THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ELECTRICAL ENGINEERING

NON-LINEAR INPUT IMPEDANCE FOR ENERGY HARVESTING BACKPACK

STEPHEN SUFFIAN
Spring 2010

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Electrical Engineering
with honors in Electrical Engineering

Reviewed and approved* by the following:

Heath Hoffman
Associate Professor of Electrical Engineering
Thesis Advisor

Ken Jenkins
Department Head of Electrical Engineering

Timothy Kane
Professor of Electrical Engineering
Honors Advisor

* Signatures are on file in the Schreyer Honors College.

ABSTRACT

The following paper investigates the efficiency of the power circuit of an energy harvesting backpack. The backpack is a spring-mass system that, with an 80 lb load, can generate over 10 Watts with normal walking gait. A 2 Hz, 5 cm, sinusoid was used for the physical excitation of the backpack in order to simulate typical walking. This mechanical energy is transferred through the spring-mass system to a brushless AC motor, which connects to a power conditioning circuit. This circuit allows for easy transfer of energy to batteries or other electronic loads. The following thesis analyzes the efficiency of the electrical circuit's previously set 10 Ω emulated load, which is accomplished through current regulation in the input inductor of the circuit's main SEPIC converter. It then seeks a more efficient, non-linear emulated load through theoretical analysis and empirical testing. Several piece-wise functions were experimentally tested to see if electrically disconnecting the power conditioning circuit at certain low voltages could improve backpack power output and efficiency. This thesis also shows experimental results for efficiency and power output of the non-linear load technique.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank Dr. Heath Hofmann for including me in his exciting research. He has been extremely helpful in everything from improving my understanding of power electronics to his timely thesis draft edits. I have learned a significant amount about the research process, which will help in my future ventures in graduate school. I would also like to thank Cheng Luo, who helped me with the implementation and design of the improved circuitry. His help in debugging the backpack circuit when necessary was invaluable in keeping my research moving. I would also like to thank Kai He for his help in testing the backpack.

Chapter 1: Literary Review of Piezoelectric and Electromechanical Energy Harvesting Systems

Several methods of human-based energy harvesting techniques are currently being investigated. Each of these approaches is designed with varying methods and with unique purposes, both of which are defined based upon the intended consumers of that product. The three most common forms are piezoelectrics, ambient biometrics, and deliberate biometrics. A major design consideration of the backpack is that of harvesting energy that is already being exerted, and therefore the following examples will focus on piezoelectrics and ambient biometric energy harvesting.

A paper written by G. Poulin et al. further explores the differences between piezoelectric and electromechanical energy harvesting applications.[i] In order to more easily compare these two systems, they simplify the electromechanical system of a magnetic linear generator to that of a spring-mass system. They then translate both this spring-mass system and the PZT ceramic bar into equivalent electrical circuits. Each electrical circuit is composed of a complex impedance, modeled by a transformer and a capacitor. This simplification allows for easy comparison of parameters such as resonant frequency, optimal loads, and power graphs.

What they initially discover is that both systems have similar power graph shapes. Many of the other parameters, however, are orders of magnitude different from each other. Therefore, it is discovered that the effectiveness of the overall system is largely dependent on the energy-harvesting application. They find that piezoelectrics, with a much higher energy density, are more appropriate for microsystems. They have very small displacement, allowing them to harvest energy in several locations that other electromechanical systems could not exist. Piezoelectrics maximize their generated power both at high resonance frequencies and at very high optimal load impedances, meaning that they have high voltages with very little current output.

Electromagnetic systems have maximum power at much lower resonance frequencies and with much lower optimal load impedances. Their resonance is on the order of Hertz, and their output consists of relatively low voltage and high current. Furthermore, the exact values of voltage and current are adjustable for electromagnetic systems, as they are based on the amplitude of the spring in the system. The major constraint for these systems is its lower energy density. A much larger area must be used, and there must be a much greater displacement, for a given amount of power.

For the purposes of the backpack, where energy is harvested from human gait, the electromagnetic system is a much better choice. The system has been designed so that the resonance is on the same order as the frequency of walking (2 Hz). Furthermore, the backpack allows for a large displacement, allowing for the efficient use of such a system. Several other applications, such as low-power wireless sensors and biomedical devices, would much better utilize a piezoelectric system. A few of those being investigated will be described in this section.

Piezoelectric Energy Harvesting Examples

Piezoelectric materials produce electric potential when a mechanical stress is applied. They are best used in powering small body sensors or providing power to very low-power electronic devices. Several points on the body have been discovered to have the ability to use previously wasted mechanical stress, in conjunction with piezoelectric devices, to generate usable quantities of power. The most traditional of these methods is that of the piezoelectric shoe device. Several variations have been investigated. Alberto Villarreal, an industrial designer from Mexico City, designed *BrightWalk*, which uses a combination of piezoelectrics and electroluminescent polymers to translate walking energy into usable light for nighttime jogs.[ii] Safety lighting can exist with very low amounts power, making this a viable application of piezoelectrics. Other entities have looked into this method, but with much greater power needs.

The applied research, technology, and sensory branch of the Space and Naval Warfare Systems Center San Diego, funded by DARPA, looked into harvesting energy from the boots of soldiers in the armed forces. A US Navy press release in 2003 indicated that two physicists, Bill McKnight and Wayne McGinnis, calculated that there was the potential of approximately 5 Watts of power for the average 150-pound individual.[iii] Unfortunately, the realization of this product has been plagued by low system efficiency, as well as discomfort to the user in attempts to increase input power.

A similar design for the same purpose, researched by the US Army Power Division, concluded in a similar fate. Their design, called the “Heel Strike,” utilizes a screw that is pushed down, rotating a gear. On this gear is a cam that produces a sinusoidal deflection of a piezoelectric material.[iv] The translation of linear to rotational to electric energy is loosely similar to that of the backpack circuit, making it a potentially helpful study to research. The output of the piezoelectric device is a high frequency sinusoidal signal, so a power conditioning circuit is included in order to produce usable DC battery charging energy. After experiments were conducted, it was found that this device only produced 90 mW, well below their target goal of 0.5 W.

Jonathon Granstom of Michigan Technological University has looked into using the straps of a soldier or healthcare workers backpack, which receives strain from its load, to generate energy by constructing the straps with piezoelectric materials.[v] This system generates energy on the same magnitude as the previously investigated piezoelectric designs, but has the advantage of avoiding the possibility of discomfort to the user. The straps are similar in material to existing nylon straps, and therefore generate energy that is truly being lost. They found that the greatest power output could be achieved by using a single strap that runs through the backpack frame and creates a single loop. However, in order to be able to hold their test load of 444 N, four straps in parallel were used to generate experimental data. By placing the straps in parallel, they also decrease the already high voltage that PVT's generate. They found that the straps generated a mean power of 45.6 mW over the duration of the simulation.

