07
2	512-FQP17P10 FQP17P10 100V P-Channel QFET	1	05/19/15	1	1.130	1.13

1 RoHS: Compliant

Shipping Notes

Merchandise Total USD	**$3.20**
Shipping	**$7.99**
8% Estimated Tax	**$0.26**

Figure 36: Invoice - 2: Order No. 233391371

MOUSER ELECTRONICS

Order Confirmation
Contact Name :**CALVIN ABSHIER**
Purchase Order Number :**8638575**
Order Number :**233124112**
Web Order Number :**8638575**
Customer Number :**1-9307E**

Calvin Abshier,

Thank you for placing your order with Mouser Electronics, Inc. For your reference, a summary of your order is included below.

As soon as your order is shipped, you will receive a Shipment Notification email.

If you have any questions, please reply to this email or call our Customer Service Team at 800-346-6873.

Thank you and we appreciate your business.

Internet Customer Service
Mouser Electronics, Inc.

Sales Rep	Ship Via	Terms	Order Date
Internet Customer Service	UPS Ground Service	Prepaid	04/13/15

Bill To: ABSHIER, CALVIN
ATTN: CALVIN ABSHIER
3797 ROLLAND DRIVE
COTTONWOOD, CALIFORNIA 96022
UNITED STATES

Ship To: CALVIN ABSHIER
256 N CHORRO STREET
APT 15
SAN LUIS OBISPO, CALIFORNIA 93405
UNITED STATES

Line No.	Mouser Part Number Customer Part Number Manufacturer Part Number Description		Estimated Shipment Date(s)	Quantity	Unit Price USD	Extended Price USD
1	78-BZX85B15 BZX85B15-TR 15 Volt 1.3 Watt 2%	1	04/13/15	1	0.100	0.10
2	747-IXGP24N120C3 IXGP24N120C3 24 Amps 1200V	2	06/22/15	1	5.600	5.60
3	512-FQP17P10 FQP17P10 100V P-Channel QFET	2	04/13/15	1	1.130	1.13
4	588-FA-T220-64E FA-T220-64E HEATSINK FOR TO-220	2	04/13/15	1	2.070	2.07

1 RoHS: Compliant through Exemption

2 RoHS: Compliant

Shipping Notes

Merchandise Total USD	**$8.90**
Shipping	**$7.99**
8% Estimated Tax	**$0.71**

Figure 37: Invoice - 3: Order No. 2333124112

MOUSER ELECTRONICS

Order Cancellation Notification
Purchase Order Number :**8638575**
Web Order Number :**8638575**
Contact Name :**CALVIN ABSHIER**
Order Date :**APR 13, 2015**
Customer Number :**1-9307E**

Calvin Abshier,

Purchase order number 8638575 has been cancelled. For your reference, a summary of the cancelled order is included below.

If you have any questions, or if you need assistance placing a new order, please reply to this email or call our Customer Service Team at 800-346-6873.

Thank you and we appreciate your business.

Customer Service and Sales

Please direct inquiries to:
Mouser Electronics, Inc.
Phone: 800-346-6873
orders@mouser.com

Office Hours:
7:00am to 8:00pm (Monday - Friday)

Customer Service Representative	Shipping Method	Terms
Internet Customer Service	UPS Ground Service	Prepaid

Bill To ABSHIER, CALVIN
Attn: CALVIN ABSHIER
3797 ROLLAND DRIVE
COTTONWOOD, CALIFORNIA 96022
UNITED STATES

Ship To CALVIN ABSHIER
256 N CHORRO STREET
APT 15
SAN LUIS OBISPO, CALIFORNIA 93405
UNITED STATES

Line Number	Mouser Part Number Customer Part Number Manufacturer Part Number Description	Quantity	Status
2	747-IXGP24N120C3 IXGP24N120C3 24 Amps 1200V	1	Cancelled

Figure 38: Invoice - 3 Cancellation: Order No. 2333124112

www.digikey.com
Orders 1-800-344-4539
Fax 218-681-3380

Invoice # 49693981
U.S. $

701 Brooks Ave. South, Thief River Falls, MN 56701-0677 USA

Sold To:
CUSTOMER 8210524
CALVIN XU
1869 CANYON CIRCLE DRIVE
SAN LUIS OBISPO CA 93410-0000

Bill To:
CALVIN XU
1908 LOCKWOOD AVE
FREMONT CA 94539-0000

Terms	Invoice Date	Page
Visa	1-JUN-2015	1

Customer Purchase Order	Sales Order
	43162825

Back Orders	Account
Accepts to 30-JUN-2015	2535186

Entered By / Date	Shipped Via	Ship Date
AUTO/31-MAY-2015	FC	1-JUN-2015

Easy to Remember:
1-800-DIGI-KEY

For Office Use Only	Received	VAT/Tax ID	Billing	Pack List No.	Printing Date	Currency Type:	MISC #
	INTERNET		BILL SHIP	1	1-JUN-2015	U.S. $	0

