Maximum Energy Harvesting Control For Oscillating Energy Harvesting Systems

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MAXIMUM ENERGY HARVESTING CONTROL FOR OSCILLATING ENERGY HARVESTING SYSTEMS

by

JOHN C. ELMES III
B. S. The College of New Jersey, 2005

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering in the School of Electrical Engineering and Computer Science in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

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ABSTRACT

This thesis\textsuperscript{1} presents an optimal method of designing and controlling an oscillating energy harvesting system. Many new and emerging energy harvesting systems, such as the energy harvesting backpack and ocean wave energy harvesting, capture energy normally expelled through mechanical interactions. Often the nature of the system indicates slow system time constants and unsteady AC voltages. This paper reveals a method for achieving maximum energy harvesting from such sources with fast determination of the optimal operating condition. An energy harvesting backpack, which captures energy from the interaction between the user and the spring decoupled load, is presented in this paper. The new control strategy, maximum energy harvesting control (MEHC), is developed and applied to the energy harvesting backpack system to evaluate the improvement of the MEHC over the basic maximum power point tracking algorithm.

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CHAPTER 1: INTRODUCTION

Harvesting energy from everyday mechanical interactions offers a potentially significant benefit. Such mechanical interactions can vary in magnitude from the motion of a wristwatch, to a large-scale ocean wave-energy-harvesting buoy. The harvesting of energy from natural and existing mechanical interactions has the potential to reduce our drain on non-renewable energy sources. Many such mechanical interactions exhibit motion that is sinusoidal in nature, which allows for the harvesting of energy due to the displacement and force of the mechanical action. Recent work has led to the development of energy harvesting mechanisms in many forms for many applications. Examples of such work are discussed in [1, 2]. Many energy harvesting mechanisms resemble the driven damped harmonic oscillator (DDHO), which is formed by an oscillating mass and an energy generation mechanism which dampens the motion of the mass [3]. Another example of the DDHO energy harvesting system is the ocean wave energy harvesting buoys, which are driven by the periodic motion of the waves [4, 5]. Recent work has also been done on the harvesting of energy from small vibrating oscillators [6]. The inherent characteristics of the DDHO require that there is some level of dampening which will result in a maximum amount of energy removed from the system. The ability to achieve the optimal level of dampening under all operating conditions is ideal for many applications, where efficiency and power density is a universal goal. A control methodology has been developed which will enable the optimal dampening of the DDHO energy-harvesting device.

There is a growing need and desire for small and portable electronics, a need that has extended through government, private business, and personal use electronics. Typically, the power sources for such devices are primary or rechargeable batteries. Many times the device is subjected to oscillating movement due to the motion of a user and the motion of the device while
being carried or transported. A prime application of an advanced method of control is the energy harvesting backpack, which is a backpack that is designed to decouple the load from the wearer with springs, which effectively creates a driven harmonic oscillator. The use of a rotary motor as a generator was performed by [7] to dampen the system oscillations. The goal was to both reduce the forces experienced by the user and to generate useful energy. This implementation did not employ any active control methodology; the sinusoidal output voltage was simply rectified and filtered with a capacitor. To optimize the power generated, this paper proposes a new control methodology that will be implemented and tested. The testbed for the system is an oscillator with variable mass, variable frequency, and fixed driving displacement, which has been developed to match the characteristics of a walking person with an energy harvesting backpack. A permanent magnet linear generator has been designed to meet the expected needs of the application. Using the developed testbed, verification and optimization of the proposed control methodology can be performed.

**Energy Harvesting Backpack**

Electronic devices are becoming increasingly important for hikers, climbers, rescue workers, and military users, but they often require bulky batteries to function for long periods of time. The proposed energy harvesting backpack will help a person carry lighter loads and offer the assurance of power delivery to critical instruments and devices. By dampening the displacement between the user and the load, it is possible to harvest energy while reducing the stresses on the user. The mechanical structure of the energy harvesting backpack, as shown in Figure 1, is structured with the load of the backpack decoupled from the frame (user’s back) with a spring and a damper. In a traditional backpack design, the load is hung from the frame, which restricts the motion of the load to the motion of the user’s body. By introducing the spring
decoupling mechanism, the load of the backpack is not constrained to the motion of the frame, which creates the potential for reduction in the energy wasted by the user, as well as the potential to harvest energy from the interaction between the user and the load.

![Diagram](image)

**Figure 1 Embodiment of the DDHO**

As the user walks, the motion of their torso approximates a sinusoidal displacement from the ground, which serves as the driving force of the DDHO [7]. The DDHO of the energy harvesting backpack has been simulated in Figure 1. The simulation allows for the adjustment of the system parameters, such as a walking speed, mass of the load, and displacement. The average person will have a vertical torso displacement of 5 cm. The frequency of the driving sinusoidal position source is dependant on the speed that the user walks, or more specifically, the frequency at which the wearer takes a step. Each step results in a full cycle in terms of the displacement of the torso. The average person walking at 5.6 km/hr (3.5 mph) results in a driving frequency of 2 Hz, while a person with a longer gait will exhibit a lower frequency at the same walking speed.
If one considers the nature of the sinusoidal driven damped harmonic oscillator, it is apparent that certain damping conditions will result in an over-damped case, while lower damping can result in an under-damped case. It is important for the system to be in a critically damped case or over-damped at all times; otherwise, the system can become unstable, which is undesirable for the energy harvesting backpack user. The act of damping the mechanical oscillator is the basis of the energy harvesting backpack, as the energy removed from the system will be converted to electricity. If one were to design the system with the goal of minimizing the net energy expelled by the user, it would be ideal to design the DDHO to minimize the change in height of the backpack. However, it is possible to design the system to extract significant energy from the interaction, while still reducing the net forces experienced by the user. It is also possible to design the system with a resonant frequency close to the walking frequency, which could result in higher net forces experienced by the user than with a typical. Such a design would result in a high amount of potential energy for harvesting, but would not be user-friendly. For the purposes of an energy harvesting backpack, it is most desirable for the system to reduce the net forces experienced by the user while still allowing for significant energy harvesting. Meeting these conditions is the design goal of this paper.

There exists a specific damping condition in any DDHO that will result in the most energy extracted from the system, as is the nature of the damped harmonic oscillator. Intuitively, this makes sense, since little damping will not result in energy harvesting because there is no force resisting the motion of the oscillator, while high damping will resist the oscillator too much, and there will be no displacement in the oscillator. Both force and displacement are necessary to extract energy from the system; in this way, voltage and current are electrical analogues for velocity and force. In this same manner, there are parallels between the
fundamental maximum power transfer theorem of electrical networks, and the maximum energy harvesting from a DDHO. It is difficult to determine the best damping coefficient for maximum power in a practical system, since the numerous system parameters affect the location of the maximum power point. Figure 2 shows the sweep of the damping constant vs. energy generated.

![Figure 2 Sweep of the Damping Constant vs. Energy Generated](image)

The user’s walking speed and height, mass of the load, spring constants, generator characteristics, and frictional losses are some of the system parameters that can affect the maximum power point of the system. The walking speed, height of the user, and mass of the load are dynamically changing parameters, which serve to constantly change the location of the maximum power point of the system. Fortunately, it is not necessary to actually know what the correct damping ratio is at any given moment; instead, it is important to know that there always
exists some maximum power point. Much like a photovoltaic power system using maximum power point tracking (MPPT) [8], the energy harvesting backpack should actively change the damping ratio of the system, so as to harvest the maximum amount of energy from the system; this will be referred to as maximum energy harvesting control (MEHC).

**Maximum Power Point Tracking (MPPT)**

It is widely known that solar photovoltaic cells exhibit a power vs. voltage curve in which the power output reaches a maximum at a specific voltage, known as the maximum power point. The P vs. V curve of a photovoltaic panel can be seen in Figure 3. When harvesting energy from a source that has a maximum power point, such as photovoltaics, it is important for the controller to vary the loading in such a way that the power from the source is maximized. The most typical method of achieving maximum power is the ‘perturb and observe’ method, which is an algorithm that will vary the loading, and then compare the generated power to the previous power. If the power increases, the algorithm will continue to vary the loading in the same direction, if the power decreases, the algorithm will change tracking directions. This MPPT algorithm is effective for any source which exhibits a parabolic power curve, meaning that there is always a single maximum power point and there are no local maxima; essentially, there are not multiple peaks and valleys. If the power curve of the source has multiple maxima, the algorithm may become trapped in a location that is not the true maximum power point. In this work, it has been shown that the DDHO exhibits a parabolic power curve containing only one maximum. This means that it is possible for the system to actively control the dampening of the mechanical oscillator in order to harvest the most energy possible from the energy harvesting backpack. A
maximum power point algorithm has been developed in this work specifically for alternating
current sources which exhibit a peak power point.