Electromechanical Energy Harvesting Examples

In order to achieve usable amounts of power for uses that require power on the order of magnitude of typical battery capabilities, electromagnetic systems have been used for human energy harvesting. One system of interest addresses the issue of having to design energy harvesting systems to resonance. In any mechanical system, the greatest efficiency occurs at resonance. The frequency of human gait is difficult to predict, and can vary greatly, making it very difficult to design systems that are dependent on running at their resonant frequency. C.R. Saha of the University of Ireland designed a small device that utilizes a magnetic spring system rather than a mechanical system, to provide better efficiency at off-resonant frequencies. His device is the size of a AA battery, and therefore generates energy on similar orders of magnitude to energy harvesting system that utilize piezoelectric materials. In this research, it was discovered that the higher damping losses of the magnetic spring system caused a lower power output than that of a similar traditional spring system of similar size. Despite these unfortunate results, the concept may be useful in future backpack design iterations.

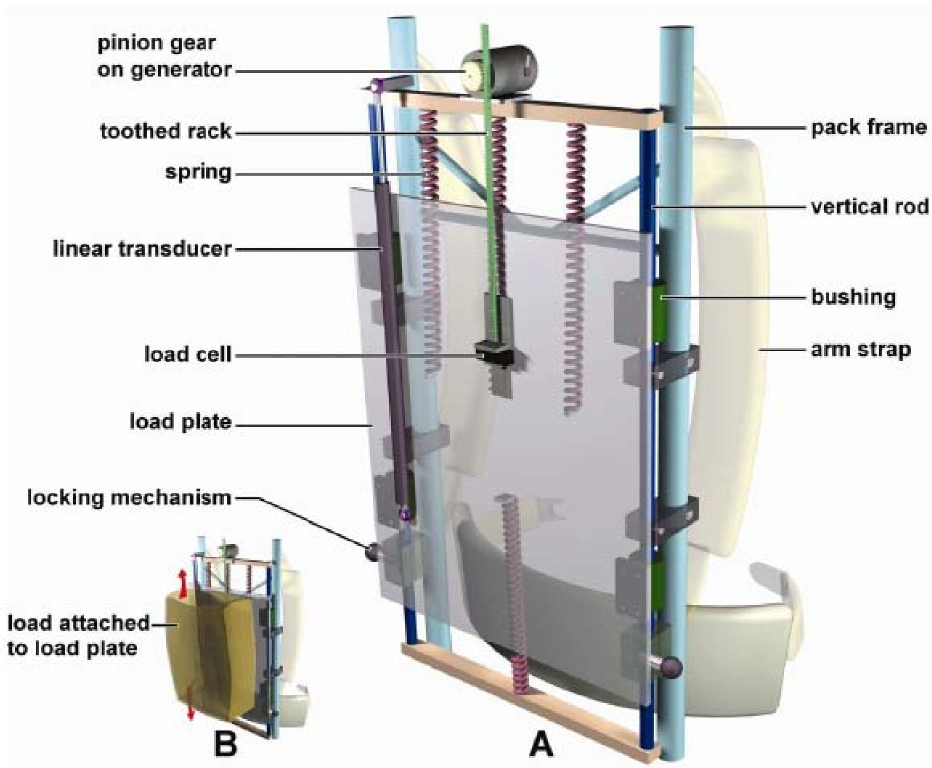
The knee-brace system, currently being developed by Dr. Donelan of Simon Fraser University, is the closest viable alternative to the energy harvesting backpack, both in design and power output. It has been known to produce approximately 5 Watts of power, significant enough to charge low-power devices and batteries.[vi] It was designed for powering prosthetic limbs and biomedical devices. The positive ergonomic effects and small size of this device make it ideal for such applications. They couple a mechanical generator to leg motion both during the acceleration and deceleration phase of each stride. It is calculated that the "cost of harvesting," a ratio between metabolic and electrical power, is lower than in conventional energy harvesting methods, such as in shoe-based harvesting. Also, it is proposed that in only harvesting energy during the deceleration portion of walking; the knee-brace would act similarly to a regenerative breaking system in a car. It would harvest about half as much power, but would also significantly reduce the increased metabolic load on the user that any harvesting technique typically produces.

Chapter 2: Observations and Preliminary Investigation

Most modern energy harvesting systems include the use of piezoelectric material. While the advance in this material has allowed for its ability to generate acceptable power in certain applications, it is limited by its physical characteristics from harvesting significant amounts of power from a system. The energy harvesting backpack instead uses traditional magnetic-field-based devices to harvest energy, allowing for the potential of significant amounts of power to be generated through normal human activity.

The energy harvesting backpack is designed based on the weight in the pack as the mass in a traditional spring-mass system. The current application of this backpack is for soldiers, who carry backpacks of approximately 91 pounds during normal operation.[vii] This is a significant weight that, when effectively used in a spring-mass system, can generate amounts of power greater than that of other current energy harvesting systems. When this system is excited at or near resonant frequency by the natural gait of the wearer, it causes displacement in the spring.[viii] A toothed rack attached to the frame rotates a pinion gear, which is in turn connected to an AC magnetic generator. A model of this system is shown below in Figure 1.

Figure 1: Representative backpack energy harvesting system, image copyright AAAS



The signal is rectified through a full-bridge rectifier. This rectified signal then enters the power-conditioning circuit. This circuit is composed of several SEPIC converters that take the rectified signal and output DC voltages. A SEPIC converter was chosen because the input voltage can be either higher or lower than the output voltage. Furthermore, the inductor at the input of the converter allows for easy input current regulation.

The main SEPIC converter outputs the bus voltage, which charges several ultra-capacitors. The ultra-capacitors act as a temporary storage device before the energy can be transferred to external devices. There are currently output terminals for military-grade battery and an emergency load resistor. The battery used in the following experiments is the BB-2590, which requires approximately 16.5 Volts to charge. The circuit was designed so that the bus voltage at the output of the SEPIC converter maintains this voltage in normal operation. The 5 Ω load resistor removes any excess energy that the backpack generates in case the battery is fully charged or disconnected.

The existing circuit controls the current so that the backpack at all times emulates a 10Ω resistive load. The SEPIC converter is controlled by a PWM signal. This signal is developed from comparing the current signal to a reference signal that is a fraction of the input voltage. In order to be able to tune the circuit, a 100 kΩ potentiometer is used to determine the exact proportionality. 10 Ω was decided upon as the proper balance between providing ergonomic benefits to the user and optimizing the circuit efficiency. The input voltage to the circuit is a function of the backpack speed. Therefore, with a constant resistance, the input current is linearly proportional to this speed. This has been previously shown to be more efficient then either a constant input current or voltage.

The following paper investigates the efficiency of the 10 Ω emulated load, as well as seeks a more efficient, non-linear emulated load. It also shows experimental results for efficiency and power output of a non-linear load technique that resulted from circuit observation.

Control of Input Current through Current Command Signal

In order to properly model the efficiency curve of the power conditioning circuit, a DC power supply was used as the input instead of the backpack. The power supply allows for iterating through each potential voltage that the backpack could see in normal operation. In order to iterate also through various input current values, the resistive load value that the circuit emulates had to be controlled. This was achieved through alterations to the current command signal in the circuit.