Idx	Box	Ordered	Cancelled	Shipped	Item Number/Description	Back Order	Unit Price US $	Amount US $
1	1	1	0	1	LT1172CN8#PBF-ND IC REG MULTI CONFIG ADJ 8DIP HTSUS: 8542.39.0000 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2014 COUNTRY/ORIGIN: MALAYSIA		4.72000	4.72 T
2	1	1	0	1	SR206-TPCT-ND DIODE SCHOTTKY 60V 2A DO41 HTSUS: 8541.10.0080 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2014 COUNTRY/ORIGIN: CHINA CAGE: 374W0		.44000	.44 T
					BOX 1 SHIPPED FC WEIGHT 0 LBS 6 OZS (0.17 KG) BOX ID 9200190106460314098568			
					TOTAL INVOICED			5.16
					SHIPPING CHARGES APPLIED			3.14
					** CHARGES SUBTOTAL **			8.30
					SALES TAX			.41
					(T INDICATES TAXABLE AMOUNTS)			
					TOTAL CHARGED TO CREDIT CARD			8.71 U.S. $$
					YOUR CREDIT CARD HAS BEEN CHARGED THE ABOVE INDICATED AMOUNT THE ORDER IS COMPLETE			
				Ship To:	CALVIN XU 1869 CANYON CIRCLE DRIVE SAN LUIS OBISPO CA 93410-0000			
				Ship From:	DIGI-KEY 701 BROOKS AVE. SOUTH P.O. BOX 677 THIEF RIVER FALLS MN 56701-0677			
				General -	WEB ORDER ID: 146327070			

Figure 39: Invoice - 4: Order No. 43162825

Digi-Key CORPORATION

www.digikey.com
Orders 1-800-344-4539
Fax 218-681-3380

Invoice # 49188873
U.S. $

701 Brooks Ave. South, P.O. Box 677, Thief River Falls, MN 56701-0677 USA

Sold To:
CUSTOMER 8305094
CALVIN ABSHIER
256 N CHORRO ST APT 15
SN LUIS OBISP CA 93405-0000

Bill To:
CALVIN A ABSHIER
3797 ROLLAND DRIVE
COTTONWOOD CA 96022-0000

Terms	Invoice Date	Page
Visa	13-APR-2015	1

Customer Purchase Order	Sales Order
	42709637

Back Orders	Account
Accepts to 13-MAY-2015	2507906

Entered By / Date	Shipped Via	Ship Date
A0FX/13-APR-2015	XGT	13-APR-2015

Easy to Remember:
1-800-DIGI-KEY

For Office Use Only	Received	VAT/Tax ID	Billing	Pack List No.	Printing Date	Currency Type:	MSC #
	INTERNET		BILL SHIP	1	13-APR-2015	U.S. $	0

Idx	Box	Ordered	Cancelled	Shipped	Item Number/Description	Back Order	Unit Price US $	Amount US $
1	1	1	0	1	IXGP24N120C3-ND		5.82000	5.82 T
					IGBT 1200V 48A 250W TO220			
					HTSUS: 8541.29.0095 ECCN: EAR99			
					LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2014			
					COUNTRY/ORIGIN: SOUTH KOREA			
					CAGE: D1794			
					BOX 1 SHIPPED XGT WEIGHT 0 LBS 6 OZS (0.17 KG)			
					BOX ID 012606078828666			
					TOTAL INVOICED			5.82
					SHIPPING CHARGES APPLIED			11.52
					** CHARGES SUBTOTAL **			17.34
					SALES TAX			.47
					(T INDICATES TAXABLE AMOUNTS)			
					TOTAL CHARGED TO CREDIT CARD			17.81
								U.S. $$
					YOUR CREDIT CARD HAS BEEN CHARGED THE ABOVE INDICATED AMOUNT			
					THE ORDER IS COMPLETE			
				Ship To:	CALVIN ABSHIER			
					256 N CHORRO ST APT 15			
					SN LUIS OBISP CA 93405-0000			
				Ship From:	DIGI-KEY CORPORATION			
					701 BROOKS AVE. SOUTH			
					P.O. BOX 677			
					THIEF RIVER FALLS MN 56701-0677			
				General -	WEB ORDER ID: 136754063			

Figure 40: Invoice - 5: Order No. 42709637

Digi-Key CORPORATION

www.digikey.com
Orders 1-800-344-4539
Fax 218-681-3380

Invoice # 48788642
U.S. $

701 Brooks Ave. South, P.O. Box 677, Thief River Falls, MN 56701-0677 USA

Sold To: CUSTOMER 8209844
CALVIN XU
1908 LOCKWOOD AVE
FREMONT CA 94539-0000

Bill To:
CALVIN XU
1908 LOCKWOOD AVE
FREMONT CA 94539-0000

Terms	Invoice Date	Page
Visa	9-MAR-2015	1

Customer Purchase Order	Sales Order
	42352306

Back Orders	Account
Accepts to 7-APR-2015	2486092

Entered By / Date	Shipped Via	Ship Date
A0FX/ 8-MAR-2015	PM	9-MAR-2015

Easy to Remember: 1-800-DIGI-KEY

For Office Use Only	Received	VAT/Tax ID	Billing	Pack List No.	Printing Date	Currency Type	MSC #
	INTERNET		BILL SHIP	1	9-MAR-2015	U.S. $	0