**Figure 3 Power vs. Voltage and Current vs. Voltage Curves for Photovoltaic Cells**

Since traditional MPPT algorithms require the sampled power be a DC value, the
algorithm will not be effective if the source is AC. One method to use the traditional MPPT
algorithm on the energy harvesting backpack is to heavily filter the power signal, but this slows
the algorithm tracking speed significantly, which is detrimental to the proper operation of the
A new control algorithm has been developed which will be able to quickly track to the maximum power point of the system without filtering the power signal. This new algorithm, named Maximum Energy Harvesting Control (MEHC), will allow the energy harvesting backpack to operate effectively.

**Unity Power Factor AC/DC Converter**

In order to generate maximum power, it is necessary for the power converter to extract unity power factor from the AC generator. In this way, the converter will approximate a resistive load, which will minimize the losses from the generator. A previous energy harvesting backpack design by [7] was used with a bridge rectifier and filter capacitor, which has been shown to only sink power when the AC source is at the peaks. This method is not effective at harvesting energy efficiently, since most of the time the system is not being damped. A unity power factor AC/DC converter was designed which will charge a battery while loading the generator resistively. The converter will be completely digitally controlled, which will allow for the controller to use a constant representing resistance as the control variable. This control variable representing resistance will then be controlled by the MEHC algorithm. In this way, the MEHC algorithm will be a slower outer control loop, while the power factor corrected (PFC) converter will be an inner control loop, which executes continuously. The converter is a boost converter, which will step the voltage up from the generator to the battery voltage, either 12 V or 24 V. The digital controller will be implemented in a Texas Instruments TMS320C2812 DSP. This DSP has enough calculation speed, memory, A/D, and dedicated PWM to properly implement this control strategy.
Linear Generator

The energy harvesting backpack must utilize a generator to capture the mechanical energy of the DDHO. Many types of generators are possible, but some are more effective at capturing the linear motion of the oscillating system. The backpack designed in [7] utilized a rotary motor as a generator, which required a lossey gearbox to increase the rotational speed in order to generate usable voltages. The better generator should directly capture linear motion. This work presents the design of a linear generator, which was used to harvest energy from a DDHO. The linear generator is based on a permanent magnet shaft, which moves through the windings of the generator, and removes energy from the system to charge the battery. The linear generator must fit the form factor of a traditional backpack, which would allow for the user to easily transition into an energy harvesting backpack.

Research Objectives

The objective of this work is to develop a complete energy harvesting system based on the DDHO. The energy harvesting backpack is the application of this work, but much of the work is applicable to other types of DDHO energy harvesting systems, such as ocean wave energy harvesting. The development of the unity power factor AC/DC converter as well as the Maximum Energy Harvesting Control (MEHC) is crucial to the effective operation of the system. The linear generator must be designed in a way that will allow it to easily integrate into an ergonomic system. The design of a mechanical testbed consisting of a DDHO and the linear generator will be designed to test the AC/DC converter and the controller. The preliminary design of the future energy harvesting backpack is also described in this thesis.
Thesis Outline

The first chapter of this thesis is the introduction, giving a short background and summary of the work. The second chapter describes the design of the energy harvesting backpack system. The subsequent chapters outline the design of the sub-systems of the energy harvesting backpack. Chapter 3 describes the research and design of the linear generator. Chapter 4 describes the design of the unity power factor AC/DC converter, which will electrically load the generator, and charge the battery. Chapter 5 establishes the need for a new MPPT algorithm to control the system for maximum power. The new algorithm named Maximum Energy Harvesting Control is outlined. Chapter 6 contains a summary of the work and conclusions as well as future work.
CHAPTER 2: ENERGY HARVESTING BACKPACK

The “energy harvesting backpack” is a general term for a backpack capable of harvesting mechanical energy from the user’s walking motion. The method of energy generation and storage is highly variable depending on the specific application. The vertical motion of the backpack has the greatest potential for energy harvesting, as the natural motion of the torso oscillates the vertical position of the backpack while walking. The motion of the torso approximates a sinusoidal position source, since the walking motion approximates an inverted pendulum. The nature of the walking mechanics is further analyzed in [7, 9]. The double-edged sword of mechanical energy harvesting is that oscillating mass is necessary to generate energy, but oftentimes additional mass is not desirable for applications which would benefit from energy harvesting. The potential of the energy harvesting backpack is that the user is already carrying a large mass, which can be utilized to help generate energy from the periodic motion of the torso. The challenge is to develop a mechanical system that would allow for the most efficient harvesting of the energy that would normally be used to oscillate the backpack. The structures of the mechanical energy harvesting system known as the DDHO is shown in [10]. This mechanical system should be as light as possible, and should match the form factor of a regular backpack.

To determine the potential amount of energy to harvest from the user, some ground rules must be established. The first is that the backpack cannot cause the user greater strain than what is normally experienced when walking with a regular backpack. The DDHO, the basis of the energy harvesting backpack, can be tuned to operate in under-damped, critically damped, or over-damped mode; therefore, it is possible for the backpack to oscillate at greater amplitude than the driving sinusoid. The mechanical oscillator actually has the potential to extract a very
high amount of energy from the user, but this would be very stressful and not sustainable. For user comfort, the DDHO of the backpack should be designed to operate in the over-damped or critically damped mode at all times. The natural frequency of the oscillator should also be such that the driving frequency will not induce such resonance that the oscillation amplitude is too great. Even a poorly designed energy harvesting backpack could generate power during simulation, but the ease of use must be considered. It is important that the backpack wearer does not experience difficulty when walking as a result of the energy harvesting design. The properly designed energy harvesting backpack should complement the normal walking motion of a person while damping the oscillation of the load and harvesting energy from the mechanical interaction.

**Non-Energy Harvesting Backpack Structure**

To understand the form factor that an energy harvesting backpack must adhere to, one must first analyze a traditional backpack that the user would normally wear. There are many variations in backpack technology depending on the application. For children, there are backpacks which simply have two main straps which rest on the shoulders, and are completely constructed from nylon or vinyl. For adults, there are more advanced backpacks which use more durable materials, but still follow the same basic structure. Hiking backpacks often have additional straps that secure the backpack to the lower torso to keep the pack from bouncing while walking. Most military backpacks, as well as some hiking backpacks, have a metal frame integrated into the pack. This metal frame supports the load by keeping the points of contact only at the shoulders and the torso. If there are many sharp or uneven items in the pack, it is not desirable for the cloth pack to rest directly on the back of the user, as it may cause discomfort. Typically, adding the metal frame enables the user to carry more weight than would be possible without the frame. The framed backpack has the capability to tightly fasten to the torso, thus
allowing the hips of the user to support much of the weight. By moving the point of load from the shoulders to the hips, only the lower body must support the weight, allowing the person to carry more weight with less stress. An example of a traditional military backpack frame system named the ALICE is shown in Figure 4.

![Figure 4 Frame of the ALICE Standard Backpack Frame](image)

The components of the traditional backpack should not be changed drastically for an energy harvesting backpack design. The backpack should be familiar to the user, and the additional manufacturing costs should only be for the energy harvesting components, while leaving the existing components untouched. Much work has been done in the past to perfect the ergonomics and design of the military-style backpacks; a successful energy harvesting backpack should utilize the previous efforts in design, not redesign the whole system. The goal of the energy harvesting backpack design is to create a system that will easily integrate into the existing components, allowing for as much of the existing system to be reused. From an economics standpoint, it is more appealing for people to spend less money on a single component to add to
their existing backpack system than for them to leave their existing backpack unused, and purchase a whole new one. As the military is the main consumer target for this application, a modification to existing backpacks would be advantageous from a budgetary standpoint.