In the most recent design of the backpack circuit, the current is regulated through the use of two operational amplifiers. The first op-amp uses the voltage across a .1 Ω current sensing resistor at the input of the circuit to create a scaled current signal, $V_{I,actual}$ shown below.

$$V_{I,actual} = V_{middle} - .5 * V_{in}$$

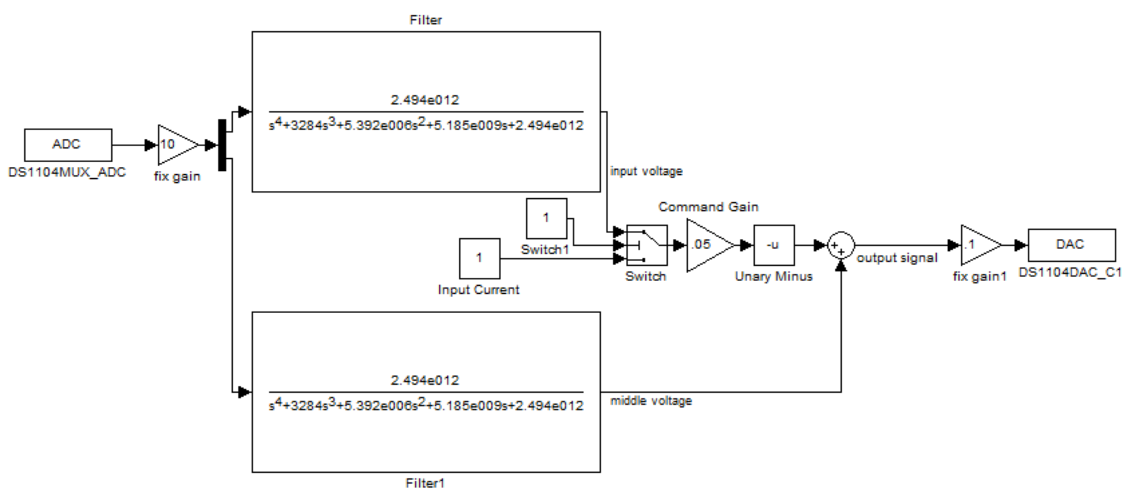
$$V_{I,reference} = V_{middle} - .05 * V_{in}$$

$$R_{emulated} = \frac{.5 * V_{in}}{.05 * V_{in}} = 10$$

V_{middle} is a voltage signal that is exactly half of the circuit supply voltage of 11 Volts. Its proximity to 5 Volts makes V_{middle} useful for powering several of the integrated circuits. V_{in} is the half-wave rectified input voltage generated from the backpack. The second op-amp creates a current command signal, $V_{I,reference}$, that the actual current signal is referenced to, shown above. In present use, the circuit emulates a 10 Ω resistive load. Two different methods could be used to alter this proportionality. The simplest is to adjust the 100 kΩ potentiometer, already built into the circuit to allow for fine-tuning of the emulated load, to alter the resistance. This method is simple to employ, as it involves nothing more than a screwdriver to turn the potentiometer. Unfortunately, it would be impossible to utilize for the testing of non-linear voltage-current relationships when the circuit is connected to the backpack. If the voltage and current are not linearly proportional, the load will emulate different resistance values depending on the input voltage. This can be best shown in Table 1. A square-root proportionality is compared with the existing linear proportionality. The last column shows the different loads that the circuit emulates at different input voltages. The circuit needs to be able to dynamically change its emulated resistance in time with the input voltage. The initial experiment of optimizing the efficiency of the circuit at each current and voltage level with a DC power supply could have been employed through simply altering the potentiometer; however, the eventual testing with the backpack needs a different method to alter the value of the emulated load.

The other method is for the $V_{I,reference}$ signal to be generated from an alternative source. As was previously described, the input current is regulated by comparing it to a reference signal. The control circuit acts to minimize the error between these two signals. In order to control the input current, this reference signal was disconnected from the control circuit and was instead generated using a computer. A Matlab Simulink file was created, which can be seen below in Figure 2. The input and output blocks of this code correspond to input and output pins on a physical dSpace DAQ card. Matlab uses the Matlab real-time workshop to translate this Simulink code into C-code that can be used by a different software program, ControlDesk. ControlDesk acts as a real-time user interface that enables the Simulink code to be employed onto the dSpace card.

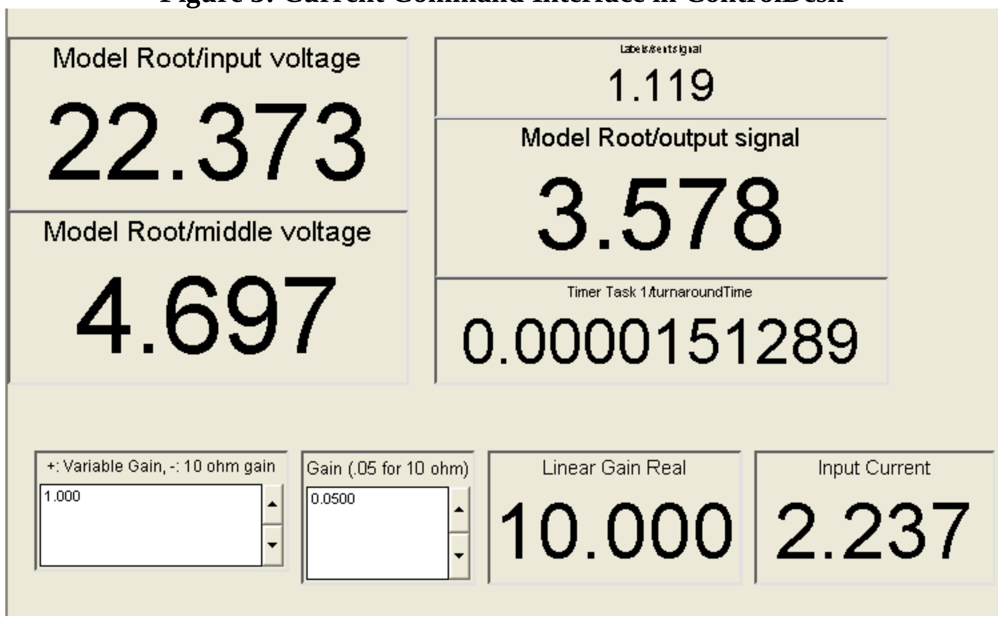
Figure 2: Current Command Code in Simulink



The Simulink file filtered the signal using a 4th order Butterworth low-pass filter generated from Matlab. A switch, controlled by a constant value, was used to toggle between normal circuit operation and altered current commands. In normal operation, the Simulink file performs the same actions as the on-board command circuitry. It takes V_{in}, scales it by .05, and then subtracts it from V_{middle}, identical to the previously stated equation. When the switch is activated, the "input current" constant then allows the user to control the current command. After creating this Simulink file, it is generated into C-code and sent to the ControlDesk program, which is the active interface for the dSpace card. This interface is shown below in

Figure 3.