Idx	Box	Ordered	Cancelled	Shipped	Item Number/Description	Back Order	Unit Price US $	Amount US $
1	1	1	0	1	1N5818DICT-ND DIODE SCHOTTKY 30V 1A DO41 HTSUS: 8541.10.0080 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED JUN-2014 COUNTRY/ORIGIN: TAIWAN CAGE: 12060		.44000	.44 T
2	1	1	0	1	811-1342-ND FIXED IND 150UH 4A 69 MOHM TH HTSUS: 8504.50.4000 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED JUL-2011 COUNTRY/ORIGIN: CHINA CAGE: 50721		2.49000	2.49 T
3	1	1	0	1	LM339NFS-ND IC COMPARATOR QUAD 14-DIP HTSUS: 8542.39.0000 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2013 COUNTRY/ORIGIN: CHINA CAGE: 07263		.48000	.48 T
4	1	3	0	3	IRL530NPBF-ND MOSFET N-CH 100V 17A TO-220AB HTSUS: 8541.29.0095 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2014 COUNTRY/ORIGIN: PHILIPPINES CAGE: 59993		1.66000	4.98 T
5	1	1	0	1	1N5369BGOS-ND DIODE ZENER 51V 5W AXIAL HTSUS: 8541.10.0050 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2013 COUNTRY/ORIGIN: CHINA CAGE: 5V1P1		.53000	.53 T
6	1	4	0	4	IRF510PBF-ND MOSFET N-CH 100V 5.6A TO-220AB HTSUS: 8541.29.0095 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2011 COUNTRY/ORIGIN: CHINA		.96000	3.84 T
7	1	1	0	1	445-8614-ND CAP CER 1UF 16V 10% RADIAL HTSUS: 8532.24.0060 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP COUNTRY/ORIGIN: CHINA CAGE: 1XFM7		.32000	.32 T

Figure 41: Invoice - 6: Order No. 42352306

Digi-Key CORPORATION

www.digikey.com
Orders 1-800-344-4539
Fax 218-681-3380

Invoice # 48788642
U.S. $

701 Brooks Ave. South, P.O. Box 677, Thief River Falls, MN 56701-0677 USA

Sold To:
CUSTOMER 8209844
CALVIN XU
1908 LOCKWOOD AVE
FREMONT CA 94539-0000

Terms	Invoice Date	Page
Visa	9-MAR-2015	2

Customer Purchase Order	Shipped Via
	PM

Easy to Remember:
1-800-DIGI-KEY

Idx	Box	Ordered	Cancelled	Shipped	Item Number/Description	Back Order	Unit Price US $	Amount US $
8	1	1	0	1	445-8455-ND CAP CER 22UF 16V 20% RADIAL HTSUS: 8532.24.0060 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP COUNTRY/ORIGIN: CHINA CAGE: 1ZFM7		.74000	.74 T
9	1	1	0	1	1285PH-ND CAP CER 470PF 1KV 10% RADIAL HTSUS: 8532.24.0060 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2011 COUNTRY/ORIGIN: CHINA CAGE: 56699		.24000	.24 T
10	1	1	0	1	1251PH-ND CAP CER 1000PF 1KV 10% RADIAL HTSUS: 8532.24.0060 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2011 COUNTRY/ORIGIN: CHINA CAGE: 56699		.25000	.25 T
11	1	1	0	1	490-8923-ND CAP CER 0.47UF 250V 10% RADIAL HTSUS: 8532.24.0060 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP COUNTRY/ORIGIN: JAPAN		.75000	.75 T
12	1	1	0	1	1273PH-ND CAP CER 220PF 1KV 20% RADIAL HTSUS: 8532.24.0060 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2011 COUNTRY/ORIGIN: CHINA CAGE: 56699		.29000	.29 T
13	1	1	0	1	493-1682-ND CAP ALUM 470UF 100V 20% RADIAL HTSUS: 8532.22.0020 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED JUN-2014 COUNTRY/ORIGIN: JAPAN CAGE: 55680		1.65000	1.65 T
14	1	1	0	1	LT1072CN8#PBF-ND IC REG MULTI CONFIG ADJ 8DIP HTSUS: 8542.39.0000 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2013 COUNTRY/ORIGIN: MALAYSIA CAGE: 64155		4.72000	4.72 T
					BOX 1 SHIPPED PM WEIGHT 0 LBS 13 OZS (0.37 KG) BOX ID 9205590106460313041223			
					TOTAL INVOICED			21.72
					SHIPPING CHARGES APPLIED			5.86
					** CHARGES SUBTOTAL **			27.58
					SALES TAX			1.74
					(T INDICATES TAXABLE AMOUNTS)			
					TOTAL CHARGED TO CREDIT CARD			29.32 U.S. $$
					YOUR CREDIT CARD HAS BEEN CHARGED THE ABOVE INDICATED AMOUNT THE ORDER IS COMPLETE			

Figure 42: Invoice - 7: Order No. 42352306