**Energy Harvesting Backpack**

The true source of the energy harvesting backpack concept is unknown, as it has probably been conceptualized by many people over the years. The most recent design has been by L. C. Rome of Lightning Packs, LLC [7]. His design utilizes the basic concept of the DDHO, which allows for the load of the backpack to oscillate with respect to the torso of the user. This oscillation is dampened with a generator to then produce electricity. This design is mostly a proof of concept, as it does not fit the form factor of an actual backpack. The load was placed on a frame, which was coupled through linear bearings to the frame that the user wears. Rome’s prototype accomplished its goal as a proof of concept device, but the device itself is not usable as a backpack. The method of generation used by Rome is a brushed DC rotary motor, which is connected through a speed-multiplying gearbox to a rack and pinion to turn the linear motion into rotary motion. This method of generation is not ideal, as the rotary motor has many drawbacks that are not desirable in such an application. One significant drawback is that the basis of the motion of the backpack is a slowly oscillating linear position source, while the rotary generator requires rotary motion at a high speed. In order to utilize a rotary generator, a method of converting the linear motion into rotary motion must be devised. Then, the rotary speed must be multiplied through gearing to achieve the high rotary speed that the rotary generator requires. Every mechanical conversion of the motion introduces mechanical loss into the system, which robs the user of potentially harvested energy.
Another major drawback of the rotary generator is that the motor is typically not well-suited for environmental stresses. Particularly concerning the brushed DC generator, the mechanical contacts will wear with time and will fail if the contacts become damaged by rain, mud, sand, or even dust. Even the rotary AC generator requires high-precision bearing to allow the generator to spin at high speeds; these bearings are also susceptible to environmental failure. For the main applications of the energy harvesting backpack being military use, hiking, and search and rescue, there are certain characteristics that are crucial:

- The energy harvesting backpack must harvest as much energy as possible without stressing the user more than a traditional backpack.
- The backpack must be reliable, such that environmental influences must not damage or disable the device.
- The backpack should be fully submersible without damage.
- The backpack should not weigh much more than a traditional backpack, as this will mitigate the benefits of the energy harvesting.
- The backpack should utilize existing backpack form factor, such that the backpack will have a very short learning curve.
- Maximum power tracking must control the loading so as to produce the maximum energy harvesting.

**Determining Generator Type**

To meet the criterion established for the successful energy harvesting backpack design, the generator type must be identified. The primary classifications of electro-mechanical generators applicable to energy harvesting are rotary generators, linear generators, and piezoelectric generators.
The rotary generator can be a permanent magnet (PM) machine, such as a brushed DC motor, or a brushless DC motor. The rotary generator could also be an induction based AC generator, which does not require a permanent magnet. Another possible rotary generator would have an externally excited field where a current is sourced to a field winding, which replaces the permanent magnet of a DC or AC machine. Each of the potential rotary generator types has advantages and disadvantages, but the primary disadvantage of all of the rotary generators is that they require high-speed rotary motion, where the backpack will provide low-speed linear motion. The loss of energy in the mechanical conversion as well as the added complexity, size, and loss of reliability make the rotary generator non-ideal for the energy harvesting backpack.

Solid-state type generators are potential sources for the energy harvesting backpack, which can use the mechanical force and displacement to generate energy. The most suitable type of generator for this application would be an advanced piezoelectric polymer, which has the capability to stretch like rubber, while generating electricity from the strain. This type of generator is potentially well-suited for this application, since the polymer itself could be the spring of the DDHO as well as the generator [11]. In terms of form factor, such a generator would fit very well into the energy harvesting backpack system. The drawback is that the current technology of such generators has not yet reached the level of efficiency and reliability that would be required. Possibly in the future such a solution will be feasible.

The linear generator is a term for a type of generator that can directly transform translational mechanical movement into electricity. The embodiment of the linear generator can take many forms, but there are a few basic structures. One such structure is the permanent magnet linear generator. This generator is fundamentally like a permanent magnet AC motor unfolded in a linear fashion. As the main shaft of the linear generator is propelled, permanent
magnets are passed by coils of wire, thus inducing a current in the wire and generating electricity. The physical structure of the PM linear generator can be variable, since the moving shaft could contain the magnets and the housing contains the windings, or the external housing could contain the magnets while the shaft contains windings. The PM linear generator can be cylindrically shaped like a piston, or could be rectangular much like the propulsion for electromagnetic trains. The advantage of such a generator is that the PM linear generator is suited for linear motion at driving speeds similar to walking speeds. The drawback of the linear generator is that it is typically larger and more massive than a rotary generator of the same power level due to the ability of the rotary generator to continually reuse the magnets to alternate the current in the windings, whereas the linear generator must have magnets and windings across the whole length of the generator. One must also consider the size and efficiency loss of the mechanical system required to convert linear motion into rotational motion for the rotary generator.

The vertical displacement of the energy harvesting backpack is important for the success of the linear generator because the structure must be long enough to generate power for the entire cycle of motion. This is not an issue for a rotary generator because the motor can continually spin in one direction and create energy. Since the displacement of the energy harvesting backpack is small, less than 5 cm peak, the linear generator can accommodate the full cycle of motion.

From the analysis, it was determined that the linear generator has the most positive attributes for this application. The ideal energy harvesting backpack will allow for the integration of the generator and the spring into the frame of the backpack, allowing the form factor to be identical to the existing backpack. There will be two rigid frames, one will interact
with the user much like the existing backpacks, and the second frame will support the load. Ideally one frame will integrate part of the linear generator, while the second frame will integrate the other part of the generator. As the two frames oscillate, the generator will extract energy from the oscillation and generate electricity.
Backpack and Frame Design

Based on analysis, it was determined that the linear generator is the best fit for the energy harvesting backpack, and that the integration of the generator into the frame is an important factor in the system design. Parallel to designing the backpack and frame structure, the linear generator was also designed. From the work described in Chapter 3, a linear generator was designed where the center shaft will be filled with alternating permanent magnets, and the outer collar will contain the windings, which will generate voltage when the magnetic field alternates as the shaft passes through the collar. From this design, it is possible to integrate the magnets into one of the frames and attach the generator collar to the other frame, allowing the frames to oscillate separately and generate energy.

Figure 5 Assembly of the Energy Harvesting Backpack
The frame that is supported by the user has already been designed for ergonomics and manufacturability, so integrating magnets into the main frame of the backpack is not a viable option. The second frame is new for the energy harvesting backpack, which will give the ability to design the frame with integrated magnets. The collar of the linear generator can be welded or bolted to the existing backpack frame, while still using all of the existing straps, pads, and backpack. The exploded view of the fully assembled energy harvesting backpack is shown in Figure 5. The additional components of the energy harvesting backpack are the PM shafts and tubing of the second frame, the collar of the linear generator, and a back pad for the top of the main frame.

The collar of the linear generator must have linear bearings to support the forces of the backpack as it oscillates, since there will be motion in addition to the vertical oscillation. The main types of linear bearings are ones with integrated ball-bearings, and solid low friction materials. The ball-bearing type linear bearing has the potential for the lowest friction, which is good for system efficiency, yet it is not environmentally durable. The bearings must stay well-oiled and completely free of debris. If the backpack was submerged in mud, for example, the bearings would seize and the backpack would not operate correctly. The solid type bearing is made of a polymer such as Teflon, which will allow the shaft to smoothly oscillate without too much friction from side loading. Even though the solid bearings have higher friction, they are very durable, and will operate under most environmental conditions. An example of such bearings can be found at [12].

As the mechanical structure of the energy backpack has been designed, the next step is to test the system. It is not feasible to test the complete energy harvesting backpack system from the beginning because the backpack involves many smaller systems and designs, all of which
must be tested and optimized before the complete backpack can be constructed. For this reason, a mechanical testbed has been designed, which will simulate the walking of a person.

**Mechanical Testbed**

To assist in the design of the energy harvesting backpack, a mechanical testbed is necessary which will integrate the linear generator, the oscillating springs, the load, and a sinusoidal position source to simulate the backpack. The mechanical testbed is planned to be a smaller-scale version of the actual backpack, as the testing of the linear generator will only require one generator, while the actual backpack will have two generators, one on each side of the frame. The theoretical structure of the testbed is shown in Figure 6. The mass of the load on the testbed will be up to 25 lbs, which would correspond to a backpack mass of 50 lbs, since the testbed is simulating half of the full backpack system. The actual backpack will be designed to operate with up to 80 lbs, but the testbed should produce usable data which can be compared to the simulations to confirm the proper operation of the system. The $\Delta h$ for the testbed is 2.5 cm, whereas the actual backpack will be 5 cm. The generated power is roughly a squared law of the displacement, meaning that the power output will be four times less than the equivalent backpack system.
Figure 6 Embodiment of the Mechanical Testbed
To create the sinusoidal position source, a rotary motor was fixed with a cam, which would raise and lower as the motor spun. This sinusoidal motion simulates the near-sinusoidal vertical motion of the torso when walking. The cam of the driving motor is shown in Figure 7. The driving motor is an externally excited brushed DC motor with a step-down gear. The motor/gear system can rotate at up to 5 rpm, which is sufficient for this application, while producing enough torque to continually lift and lower the oscillating load. By using an externally excited DC motor for the sinusoidal position source, the torque can be held constant while the armature voltage is varied to control the driving speed. This will allow testing of a
variety of walking speeds and load mass, but the displacement distance cannot be changed for the testbed.