Figure 3: Current Command Interface in ControlDesk

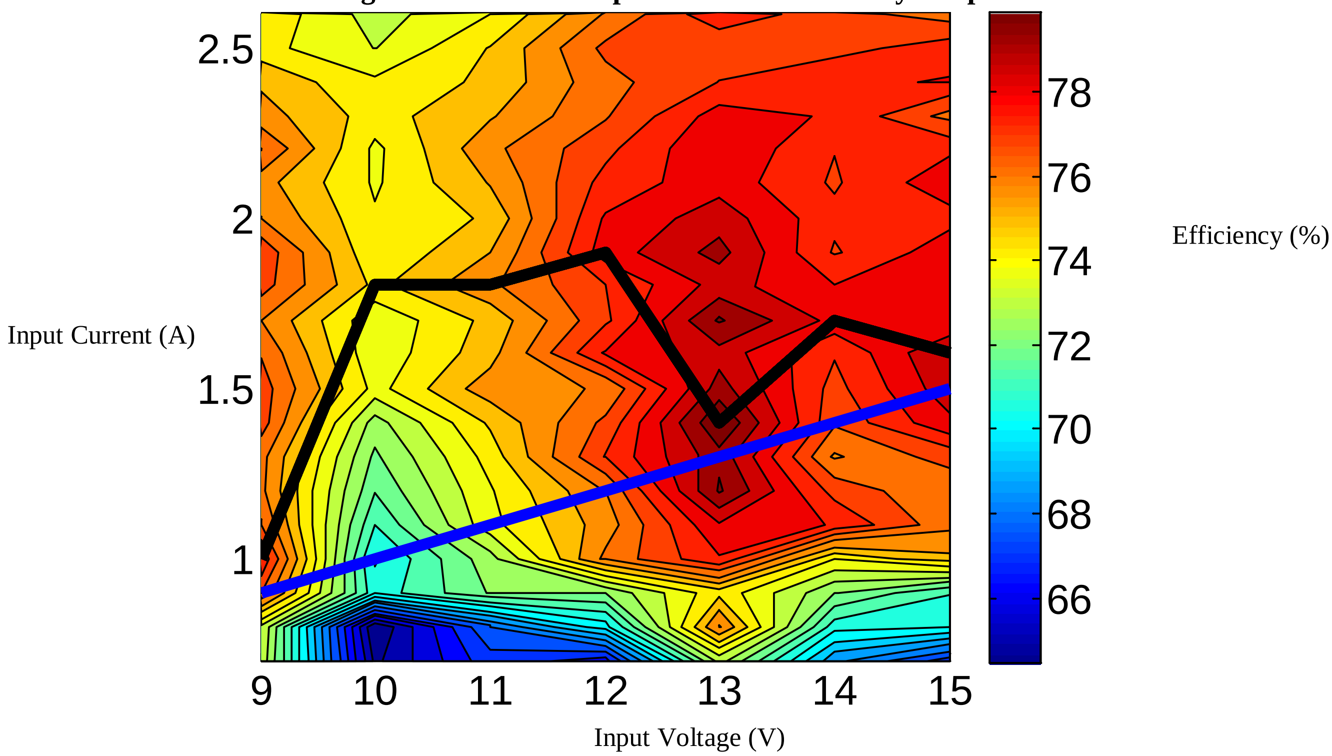


The card used to acquire data is limited to 10 Volts, so an operational amplifier was used to measure the input voltage. The middle voltage, which is half of the power supply voltage, is around 4.5 to 5 Volts at all times, so did not need an op-amp to be measured. The input current was changed by altering the gain of the current reference signal. In normal circuit operation, this gain is .05, which causes the input current to be 1/10th of the input voltage. By changing this gain, and therefore the voltage-current proportionality, the input current is changed. The output signal value is the actual voltage signal that is sent out of the dSpace card, $V_{I-reference}$.

Mapping Efficiency and Finding Alternative Voltage-Current Relationships

Several experiments were completed in order to achieve an accurate depiction of the maximum efficiency at each voltage level of the circuit. Each trial consisted of adjusting the input voltage from 9 to 15 Volts. At each voltage, the current command was used to iterate the input current from 700 mA to 2600 mA. The input and output power was measured at each point, and a curve for maximum efficiency of the circuit was found. The voltage values of 9V to 15V were chosen as representative of the backpack voltages. The 9 Volt minimum was decided based on observations of significantly lower circuit efficiencies at input voltages below 9 V. The 15 Volt maximum was decided due to prior knowledge that the backpack mean voltage in the 80 pound operating condition was within this range. This knowledge was obtained by conversations with Cheng Luo, a PhD student working on the backpack project. This value was also confirmed through experimental testing, where RMS voltages never exceeded the 15 Volt value. Figure 4, shown below, plot the efficiency values at each voltage and current level. Overlaid on this plot is a line that graphs the current that provides maximum efficiency at each of the voltages. The black line corresponds to the maximum efficiency curve. The blue line represents the existing voltage and currents. It can be seen that by altering the voltage-current relationship, efficiency could be improved.

Figure 4: Contour Map of Previous Efficiency Graph



Based on the figure above, it can be seen that the current voltage-current proportionality, shown by the blue line, does not optimize the efficiency of the circuit. At almost every voltage, the circuit is most efficient at an input current of at least 1.4 Amps. Even at 9 Volts, where the maximum efficiency is at 1 Amp, the efficiency does not change with statistical significance at higher current values. The initial conclusion was to create a new voltage-current proportionality that allowed the circuit to pull higher currents even at lower voltages. A limiting factor that must be considered is the limit of the battery that the circuit charges. The battery used was a BA 5590 battery with a 3 Amp continuous current limit. Through theoretical analysis of mathematical models of the electro-mechanical system, it can be seen that a square root relationship may be a more efficient means of relating the voltage and current. Using basic optimization theory, the following equation was computed relating current to rotor speed:

$$I = \frac{-\tau_{loss} R + \sqrt{[\tau_{loss} R]^2 + \Lambda_{PM} \omega_r R \tau_{loss}}}{\Lambda_{PM} R}$$

Where Λ_{PM} is the flux-linkage between the magnets, mechanical losses are modeled with a constant torque τ_{loss} and R is the electrical resistance. Simplifying this equation by neglecting the mechanical losses, and with the knowledge that rotor speed is proportional to input voltage, this equation indicates proportionality between current and voltage: $I \propto \sqrt{V}$.

Based on the data of maximum efficiency at each input voltage, a relationship of $I = \sqrt{V}/2$ was hypothesized. This relationship was designed so that the input currents at each voltage would be at measured efficiency close to the maximum. Table 1, shown below, indicates the theoretical improvements in efficiency that would come from this relationship. The efficiency data from the linear relationship is taken from the previously described experiment. A subsequent test was taken for that of the non-linear relationship, with the dSpace current command controlling the input current so that it reflects that of the square root relationship.