The PM shaft of the linear generator will be designed to be integrated into the frame of the backpack, and designed as outlined in Chapter 3. For the mechanical testbed, a PM shaft from a linear motor was used; the specifications can be found at [13]. The PM linear motor is much like the PM linear generator, but a controller will generate AC in the windings to force the PM shaft to move. Since this PM shaft was available, it was much easier to use the existing shaft because the testbed is a proof of concept, and as long as the simulation agrees with the experimental results, this will prove that any simulation should be similar to reality. The PM shaft used has a pole-to-pole distance of 25.6 mm and a diameter of 25 mm. The magnets are neodymium with field strength of .32 T. The magnetic shaft is made of thin-walled steel tubing and is filled with epoxy for strength. The ends of the shaft are capped with threaded studs, which make the shaft easy to integrate into the system. The magnetic shaft is affixed to a wood block, which is attached through cord to the motor, which is generating the sinusoidal displacement. From this, block springs are hung which support a lower block that masses will be hung from. By placing the windings of the generator on the bottom block, the generator will dampen the motion of the oscillator, and generate energy for harvesting. The energy harvesting testbed is shown in Figure 8.
The energy harvested from the DDHO is a function of driving frequency, driving displacement, the oscillating mass, the spring coefficient, and the dampening coefficient. The testbed will allow the variation of all of the parameters except for displacement. By rapidly changing the driving frequency, a change in walking speed can be simulated so as to see the response of the maximum power tracking algorithm. By changing the mass, the effect of different masses on the system can be observed. Since the spring constant cannot change, the
springs must be designed so as to have good performance over a wide range of operating conditions.
CHAPTER 3: LINEAR GENERATOR DESIGN

The linear generator is a critical component of the energy harvesting backpack; it must dampen the motion of the DDHO, generate electricity efficiently, and have low mass so as to not add too much weight to backpack. The permanent magnet shaft is ideal for this application, as it can be easily integrated into the tubing of the frame. There are many parameters to optimize when designing a PM linear generator. Simply designing the PM shaft is an involved process, as the pole distance, magnet diameter, magnet strength, gap between alternate magnets, and material between magnets has an effect on the system performance. To design the generator, general guidelines such as those illustrated in [14] and [15] can be used, but these guidelines are not meant for the specific application of the linear generator for an energy harvesting backpack. To properly design the generator, a method of comparison is necessary, which in this case is simulation. By designing a simulation of the entire system including the linear generator, each parameter can be optimized to result in the best generator design. Once the system is designed and built, the performance can be tested using the mechanical testbed, thus verifying the design.

Existing Energy Harvesting Linear Generators

The structure of the PM linear generator is based on a permanent magnet AC rotary motor, but

\[ Emf = N \frac{d\Phi_B}{dt} \]  \hspace{1cm} (1)

\[ F = i \times l \times B \]  \hspace{1cm} (2)

the motor is stretched out linearly. As the field PM shaft passes through the winding of the generator, by Faraday’s law, the voltage generated is shown in equation (1), where \( N \) is the number of turns in the generator winding. The resistive force that extracts energy from the
mechanical system is shown in equation (2), this force is the dampening of the DDHO. There has been much work in the field of energy harvesting linear generators, but none for the energy harvesting backpack. Many researchers have used so called “voice coils” that are essentially PM speakers which, when vibrated, will generate voltage. This type of generator is more suited for very small power levels and higher frequency oscillations. The authors in [16] analyze different linear generator types for the application of wave energy harvesting, which is similar to the energy harvesting backpack in the way the system approximates a DDHO. The applicable linear generators are the permanent magnet linear generator, the switched reluctance generator, and other induction based generators such as the vernier hybrid generator [17]. The generator types were compared, and an ideal structure was determined for this application.

**Linear Generator Type Comparison**

The applicable linear generator types identified were the PM linear generator, and the induction based linear generator. The PM linear generator is a more simple machine to understand, as it is based on the PM synchronous generator, where the magnetic field continuously rotates and alternates on the windings, generating AC. The induction based linear generator is somewhat based on the induction motor, and as a result is more complicated to design and build. The advantage of the induction based generator is that permanent magnets are not necessary, which can be a potential cost savings. The downside is that a complicated iron structure is still required for the induction motor, and for the linear generator this structure will be very difficult to integrate into the frame of the backpack, whereas cylindrical permanent magnets are easy to integrate into the frame. For these reasons, it was decided to primarily focus on PM type linear generators.
Axially Magnetized Linear Generator

The axially magnetized linear generator is perhaps the simplest of the PM linear generator family. As shown in Figure 9 the PM shaft contains cylindrical magnets that are axially magnetized, meaning that the field leaves one side of the cylinder and returns on the other side. This is the most common of cylindrical magnet types. Iron or other high permeability material is placed as a gap in between the alternating orientation magnets. This gap allows the field to escape from the sides of the shaft, pass through the windings, and return at the opposite end of the magnet to complete the magnetic circuit.

![Figure 9 Axially Magnetized Linear Generator](image)

The advantage of this type of PM linear generator is that the magnetic structure is simple to build, and the windings are easy to assemble. The downside is that there is some
power density lost in the magnetic structure because the gap material does not have magnetic properties, so it is not adding to the field, only helping to properly direct it. It is also important to note that the outside of the generator windings should be encased with a magnetically conductive metal such as sheet-metal in order to shorten the length of the magnetic circuit, and increase generated power. Otherwise, the field would have to return through a path in the air to return to the opposite pole. The analysis and design of the axially magnetized linear generator for an energy harvesting DDHO system is performed in [18]. An initial prototype was created to evaluate the initial estimations of voltage and power. The small prototype is shown in Figure 10. The voltage waveforms of the generator unloaded were confirmed as the axially magnetized PM shaft was passed through the generator at a constant speed.

Figure 10 First Prototype of Axially Magnetized Linear Generator
Transversely Magnetized Linear Generator

In the transversely magnetized linear generator, the permanent magnets are magnetized from right to left when standing vertically as a cylinder. This is shown in Figure 11. Now, instead of wrapping the windings around the housing in a uniform fashion, the windings must pass back up to the alternating magnet in order to see the same field polarity on the whole winding at one time. Otherwise, the fields will cancel out, and no power will be generated.

![Transversely Magnetized Linear Generator](image)

**Figure 11 Transversely Magnetized Linear Generator**

The advantage of this magnetic structure is that the magnetic shaft does not require a gap material to direct the field like the axially magnetized generator. This means that the shaft could have higher field density, resulting in either less mass or more power. The drawback of this
structure is that the windings are difficult to make, and would not be feasible for production, especially considering there are over 200 turns per pole of the generator.

Figure 12 Prototype of Transversely Magnetized Linear Generator

Radially Magnetized Linear Generator

The radially magnetized linear generator has a magnetic shaft with cylindrical magnets that have a hole through the center. The magnets are magnetized from the inner hole to the outer surface, so one magnet will have north on the inside of the cylinder, and south on the outer surface. The structure is shown in Figure 13. By alternating the type of magnetization, and using a high permeability inside shaft, the magnetic circuit will flow out of the surface of one
magnet, through the windings, back into the surface of the other magnet, and through the inner shaft back to the first magnet.

![Figure 13 Radially Magnetized Linear Generator](image)

This structure has the shortest magnetic circuit and the potential for the highest energy density. Another advantage is that the winding technique is similar to the axially magnetized generator, as the wires are uniformly wrapped around the generator structure. The only disadvantage is that the radially magnetized magnet is difficult to produce, and as such, is more expensive than the normal axially magnetized magnet. Typically, when a magnet is produced, a high permeability material such as neodymium is exposed to a very high magnetic field, which aligns the poles to their proper orientation. To produce an axially or transversely magnetized magnet, the field is simply applied from one side of the magnet to the other. For the radially
magnetized magnet, the field must originate on the inside of the magnet, and pass radially outward. To generate a high magnetic field from within the magnet is difficult to achieve, thus driving the production cost of that magnet much higher than other magnets. Perhaps in the future, with greater availability, the radially magnetized generator will be feasible.