Table 1: Efficiency Graph at Input Voltages and Currents

	LINEAR: $I = V/10$			$I = \sqrt{V}/2$			
Vin(V)	I_{in} (A)	Efficiency	Pout(W)	I_{in} (A)	Efficiency	P_{out} (W)	$R_{emulated}$
9.00	0.90	69.9%	5.66	1.50	79.1%	10.7	6.00
11.0	1.10	76.0%	9.19	1.66	80.4%	14.7	6.63
13.0	1.30	78.3%	13.2	1.80	81.7%	19.1	7.21
15.0	1.50	81.3%	18.3	1.94	80.0%	23.2	7.75
17.0	1.70	80.2%	23.2	2.06	80.2%	28.1	8.25
19.0	1.90	80.8%	29.2	2.18	80.7%	33.4	8.72
21.0	2.10	81.7%	36.0	2.29	81.3%	39.1	9.17
23.0	2.30	81.5%	43.1	2.39	82.3%	45.6	9.62
25.0	2.50	81.1%	50.7	2.50	82.0%	51.6	10.0
Average:		**79.0%**	**25.4**		**80.9%**	**29.4**	

This table above shows that by altering the input voltage-current proportionality to that of a square root relationship, both an increase in efficiency and in output voltage can be achieved on average. It can also be seen by this table that the output power is improved through the non-linear relationship even when efficiency slightly decreases. This is due to the higher current demand at each given voltage, which was the reason why this proportionality was initially chosen.

An experiment was subsequently conducted using this information to see if the backpack would be more efficient with such a relationship when the input voltage and current became dynamic values. Immediately following the start of this experiment, it was clear that the theoretical improvements in efficiency did not translate to the dynamic operation of the backpack. The backpack was unable to achieve a high enough voltage to provide a significant amount of output power, therefore preventing this approach from improving the backpack efficiency.

The input voltage, dependent upon the backpack velocity, was affected by the increased current demands at the low voltages. With such a large current pull at lower voltages, the backpack system was overdamped, preventing it from reaching higher velocities, and henceforth higher voltages. The new proportionality did make the circuit more efficient in the instantaneous case. Since the circuit was overdamped, the rectified input voltage signal had much lower amplitude, meaning it spent much more of its time below 9 Volts, where the circuit is generally not efficient. Therefore, output power was significantly decreased by this design change. This made such proportionality impractical for circuit implementation.

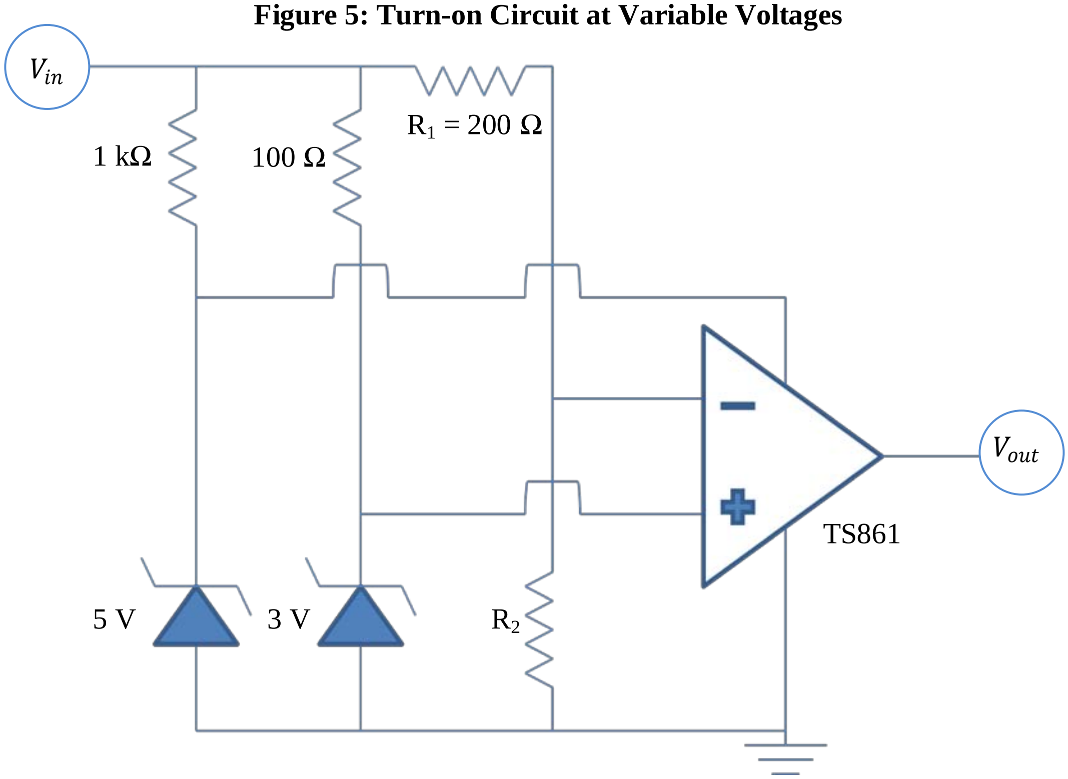
Alternative Solution Investigated

Several lessons were learned by this experiment which would form the basis for the results of this paper. Rather than optimizing the backpack at individual voltage values, it is more important to optimize the input voltage signal as a whole. A viable solution to improving circuit performance would have been to both keep the backpack at higher voltages for a greater period of time and minimize the power that is wasted on the circuit when the voltage is below 9 V. In order to achieve such an input voltage, data was taken with the backpack being turned off at lower voltages.

This approach was first analyzed by applying a current command of 0 Amps through dSpace, and then through the design of a realized circuit that electrically disconnected the power conditioning circuit from the backpack altogether. The second approach was through the use of additional circuitry that shut down the entire circuit below a certain voltage.

This second approach was achieved by employing the shutdown capabilities of the power supply SEPIC converter. The power supply SEPIC converter creates the 11 Volt and 5.5 (middle) voltage signals that power all of the other IC's on the board. Therefore, through disabling this converter, the circuit no longer will be able to draw current from the backpack. This circuit was realized by referencing a fraction of the voltage, through a voltage divider, with a 3 V zener diode voltage. The comparator that computes this reference has an 11 V maximum power supply voltage, and therefore is powered by a 5 V zener diode. The circuit was created to output the input voltage up to 5 Volts, and then the 5 Volt zener voltage, when the input voltage is below a certain level. After it is above that level, the circuit outputs ground. This works in time with the shutdown pin of the mosfet of the power supply SEPIC converter, which shuts down when the pin sees a voltage higher than 1.3 Volts. The circuit is shown below in Figure 5.

Figure 5: Turn-on Circuit at Variable Voltages



There are three distinct cases to the above circuit operation. When V_{in} is below 2.7 Volts, the TS861comparator chip does not operate.

Between 2.7 and 3 Volts, neither zener diode is operating. The positive input to the comparator is V_{in}, and the negative input is $V_{in} * \frac{R_2}{R_1+R_2}$. Therefore, the comparator outputs high, causing the MOSFET and the circuit to be off. In this case, the high value of the comparator is the input voltage because the 5 Volt zener has not yet been activated.