**Linear Generator Design**

To design the linear generator, a set of comprehensive design equations must be generated. To optimize the design, one must be able to vary individual system parameters and observe the effect. The first task in this process was to determine the system equations. The equations of the mechanical, electrical, and electro-magnetic behavior of the system were derived and integrated to allow for the estimation of system performance. The system equations were used in a Mathcad sheet to develop the linear generator design tool. With this calculator, each parameter such as pole distance, number of poles, number of windings, and wire gauge can be varied to see the performance. The design parameters used are shown in Figure 14, where the calculator will use the design parameters in the derived design equations in Figure 15. Using the calculator, a moderately optimized design was created.
Linear Generator Calculator

**Inputs:**

- Number of phases \( \text{phases} := 1 \)
- Number of turns \( \text{Nturns} := 235 \)
- Number of poles \( \text{P} := 8 \)
- Magnetic field strength \( B := \frac{3265}{10000} \)

**Wire radius (m)**

\( \text{rwire} := .0002553 \)

- 24guage = .0002553
- 25guage = .000227
- 30guage = .000127

**Wire resistance (per 1m)**

\( \text{reswire} := .03329 \)

- 19guage = .0264
- 20guage = .03329
- 22guage = .05294
- 24guage = .0842
- 25guage = .1062
- 30guage = .3385

**Distance btwn poles (m)**

\( \text{dpoles} := .0256 \)

**velocity (m/s)**

\( \text{vel} := .5 \)

**winding radius (m)**

\( \text{windrad} := .018 \)

**ideal min efficiency**

\( \text{eff} := .8 \)

**acceleration (m/s)**

\( g := 9.8 \)

**Dimensions:**

- Full motor length (m)
  \( \text{motorlength} := \text{dpoles} \cdot \text{P} \)
- Wire length (m)
  \( \text{wirelength} := \text{P} \cdot \text{Nturns} \cdot 2 \pi \text{windrad} \)
- Motor Mass (lbs)
  \( \text{mass} := \text{wirelength} \cdot 0.0101706 \), \( \text{per phase} \)
  \( \text{copper} = .0101706 \text{ lbs/m} \text{ Al} = .00380577 \)

*Figure 14 Design Parameters and Calculator for the Linear Generator*
**Outputs:**

**Time to cross one pole**
\[ t_{pole} := \frac{d_{poles}}{v_{el}} \]
\[ t_{pole} = \]

**Loop area (m^2)**
\[ A := \pi \left( \text{windrad}^2 \right) \]
\[ A = \]

**Peak output voltage**
\[ \text{Emf} := P \cdot N_{turns} \cdot A \cdot \frac{B}{t_{pole}} \]
\[ \text{Emf} = \]

**Winding resistance**
\[ \text{windres} := \text{wirelength} \cdot \text{reswire} \]
\[ \text{windres} = \]

**Max current**
\[ \text{maxcurrent} := \frac{\text{Emf}}{\text{windres}} \]
\[ \text{maxcurrent} = \]

**Max force**
\[ \text{maxforce} := \text{maxcurrent} \cdot \text{wirelength} \cdot B \]
\[ \text{maxforce} = \]

**Max power**
\[ \text{maxpower} := 0.25 \cdot \frac{\text{Emf}^2}{\text{windres}} \]
\[ \text{maxpower} = \]

**Current at max power**
\[ \text{imaxpower} := \frac{\text{Emf}}{2 \cdot \text{windres}} \]
\[ \text{imaxpower} = \]

**Force at max power**
\[ \text{Fmaxpower} := \text{imaxpower} \cdot \text{wirelength} \cdot B \]
\[ \text{Fmaxpower} = \]

**Vout at max power**
\[ \text{Vmaxpower} := \text{imaxpower} \cdot \text{windres} \]
\[ \text{Vmaxpower} = \]

**Rload at ideal efficiency**
\[ r_{loadeff} := \text{eff} \cdot \frac{\text{windres}}{1 - \text{eff}} \]
\[ r_{loadeff} = \]

**Current at ideal efficiency**
\[ i_{eff} := \frac{\text{Emf}}{r_{loadeff} + \text{windres}} \]
\[ i_{eff} = \]

**Vout at ideal efficiency**
\[ \text{Veff} := \text{ieff} \cdot r_{loadeff} \]
\[ \text{Veff} = \]

**Power at ideal efficiency**
\[ \text{peff} := \text{ieff}^2 \cdot r_{loadeff} \]
\[ \text{peff} = \]

**Force at ideal efficiency**
\[ \text{Feff} := \text{ieff} \cdot \text{wirelength} \cdot B \]
\[ \text{Feff} = \]

---

**Figure 15 Design Equations for the Linear Generator**
The goal of this design process was not to determine the completely optimal final design, given that this is a new system and how all of the sub-systems of the backpack will interact is unknown. The goal is to design a moderately well optimized generator for evaluation in the mechanical tested. Then, a system simulation can be created to compare with the experimental results. Once the simulation tools have been verified to be accurate with experimental results, comprehensive optimization steps can be made which will result in a final design.

The PM shaft of the linear generator is a shaft used for a linear motor. In this case, it is used in a similar fashion, but instead of moving the motor, motion is used to generate energy. Since it is already manufactured, the rest of the generator will be designed around the specifications of the PM shaft. The design of the backpack structure is shown in Figure 16. In a final design, the PM shaft will be designed for size, efficiency, and cost. The diameter of the PM
shaft is 25 mm, and the distance between poles is 25.6 mm. To design the generator, a thinwalled tube must be found which will allow for the shaft to easily slide through without allowing too much space, which will diminish the field strength. The body tube must be non-ferrous, strong, and light. For a final design, a plastic polymer would be used, as it is durable and will work well in this application. For the prototype, a cardboard tube was found with the proper diameter. The tube was saturated with polyurethane and allowed to dry, which resulted in a strong body tube of polyurethane, as the polymer completely fused with the fibers of the cardboard.

The designed generator has 8 poles, which means there are 8 alternating groups of wire windings. One might think that as more turns are added, more power can be extracted, since the generated voltage is proportional to the number of turns, but this is a fallacy. The field diminishes with distance from the generator and the resistance of the generator will increase with more windings. Thus, there is an optimal number of windings which will result in the most power and efficiency. Based on the linear generator calculator that was designed, 235 turns were used in each pole. To keep the windings for each pole in place, the winding spacers were constructed of acrylic rings with grooves for the internal passing of wire between each phase. The windings are secured with cyanoacrylate glue and gap filling accelerant. Wire was wound alternating direction between poles, and sealed with polyurethane to keep the winding from shifting. The completed generator can be seen in Figure 17. The field of the axially magnetized PM shaft is shown in Figure 18. The generator tube was mounted to a support block that has hooks for holding different masses, allowing the testing of the generator under different loading conditions. The spring of the testbed can be changed as well, along with the walking speed.
Figure 17 Windings of the Linear Generator

Figure 18 View of the Magnetic Field from the PM Shaft
Energy Harvesting Backpack Simulation

The mechanical system was simulated using Ansoft Simplorer, which allows for the combination of mechanical systems with electrical and control systems. A controlled sinusoidal position source was created to simulate the user’s back. A spring and a dampener were connected in parallel, with the mass independently hanging under the force of gravity. The simulation is shown in Figure 19. The simulation allows for verification and optimization of the system.

![Simulation Diagram](image)

**Figure 19 Simulation of the Energy Harvesting Backpack**

As the damping ratio is swept, it can be seen that the steady state system will react accordingly. The maximum power point can be seen in Figure 20, while the interaction forces between the user and the system can be seen in Figure 21. The simulation allows for the probing and graphing of any desirable system information, which is not practical in a real device. Such a feature offers accurate optimization of the system at a minimal cost. This also allows the testing of the control algorithms before the complete prototype has been constructed. In this way,
multiple aspects of the project can be completed in parallel, without relying on one specific portion to permit further work.

The simulation confirms the expectation of a system with multiple ideal operating conditions dependent on the user’s objectives. There exists a maximum power point, which is the loading condition that will result in the maximum harvested energy. There also exists a maximum comfort point, which is a loading condition where the user will experience the least forces. The simulation shows that the dampener will dissipate up to 37 Watts under completely ideal conditions and in the most ideal operating condition.

![Figure 20 Harvested Power vs. Dampening Coefficient](image)

The ideal power generated in the maximum comfort point is only 4 Watts, but the peak-peak forces experienced by the user are significantly less. After non-idealities are introduced throughout the mechanical and electrical system, the expected maximum power is approximately
15 Watts. The estimation of electrical efficiency can be made relatively accurately, as the known idealities of electrical components are fairly constant. However, the losses of the mechanical system are much more difficult to estimate, as the non-idealities vary with system design and optimization. A mechanical efficiency of 50% is anticipated, while an electrical efficiency of 85% is expected.

![Figure 21 Body Contact Force vs. Dampening Coefficient](image)

**Figure 21 Body Contact Force vs. Dampening Coefficient**

The mechanical simulation uses an ideal dampener to simulate the generator, but the actual energy harvesting system uses the electro-mechanical system, which can also be simulated. If an accurate model of the linear generator is created, the designer can vary any of the system’s mechanical, electrical, or controller parameters to evaluate the performance. Since the design equations that were derived earlier apply for all instances of time, it is possible to
apply them to a continuous simulation of the linear generator; this is described in the next section.

**Linear Generator Simulation**

By using the system equations that were derived to describe the behavior of the linear generator, it is possible to create a continuous simulation of the linear generator, which can be implemented into the mechanical simulation of the energy harvesting backpack. A sub-mask was create in Simplorer which has two ports representing the mechanical connections of the shaft and the generator housing, and two ports representing the generated voltage. Inside the model of the linear generator, a controlled force source was used to simulate the physical resistance to motion. The position, velocity, and acceleration of the force source is measured and processed with the system equations that were derived earlier.
Figure 22 Continuous Simulation of the Linear Generator

The equations are completely parameterized, meaning that the designer can easily change system parameters, such as wire gauge or the number of poles, to see the effect. The generated voltage is calculated and fed to a controlled voltage source, which is interfaced to the outside of the model. Depending on the loading of the voltage source, the current will vary, which affects the resistive force of the generator. The continuous equations generate the appropriate resistive force, which is fed to the mechanical force source. The parameterized continuous simulation of the linear generator is shown in Figure 22. This model of the linear generator then replaces the dampener of the energy harvesting backpack simulation, allowing verification of the model.
To verify the proper operation of the linear generator model, the experimental waveforms of the mechanical testbed with the linear generator can be compared to the waveforms from the simulation. The simulation was configured with all of the parameters of the mechanical testbed, with the hopes that the experimental and simulated results are similar. The simulated results are shown in Figure 23 and Figure 24.

![Simulated Output Voltage from Linear Generator](image)

Figure 23 Simulated Output Voltage from Linear Generator
Now that simulated results have been achieved, the actual linear generator can be tested using the mechanical testbed. The mass used was 11.33 kg (25 lbs), the walking frequency is 1.5 Hz, and the driving amplitude is 1.7 cm. The experimental waveforms are shown in Figure 25. It was found that the experimental and simulated results were quite similar, considering that the simulation does not consider mechanical losses of the system. In fact, the simulated power was less than the experimental results, leading one to believe that there is either an underestimation of the magnetic field strength in the PM shaft, or the spring constant may not be accurate in the simulation. The simulation projected .86 Watts, while the experimental resulted in 1.0 Watts of
generated power. The simulated voltage waveform with the experimental waveform overlaid in Figure 26 shows how close the simulation is to reality.

Figure 25 Experimental Voltage and Current from Linear Generator

Figure 26 Comparison of Simulated and Experimental Voltage Waveform
With the assumption that the simulation is accurate, and by extrapolating the experimental results, an estimation of generated power at different operating conditions can be made. The expected generated power at different walking speeds and load conditions are shown in Table 1. From these results, it is promising that the energy harvesting backpack will be beneficial to users who are away from traditional energy sources for long periods of time.

**Table 1 Estimated Energy Harvested**

<table>
<thead>
<tr>
<th>Load Weight</th>
<th>2.5 mph</th>
<th>3 mph</th>
<th>3.5 mph</th>
<th>4 mph</th>
<th>4.5 mph</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>40 lbs</strong></td>
<td>3.84</td>
<td>4.6</td>
<td>5.37</td>
<td>6.14</td>
<td>6.9</td>
</tr>
<tr>
<td><strong>50 lbs</strong></td>
<td>6</td>
<td>7.2</td>
<td>8.4</td>
<td>9.6</td>
<td>10.8</td>
</tr>
<tr>
<td><strong>60 lbs</strong></td>
<td>8.63</td>
<td>10.36</td>
<td>12.09</td>
<td>13.8</td>
<td>15.54</td>
</tr>
<tr>
<td><strong>70 lbs</strong></td>
<td>11.75</td>
<td>14.1</td>
<td>16.45</td>
<td>18.8</td>
<td>21.15</td>
</tr>
</tbody>
</table>

The successful design and mechanical testing of the linear generator in the energy harvesting backpack system shows that the concept is feasible, and given proper processing of the energy and proper control, the energy harvesting backpack will be successful. The accurate simulation will allow for further testing of the control strategies and the power converter. The next chapters will show the design and testing of the AC/DC converter as well as the design of the control strategy.
CHAPTER 4: UNITY POWER FACTOR AC/DC CONVERTER

Now that a method of energy harvesting and generation has been developed, it is necessary to develop a converter, which will take the AC from the linear generator and charge a battery for storage of the energy. The source is a non-uniform AC voltage from the linear generator with a peak voltage of up to 10 Volts, and a maximum power of 20 Watts. A compact and efficient AC/DC converter must be designed and built which will allow the harvested energy to be controlled to charge a battery or run electronics. The voltage at which the AC/DC converter should charge batteries is up to the designer, and in this case charging either 12 V or 24 V batteries is the most useful, since most military personnel will carry 12/24V Li-Ion batteries as shown in Figure 27. The AC/DC converter should be a switching converter with high efficiency and small size. To achieve the desired performance, simulation and power electronics design techniques were used.

Figure 27 Typical Li-Ion Battery for Military Use, UBI-2590
Existent AC/DC Converters for Energy Harvesting

The AC/DC converter is a blanket term for any converter, which will convert AC voltage to some other level of DC voltage. The term AC/DC does not indicate the actual structure of topology of the converter, as this is highly variable depending on the application. A simple digitally controlled unity power factor converter is implemented in [19]. Another method of achieving near-unity power factor is shown in [20]. A low power PM linear generator is shown in [21], where a non-controlled rectifier is used to perform the AC/DC conversion. By not controlling the loading, the power generated is not optimized. Work to develop a unity power factor AC/DC converter for micro energy harvesting is shown in [22], where the optimal performance was found when the load approximates a resistor. Also in [6] a DDHO with a linear generator was used with a boost converter to approximate a resistive load and harvest energy from the system. The method of achieving high power factor was through feedforward control, which was ideal for that application, since the power levels were considerably less than that of the energy harvesting backpack, which will benefit from the added control complexity to design a true unity power factor AC/DC converter.

Proposed AC/DC Converter

In order to maximize the efficiency of the linear generator, it is ideal to have a purely resistive load, since a resistive load is synonymous with unity power factor. Power factor is a measure of the distortion from a purely resistive load, with a 1 representing unity power factor, where voltage and current are completely in phase. If a generator is loaded with less than unity power factor, efficiency and capacity are lost, since more current must be sourced in order to deliver the same real power. An example of this problem is power factor for electric distribution systems, where the load is often inductive, and the current lags the voltage. Since real power is
the multiplication of current and voltage, when they are out of phase, more current is required to deliver the same amount of power. As such, the losses are higher even though the same amount of power is being delivered. This is the same case for the linear generator, if the load is not purely resistive, higher currents will be necessary to generate the same amount of power, which will result in higher losses. Since the resistance is relatively high for the linear generator (7 Ω), the $i^2R$ losses will be a significant portion of the total system losses, and excess current due to bad power factor should be avoided for an efficient system.