When V_{in} is more than 5 Volts, but $V_{in} * \frac{R_2}{R_1+R_2}$ is less than 3 Volts, the circuit outputs high. If the input voltage is above 5 Volts, the high of the comparator becomes 5 Volts. This was done to protect the comparator from V_{cc} values that exceed its maximum ratings.

When $V_{in} * \frac{R_2}{R_1+R_2}$ becomes greater than 3 Volts, the comparator output is low, activating the MOSFET of the power supply and the rest of the circuit. This circuit proved much more effective than the use of the current command. The current command simply disabled the PWM going to the main SEPIC converter. The IC's on the board were still being powered, and the circuit was still absorbing hundred's of milliamps of current. By turning off the power supply SEPIC converter instead, no current enters the circuit. The objective of these circuits was for the backpack at lower voltages to be undamped, which would allow it to more quickly achieve a greater rotor speed, and therefore maintain high voltages for a greater amount of time. Furthermore, it would eliminate a current spike that currently drains power at low voltages. In terms of the emulative resistance of the circuit, this solution creates an open circuit, or infinite resistance, below a specified turn-on voltage. At that turn-on voltage, the emulative resistance then becomes the originally specified 10 Ω. Results for this hypothesis are to follow.

Chapter 3: Results of Experiments of Turn-on Voltages from 0-12 Volts

Several tests were conducted to discover the turn-on voltage that was most efficient and had the highest power-output. All tests were conducted with an 80lb load in the backpack, as a lesser weight would not provide enough power output to receive reliable data. The backpack was first tested for turn-on voltages of 0, 4, 6, 8, 10, and 12 Volts. The value of 2 Volts was skipped, as the existing circuit naturally turns on at 2.9 Volts, which is the minimum voltage for the SEPIC control chip for the circuit's power supply. First, resistor values for R2 (in the circuit in Figure 5), had to be found that would accurately turn the circuit off at these several voltages. Rather than calculate theoretical values for this resistor, experimental measures were taken. A 100kΩ potentiometer was placed in R2. A power supply was used instead of the backpack to allow a constant input voltage and current. With the input current and voltage measured through an oscilloscope, it could be easily seen when the circuit turned on. By changing the potentiometer during operation, accurate turn-on voltages could be achieved. After each voltage was achieved, the resistance of the potentiometer was measured, and static resistors were used that closely matched each resistance. Table 2 indicates the resistances that were found, and the resistors used to emulate that resistance.

Table 2: Potentiometer resistances for varying turn-on voltages

Turn-on Voltage (V)	Potentiometer Resistance (kΩ)
4	372
5	247
6	184.5
8	123
10	88
12	72.3

After these resistances were found, the test could be conducted. A military battery was used as the load to provide for a constant output voltage. The input and output current and voltage waveforms were saved on the oscilloscope and transferred into Matlab. The two sets were taken with a sampling rate of 1 kHz, with 5000 samples taken. The data was then filtered by removing all but the first 5 and last 5 data points of each waveform's FFT. This action removed the switching frequencies of the data, allowing for better analysis.

An increase in the turn-on voltage corresponded with an increase in the input voltage, with the 10 and 12 Volt values bringing the input voltage near its safe limits of 30-35 Volts. It can be seen that the largest output power occurs when the turn-on voltage is 4 Volts, with the highest efficiency being when the voltage is 6 Volts. The output power averaged at 4 Volts is 14.57 Watts with an average efficiency of 80.9%. The output power averaged at 6 Volts is 14.38 Watts with an efficiency of 83.0%. The graphs of input and output power are shown below in Figure 6, with the respective efficiencies in Figure 7.

Figure 6: Input and Output Power at Turn-on Voltages

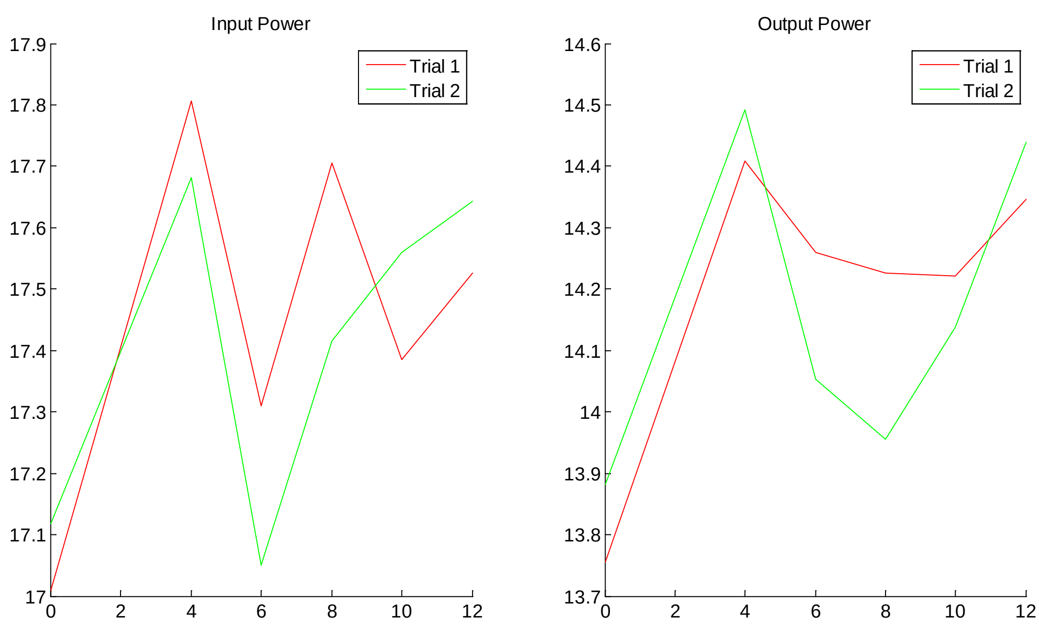
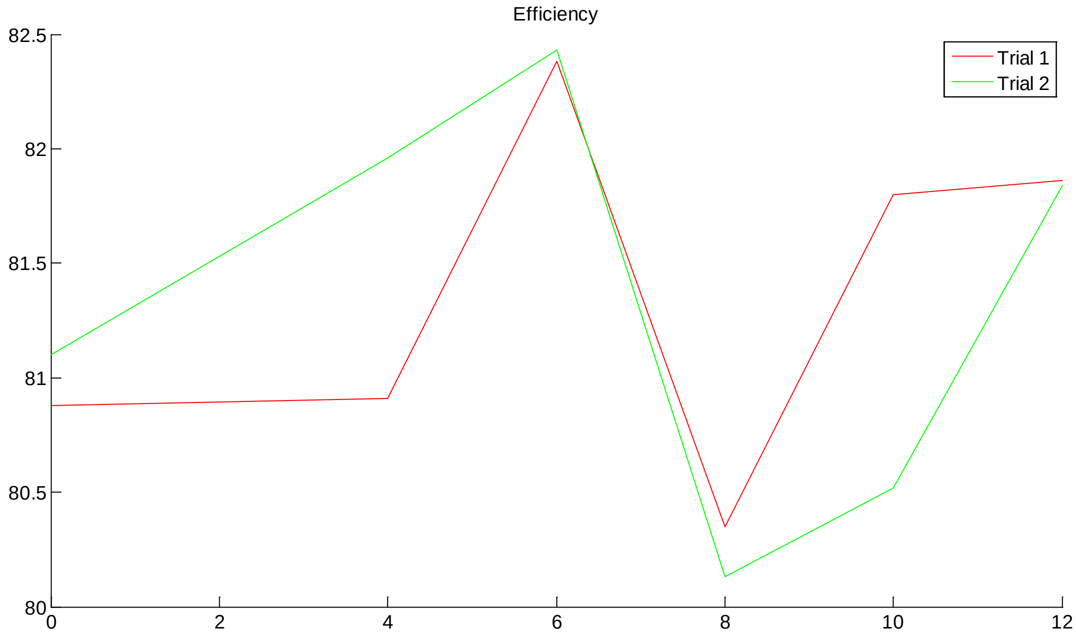