A unity power factor AC/DC converter is the ideal power converter to charge the battery, since it is necessary for the converter to approximate a resistive load. In order for the converter to be able to push current to the battery at all voltage levels from the generator, the converter must be capable of boosting the voltage to the battery voltage. The boost converter is the most desirable for this application and while many potential topologies exist, the boost converter is simple, efficient, and capable of small size. If the converter is operated in continuous conduction mode (CCM), the current ripple will be smaller than the dc current. When in deep CCM, the input current is nearly constant, which is necessary to minimize the current ripple from the generator and maximize efficiency.

To achieve unity power factor, as the input voltage changes, the controller for the boost converter should change the amount of current pulled by the converter, keeping the ratio of voltage and current at a constant value. The constant ratio between input voltage and load current represents the input impedance of the converter, allowing the controller to change the ratio to simulate different load resistances. To the generator, it will seem that the load is a resistor, while in reality the energy is being boosted up to the voltage of the battery for storage and later use. The input of the boost converter is a full wave rectifier, which will convert the
AC into rectified AC, which has the same shape as the original AC, but is only positive. The topology of the AC/DC boost converter is shown in Figure 28.

![Figure 28 AC/DC Boost Converter Topology](image)

**Unity Power Factor Control**

To control the input current to be unity power factor, a current control loop is implemented, which can control the current to be a value that is equal to \( V_{in}/R \), where \( R \) is a variable that can be controlled by a higher-level controller to achieve the desired generator performance. The entire energy harvesting backpack system is digitally controlled, since advanced control strategies are being performed, control which would be costly and complicated to implement using analog control. The advantage of the digitally controlled power electronics system is that the system parameters can be adjusted on the fly, allowing for a very versatile and effective system. The innermost control loop is the input current controller, which will quickly adjust the pulse width modulation (PWM) of the boost converter to achieve the desired input current. The outer loops are the controllers for the maximum power point tracking, and the battery charge controllers. Since the other controllers are less time critical than the current controller, they can run in the background with free computing time that the controller is not
using. The interrupt service routine is designed so that the input current controller is updated on every switching cycle, while the other control loops will only execute occasionally.

![Diagram](image)

**Figure 29 Unity Power Factor Digital Controller**

To control the input current, a digital controller with some controller compensation was implemented using the Texas Instruments TMS320C2812 DSP, as is shown in Figure 29. The controller actually uses G as the conductance instead of R for impedance, since that allows for multiplication by Vin to determine the current reference. This seems like an insignificant difference, but it has the potential to speed up the operation of the controller depending on the type of mathematical operations that are being used.

**Prototype AC/DC Boost Converter**

The prototype AC/DC boost converter was designed and constructed for evaluation of the control techniques and to verify the proper interaction between the energy harvesting system and the unity power factor converter. It is important to verify that the linear generator will be able to effectively charge a battery. The system parameters of the converter are shown in Table 2. A photograph of the converter is shown in Figure 30.

**Table 2 Characteristics of the AC/DC Converter**

<table>
<thead>
<tr>
<th>L</th>
<th>f&lt;sub&gt;sw&lt;/sub&gt;</th>
<th>V&lt;sub&gt;in&lt;/sub&gt;</th>
<th>V&lt;sub&gt;out&lt;/sub&gt;</th>
<th>I&lt;sub&gt;out&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>273 uH</td>
<td>150 kHz</td>
<td>0Vac – 10Vac</td>
<td>12V-24Vdc</td>
<td>0A - 3A</td>
</tr>
</tbody>
</table>
To design the digital controller, first an integrator was used with some gain as a basic controller. It was found that the converter would track to the reference command, but the transient response was too slow. To increase the performance of the converter, the controller was digitally compensated with a digital zero to boost the phase margin, and allow a higher gain and enable a faster response.

Figure 30 Experimental AC/DC Prototype

To design the digital controller, first an integrator was used with some gain as a basic controller. It was found that the converter would track to the reference command, but the transient response was too slow. To increase the performance of the converter, the controller was digitally compensated with a digital zero to boost the phase margin, and allow a higher gain and enable a faster response.
The result was that the converter could quickly track to the desired current reference while maintaining stability. The next step was to sense the input voltage with the converter, and then multiply the value of the input voltage by the constant $G$, which would cause the controller reference to vary with the input voltage, thus controlling the input current to be at a constant ratio with input voltage, and thus achieving unity power factor. The experimental waveforms of a pure sinusoidal AC input voltage prove that the converter will be able to operate at the frequency of the linear generator. The unity power factor of a sinusoidal input voltage is shown in Figure 31. The current matches the phase of the voltage very well, with the only error being at the crossing points, which are unimportant since there is little power delivered at the crossing points.
Experimental Results from AC/DC Converter

The AC/DC was tested with a pure sine wave voltage source to determine if the unity power factor control was operating correctly. The converter was found to have a power factor of .98, which is near unity, and acceptable for this application. While the converter works well with a pure sine wave, and is expected to work well with the actual linear generator, since the AC wave from the generator is irregular, the operation of the AC/DC converter still must be analyzed.

The mechanical testbed was tested previously with a resistive load, which resulted in the experimental waveforms matching the simulated waveforms, thus verifying the proper interaction between the two systems. Now a third system being the AC/DC converter must be implemented, which will load the generator resistively while boosting the voltage to charge a 24V battery. The digital controller was set to a constant resistive value for the evaluation of the controller, since the AC/DC controller should now exactly match the results of a resistor as was tested earlier. As shown in Figure 32, as the input voltage changes, the input current is controlled to follow the voltage by a constant value R, which confirms that the AC/DC converter is operating properly. This proves that the unity power factor AC/DC converter was designed properly, and should be able to load the generator properly under the control. Since the inner loop is free running, the controller must only deliver a variable representing the desired virtual impedance. This will allow the master controller to execute at a much slower rate than the controller, which executes at the switching frequency (100 kHz).
Figure 32 Experimental Waveforms of Linear Generator with AC/DC Converter
CHAPTER 5: MAXIMUM ENERGY HARVESTING CONTROL

The basis of Maximum Energy Harvesting Control is maximum power point tracking (MPPT) for photovoltaic arrays, where the I-V curve of a solar cell is such that there exists a maximum power point. The proper active control of the loading on a photovoltaic cell will allow the device to deliver maximum power, which is similar to the case of the DDHO. There are some significant differences between the application of MPPT for solar cells and the DDHO. So-called “fast MPPT” algorithms are designed to quickly track the maximum power point of a solar array so as to ensure that little energy is lost as a result of disturbance to the power flow, such as the passing of a cloud. By designing the algorithm to quickly achieve the maximum power point of the solar array, the designer hopes to increase the effectiveness of the design [7]. In the case of the DDHO energy harvesting device, the time constants of the system are orders of magnitude larger than that of a solar array, which can be detrimental to an effective maximum power seeking algorithm. While it may be acceptable for a solar MPPT algorithm to take 1 second to reach the maximum power point, it is unacceptable for the same algorithm to require 200 seconds to achieve the maximum power point on a backpack generator, considering that the operating conditions are likely to have already changed in that time. A slow MPPT algorithm might never reach the maximum power point in a system that is constantly changing.

An MPPT algorithm for wind-energy harvesting was described in [23] which the MPPT algorithm operates in a hill climbing manner, but since the time constants of the mechanical system are slower than that of a PV array, the tracking time is considerably longer. Another MPPT algorithm for wind energy is shown in [24].

The problem of the slow reaction speed of the DDHO is exacerbated by the need of the MPPT algorithm to know the average output power of the generator so as to identify whether a
change in loading has resulted in increased or decreased power. The frequency of the AC power delivered by the DDHO in a backpack application is approximately 2 Hz; to filter this incoming power to a DC average level will further decrease the system reaction speed significantly. The resultant could be a system with a time constant of over 5 seconds, which would require that the MPPT algorithm wait over 5 seconds between each single step in order to determine if the power is increasing or decreasing as the algorithm tracks. As the MPPT algorithm must perform a multitude of iterations to achieve maximum power, it is clear that a new adaptation of peak power tracking is necessary for this application.
Traditional MPPT Simulation

In order to gauge the effectiveness of new maximum power point tracking algorithms, the performance of traditional MPPT must be tested. The simulation of the energy harvesting backpack was adapted to utilize the MPPT algorithm, as shown in Figure 33. The simulation implements a traditional MPPT algorithm, which utilizes a filter to average the AC power signal into a DC representation of average power. Since the act of filtering requires multiple cycles of AC to occur before the filter settles to a steady state, the speed of the MPPT algorithm is significantly slowed when applied to AC sources.