Figure 7: Efficiency at Turn-on Voltages

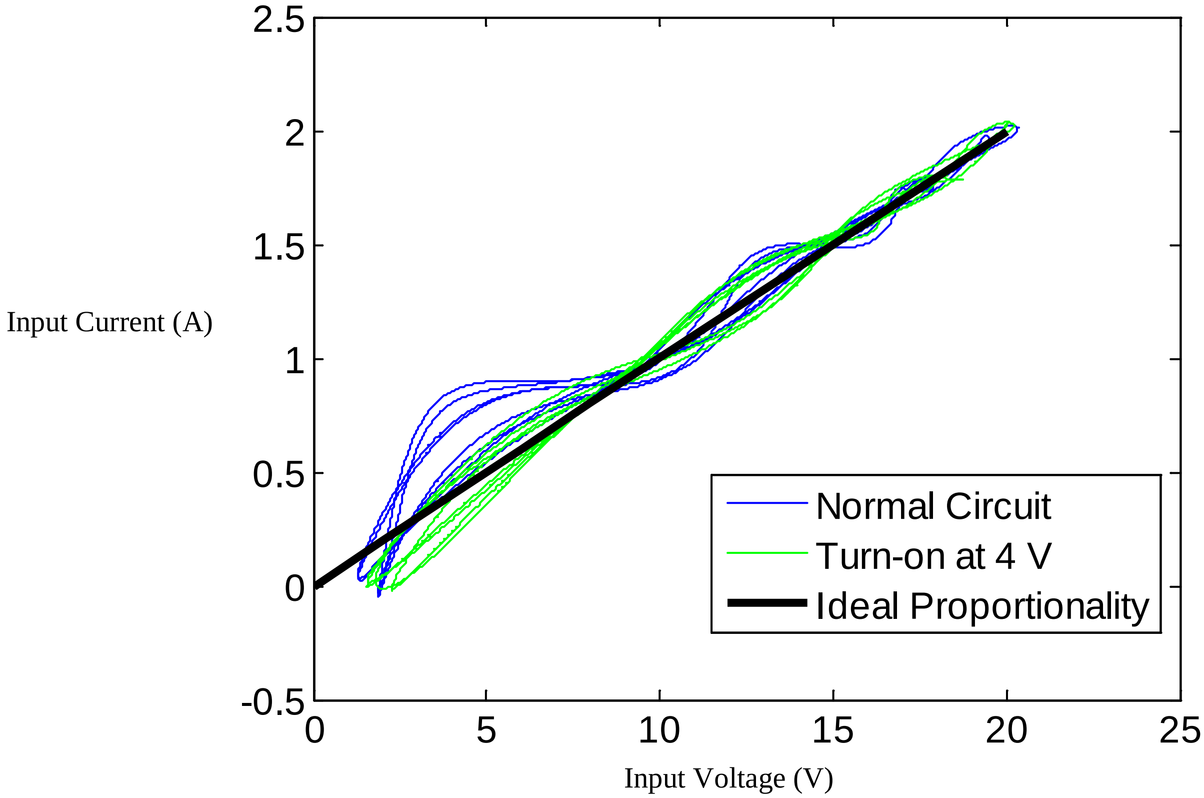


Based on this data, the circuit is clearly improved by turning it on at a higher voltage than existing. This is due largely to two factors.

The first is that in normal operation, a large current spike occurs when the input voltage is between 3 and 4 Volts. This is due to the SEPIC converter power supplies turn-on operations. It can be seen that this phenomena corrupts the linear proportionality. This can be better seen when the input voltage is plotted vs. the input current. The blue line in

Figure 8 deviates from the ideal proportionality at voltages between 3 and 4 Volts, where the green line does not. This voltage is too low to activate the entire circuit, and therefore the current spike does not proceed to the battery. Therefore, this extra input power is simply wasted.