Figure 33 Simulation of MPPT for the Energy Harvesting Backpack
Figure 34 Simulated Output Power after MPPT Control Steps
Figure 34 shows the step response of the output power as the MPPT algorithm changes the control variable; it is evident that the power output has increased with each step, since the amplitude of the instantaneous AC power signal will quickly increase. Figure 35 shows the filtered version of the output power, which takes much longer to settle to a DC value. Because of this delay, the MPPT algorithm cannot execute faster than 5 seconds per step, which resulted in a total tracking time of 250 seconds, as is shown in Figure 36.
Typically, a MPPT algorithm will have a constant loop frequency, which is the speed in which the algorithm performs the “perturb and observe” operation. This loop frequency is designed for the reaction characteristics of the system that is being controlled. Typically, the loop speed is set to a time constant greater than that of the system, so as to prevent instability. In the case of the DDHO, the time characteristics of the system are highly variable and are constantly changing. A key characteristic of the MECH algorithm is variable loop speed, which allows the inherent MPPT actions to be performed as quickly as the system will allow. To
achieve variable loop speed, it can be observed that the voltage delivered by the generator consists of a higher frequency sinusoid enveloped in a lower frequency sinusoid.

Figure 37 Maximum Energy Harvesting Control Structure

Figure 37 depicts the MEHC algorithms and the basic composure of the generated voltage. The lower frequency envelope represents the velocity of the oscillating system, since the oscillator must continually pause and accelerate in the opposite direction, fundamentally there is always a period where the voltage must be zero. The higher frequency sinusoid represents the multiple poles of the generator, which create AC voltage as the windings pass the alternating permanent magnets. By actively detecting the zero voltage condition associate with the change of direction of the oscillating system, the MPPT algorithm can be activated at a period corresponding to each oscillation of the system. The zero-voltage detector has a
minimum time window, which prevents false triggering as the higher frequency AC crosses the zero voltage line.

Now that the MEHC controller can determine when a single oscillation has occurred, the controller can accumulate the instantaneous power generated over the oscillation period, which corresponds to the energy delivered to the storage battery in that period. After each completed oscillation, the controller will execute a single iteration of the MPPT algorithm, using the accumulated energy of the last pass as the variable to maximize. After the execution of the MPPT algorithm, the energy accumulator is reset, which will then restart the process as the next oscillation occurs.

![Figure 38 MEHC MPPT Tracking after Driving Frequency Step](image-url)
By triggering the MPPT loop based on the frequency of the DDHO and not filtering the AC power signal, the MEHC methodology is sure to reach the maximum power point much sooner than the filtered AC constant loop frequency MPPT algorithm. Using the previously mentioned simulation of both the mechanical system and the linear generator, a simulation of the MEHC algorithm was created. The results showed that the MEHC algorithm was very effective in quickly reaching the maximum power point of the system. In Figure 38 it can be seen that the algorithm found the maximum power point in approximately 20 seconds after a step in the walking speed. It can be seen when comparing to the step response from regular MPPT, the rising slope of the MECH controller is faster, since it takes less time to make a decision and increment the controller variable.

The boost converter was designed for the expected peak input voltage of 10V, and an output battery of 24V. The boost converter was designed to always operate in continuous conduction mode, which enables the smooth input current to achieve unity power factor. The boost converter is synchronously switching, which is to achieve higher efficiency. The control was achieved completely using the Texas Instruments TMS320F2812 DSP, which is overkill in terms of computing power with respect to this application, yet was used for the convenience as a proof of concept. The mechanical testbed was operated at a frequency of 1.67 Hz, which corresponds to a walking speed of 4.67 km/hr (2.9 mph). The oscillating mass was 9 kg (20 lbs), which is less than the projected mass of 35 kg (77 lbs) for the final application. It should be noted that increase in power from an increase in mass or speed is non-linear, meaning that the final application is expected to generate considerably more power than the testbed.

The existence of a maximum power point was confirmed by sweeping the virtual impedance of the PFC boost converter while maintaining a constant oscillation frequency. It was
found that for this operating condition, the maximum power point occurs at a virtual impedance of 20 Ω, this can be seen in Figure 39. The experimental waveforms match the simulated waveforms, which verify the correct operation of the simulated mechanical system as well as the simulation of the linear generator (Figure 26). Basic MPPT algorithms have been executed as a baseline in judging the performance of the MEHC algorithm. As expected, the basic MPPT algorithm is quite slow to find the maximum power point due to the necessary filtering of the AC power waveform, and the very slow time constants of the mechanical system. It is expected that the MEHC algorithm will perform as was found through simulation.

![Figure 39 Experimental Results Confirming Maximum Power Point](image)

The difficulty in implementing the MEHC algorithm is in the establishment of the timing in the digital controller. The rate at which the power-sampling accumulator executes must be high enough to calculate a reliable energy comparison between two operating conditions. At the same time, if the sampling rate is too high, the accumulator may overflow, and the controller will require higher resources. Another challenge is in the determination of the proper minimum window of the zero-voltage detector. It is expected that these challenges should be met with
careful design of the controller, and the tracking speed of the MEHC algorithm will be compared to the typical MPPT algorithm.
CHAPTER 6: CONCLUSIONS

Many existing and future energy harvesting devices exhibit the behavior of the driven damped harmonic oscillator (DDHO), most of which will produce power in an alternating or pulsed manner. Most existing maximum power point tracking (MPPT) algorithms are optimized for DC sources with very small time constants. Since mechanical systems inherently have much larger time constants, a new peak power-seeking algorithm has been developed which can significantly reduce the time necessary to reach the maximum power point compared with traditional means. The development of the maximum energy harvesting control (MECH) structure has been directly applied to the challenge of the energy harvesting backpack, of which minimum tracking time is crucial. The development of a fully digital controller had resulted in a low complexity solution, which will sink unity power factor current from the generator, and optimize the virtual impedance of the PFC boost converter so as to maximize the energy captured from the mechanical system.

An energy harvesting backpack system has been designed which will effectively harvest energy from the mechanical interactions between a person walking and a carried load. The PM linear generator design was tested and has been shown to effectively generate power. The simulation of the mechanical and electromechanical system has been shown to correctly match the experimental performance, showing that simulations of future systems can effectively help to design a working system. The mechanical testbed was then used with the prototype unity power factor AC/DC converter to charge batteries at maximum power, successfully completing the proof of concept for the energy harvesting backpack.

Other energy harvesting systems beyond the energy harvesting backpack also exhibit the maximum power point characteristic as well as the irregular AC source that is inherent in the
DDHO. Many wave energy harvesting systems exhibit characteristics similar to the DDHO, such as that done in [25]. The nature of the oscillations from a buoy floating on the ocean of which the motion is captured using either linear generators or AC rotary generators is similar to the energy harvesting backpack, since the produced voltage will appear as a higher frequency AC wave enveloped in a lower frequency AC wave. The higher frequency is related to the alternating poles on the AC generator, the lower frequency corresponding to the position of the buoy as the wave passes by. To maximize the harvested energy, the existing art would filter the power waveform, and then perform a slow maximum power point tracking operation to maximize the energy harvested. The nature of ocean waves is similar to that of the energy harvesting backpack, as the amplitude and frequency of the oscillations can vary greatly and change quickly. To implement the MEHC algorithm could increase the tracking time significantly, which could result in a higher amount of harvested energy.

A novel energy harvesting system was proposed in [26], in which the authors developed an energy harvesting eel based on piezoelectric polymers. The system does not embody the DDHO, yet it does produce AC voltage. Depending on the electrical loading of the generator, the output power will vary, as well as with variation in the operating conditions. The MEHC algorithm could be applied to this type of system, where AC voltage would normally be filtered before the MPPT algorithm can be executed. By using MEHC, the system time constants can be decreased by removing the filtering of the AC input power.

Future Work

Undoubtedly, there are other energy harvesting sources that also exhibit such behavior as the energy harvesting backpack, future work will be to determine these applications and attempt to apply the MEHC algorithm to improve the performance. The implementation of MEHC as
outlined in this paper is a basic guideline for a new control strategy, but it does not outline the methods of optimization and design. As with any MPPT system, the algorithm parameters such as tracking step size and noise immunity are variables, which can have significant affects on the performance of the system. Future work will be to study the control dynamics of the MEHC system and develop tools for easy design and implementation in new and current systems.
REFERENCES