Figure 8: Input Voltage vs. Input Current

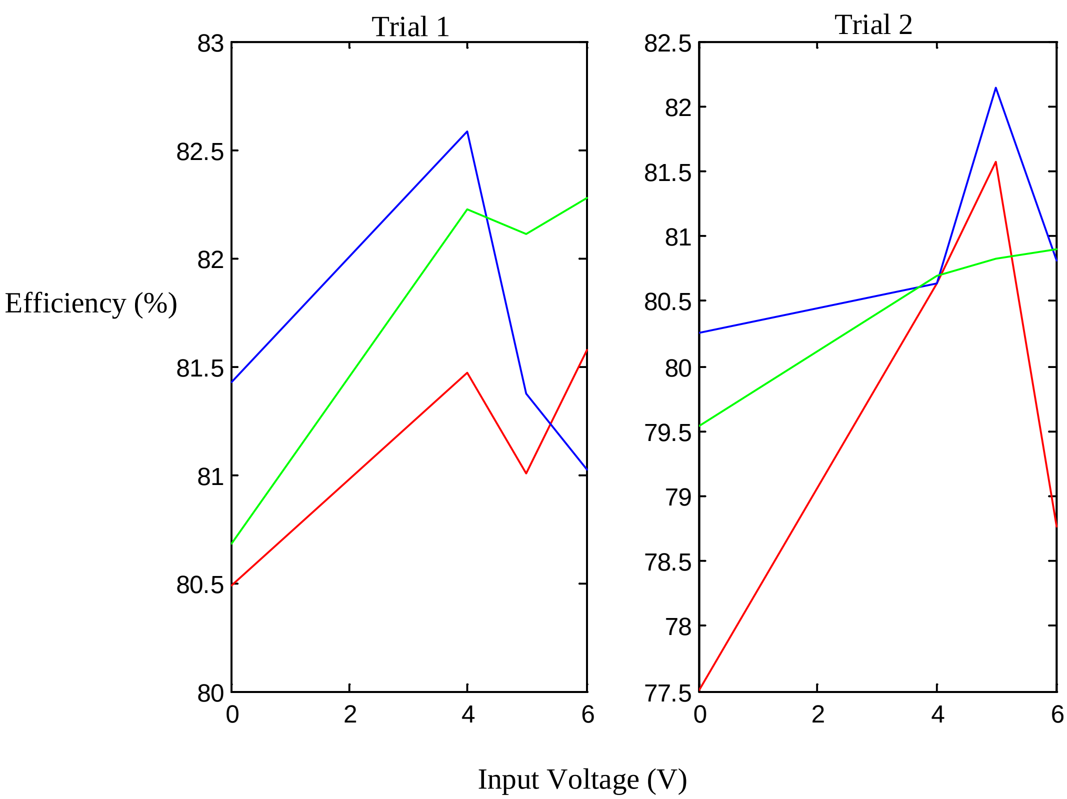


The other reason that a higher turn-on voltage may increase the output power and efficiency is based on the concept that it reshapes the input voltage signal. By allowing the backpack to be underdamped when it is at a lower speed and voltage, it is proposed that it will achieve a higher speed and voltage more quickly. After this experiment, it can be seen that this second factor may be less important than previously thought. Although it may achieve a higher voltage more quickly, as the turn-on voltage rises, the percentage of each period of the rectified input voltage that the circuit is charging is decreased. Therefore, the circuit is outputting power less of the time, overall making it less effective. In order to further investigate the best turn-on voltage, as well as see if the emulative resistance value would be a factor, another experiment was undertaken.

Chapter 4: Results of Experiment with Turn-on Voltages of 4, 5, and 6 Volts and Emulative Loads of 8.6, 10, and 11.4 Ohms

In order to further investigate the best possible turn-on voltage for the circuit, a more detailed experiment was conducted that focused on the turn-on voltages between 4 and 6 Volts. Furthermore, it altered the emulated resistance to see if that would play a factor in which turn-on voltage was most effective. The results, shown below in Figure 9, show that similar efficiency and output power occurs at the 4 and 5 Volt turn-on voltage. Furthermore, the circuit is most efficient at 10 Ω. It does generate a greater amount of power when the emulative load is 11.6 Ω, which is a factor that should be considered in future iterations of the circuit.

Figure 9: Output Power and Efficiency at Turn-on Voltages and Loads



The blue line indicates the circuit at a 10 Ω resistive load, the red line is at an 8.6 Ω load, and the green is at an 11.6 Ω load. In the first trial, a turn-on voltage of 4 Volts was shown to be the most efficient case. At this voltage, the 10 Ω case achieves the best efficiency at 82.6%, as opposed to the circuit in its initial condition, where it achieved an efficiency of 81.4%. In the second trial, the turn-on voltage of 5 Volts was shown to be the most efficient case, where it achieved 82.1% at 10 Ω. This is again greater than 10 Ω at the initial condition, where it achieved 80.3%. Overall, a clear improvement in efficiency can be noted.

Chapter 5: Conclusion and Future Work

Through the introduction of the proposed circuit, the backpack efficiency can be improved by over 1%. Furthermore, the output power is increased by approximately 0.5 W. The current spike that previously affected the shape of the input waveforms is eliminated through the use of this circuit addition as well. It can be seen that by increasing the turn-on voltage of the backpack circuitry, the overall efficiency and power output are improved for an 80 lb load. While other emulated resistance values were utilized, further research into the most effective resistance could potentially improve backpack efficiency to a greater extent. It was noticed that a larger emulated resistance actually resulted in a greater amount of output power, which should be further investigated. The results of this thesis are currently set to be implemented in the next circuit design iteration.

References

[i] Poulin, G., E. Sarraute, and F. Costa. "Generation of Electrical Energy for Portable Devices Comparative Study of an Electromagnetic and a Piezoelectric System." *Sensors and Actuators A* 471st ser. 116.461 (2004): 461-71. *Science Direct*. Web. 15 Mar. 2010.

[ii]Henderson, Tessa. "Power Generating Shoes." *Energy Harvesting Journal* (2009). *Energy Scavening, Power Scavenging - Making Small Electronic and Electric Devices Self-Sufficient.* IDTechEx, 3 Sept. 2009. Web. 15 Mar. 2010.

[iii] US Navy. Navy Region Southwest Public Affairs. *Harvesting Energy Through a Walker's Shoe. Harvesting Energy Through a Walker's Shoe*. US Navy, 10 July 2003. Web. 15 Mar. 2010. <http://www.navy.mil/search/display.asp?story_id=8203>.

[iv] Howells, Christopher A. *Piezoelectric Energy For Soldier Systems*. Tech. Belvoir: Army Power Division. *Piezoelectric Energy for Soldier Systems*. Defense Technical Information Center, 1 Dec. 2008. Web. 15 Feb. 2010. <http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA504251>.

[v] J. Granstrom, J. Feenstra, H.A. Sodano, and K. Farinholt. ”Energy harvesting from a backpack instrumented with piezoelectric shoulder straps”. *Smart Materials and Structures*, 16(5):1810–20, Oct. 2007.

[vi] Donelan, J. M., Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, and A. D. Kuo. "Biomechanical Energy Harvesting: Generating Electricity During Walking with Minimal User Effort." *Science*319.5864 (2008): 807-10. *AAAS*. Web. 21 Feb. 2010.

[vii] Ehlrich, Robert J. "Chapter 11: Soldier's Load and Combat Readiness." *Joint Readiness Training Center: NCO's "Make It Happen" - JRTC Observations* 01-15 (2001). *GlobalSecurity*. Web. 17 Feb. 2010. <http://www.globalsecurity.org/military/library/report/call/call_01-15_ch11.htm>.

[viii] Luo, Cheng. "Energy Harvesting." *Power Electronic Circuitry for Energy Harvesting Backpack*. Proc. of 2009 IEEE Energy Conversion Congress & Expo, Convention Center, San Jose, CA. Print.

ACADEMIC VITA

Stephen M. Suffian
1567 Gregory Drive
Warrington, PA 18976

Education: Bachelor's of Science in Electrical Engineering
Minor in Civic and Community Engagement
Honors in Electrical Engineering
Thesis Title: Non-Linear Input Impedance for Energy Harvesting Backpack
Thesis Advisor: Heath Hofmann

Related Experience:

Internship at Phillips-Respironics
Supervisor: Bradley Ryba
Summer 2008

Internship at Lutron Electronics, Inc.
Supervisor: Frederick Giordiano
Summer 2009

Awards:

Tau Beta Pi Inductee
Dean's List
College of Engineering Academic Scholarship

Activities:

Vice President of NECA Student Chapter 2009-2010
- took 3rd place in Green Energy Proposal Challenge
  - design and financing of solar array as part of energy audit on Radio Park Elementary School
- installed a solar array on a local school in Roatan, Honduras

Senior Design Project – ToolTrailer PV Retrofit
- design and installation of a 1 kW solar array for tool charging and operation

MLK Jr. Community Outreach Director 2008-2010
- created and developed short story/essay contest and showcase for local school district