“BREEZE FARMER”
AN OPEN-SOURCE BIKE WHEEL WIND TURBINE

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Executive Summary

Geopolitical and environmental concerns means the demand for alternative energies will continue to rise, but the largest inhibiting factor right now is cost as compared to cheap oil. To avoid environmental catastrophe, inexpensive solutions need to become available: distributed power generation, from a ubiquitous energy source such as wind, has the potential to fill this gap. However, the average household wind is typically slow for most of the year, so turbines need to be efficient and low-friction to take advantage of these slow winds. Since most mechanical friction results from the complexities of the hub and shaft assembly, where power is typically generated in most turbines, a key design feature would be to make the hub as simple as possible so that it spins freely like a bicycle wheel. This outer-rim induction is the basis for our project Breeze Farmer, an open-source home wind turbine that is designed to be assembled cheaply out of parts like a used bicycle wheel.

Wind blades are first mounted onto the wheel, which itself can be mounted onto a rotating frame so that the wheel is always perpendicular to the wind. The induction required to convert mechanical to electrical energy takes place around the rim of the wheel, where a number of magnets are mounted. As these pass by inductor coils mounted onto a stator wheel frame mounted right behind, alternating current is produced. This induction will slow down the wheel, but since this drag is purely electromagnetic and not mechanical, it should be at a theoretical minimum. The current is fed into a circuit which converts it to DC, which can then be used to charge a 12V battery. This is but one possible application for the current produced.

The Breeze Farmer prototype was constructed and tested in the Engineering Physics Project Lab. It was sponsored by Bernhard Zender of the same lab, who came up with the project idea. Breeze Farmer is based on the design of the far more expensive Honeywell Wind Turbine, but aims to be a cheap do-it-yourself endeavor. The prototyping project consisted of several different configurations of magnets, inductors, blade material and shape, and other variables in order to derive the most efficient setup for maximal power generation with a minimal start speed. These metrics were probed using very basic measurements of wind speed, rotational speed, load, and rectified power.

After developing a Breeze Farmer prototype, it has been found that, with a reasonable number of magnets and many coils, the electrical power generated is rather small. Large factor of this is power losses in eddy currents in our aluminum stator rim, and losses in the coil conductors.
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<td>BJT</td>
<td>Bipolar junction transistor</td>
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<tr>
<td>DAQ</td>
<td>Data acquisition module</td>
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<td>DMM</td>
<td>Digital multimeter</td>
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<tr>
<td>DSP</td>
<td>Digital signal processing</td>
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<tr>
<td>EMF</td>
<td>Electromotive force</td>
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<tr>
<td>ESR</td>
<td>Effective series resistance</td>
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<tr>
<td>IC</td>
<td>Integrated circuit</td>
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<tr>
<td>FET</td>
<td>Field effect transistor</td>
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<td>HAWT</td>
<td>Horizontal-axis wind turbine</td>
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<tr>
<td>MSRP</td>
<td>Manufacturer suggested retail price</td>
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<tr>
<td>Op-Amp</td>
<td>Operational amplifier</td>
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<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
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<td>RPM</td>
<td>Revolutions per minute</td>
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1.0 Introduction

1.1 Background and Motivation

Wind power, based on simple scientific principles dating back to antiquity, has been harnessed in a diverse range of applications across much of recorded history. After centuries of use in providing direct mechanical power, wind turbines began producing electricity in the late 19th century and their use has become more and more widespread since. Much like the hydroelectric dam, wind turbines convert the raw power of nature into useful energy with a minimal environmental footprint. As the world’s supply of inexpensive oil begins to diminish, and environmental issues such as climate change become impossible to ignore, the world will require alternative energies, including wind power, to take an increased role in providing power to the population. Although this transition won’t happen overnight, it can be aided by providing the opportunity for consumers to supplement their reliance on the power grid with decentralized alternative power production. A relatively inexpensive consumer wind turbine for home use provides this opportunity, not only providing the consumer with long-term savings in utilities bills, but lowering the consumer’s carbon footprint and aiding the gradual transition from fossil fuels to alternative energies.

Although several wind turbine designs exist, some harnessing drag and some harnessing lift, some with a vertical axis and some with a horizontal axis, the most common type is the modern horizontal-axis wind turbine (HAWT). Harnessing lift, its use is the most widespread due to its high efficiency, a result of the blades always moving perpendicular to the wind and hence eliminating wasteful backtracking. Most new wind turbines tend to be rather large, and placed in strategic geographic locations where average wind speeds are highest. They use a small number of aerodynamic blades (typically 3) to efficiently capture wind at reasonable speeds (typically up to 47km/h) before shutting down in higher speeds to prevent catastrophic failure of their mechanical systems; this type of design is optimized for areas of high average wind and where the presence of large turbines is tolerated. The typical household, on the other hand, usually experiences modest to low average wind speeds: 90% of wind resources in North America are below 14.5km/hr on average. Thus, a market exists for small turbines that can start and run in very low wind speeds, but are also able to run in higher wind speeds without damage. There is one key innovation that is vital to these goals.
The Honeywell Wind Turbine, developed by WindTronics and shown in Figure 1, is an upcoming consumer product that satisfies the aforementioned requirements. It uses many blades to increase efficiency in low speeds while sacrificing efficiency in high speeds, but its key lies in its ‘Blade Tip Power System’: rather than using shaft rotation (possibly involving a gearbox) to run a generator, the blade tips themselves interact electromagnetically with inductor coils placed around the perimeter of the turbine. With this type of setup, the only mechanical resistance remaining lies in the hub, but since this no longer involves a central shaft and gear, it can be quite minimal. Meanwhile, higher wind speeds are tolerated because the simplicity of the mechanical component allows for a far higher rate. The many-blade design also deliberately slows the rotation rate proportional to wind speed at higher velocities. With a manufacturer’s suggested retail price (MSRP) of $6,495, the turbine is supposed to pay for itself in energy savings within a typical 1-3 years.  

However economical the Honeywell Wind Turbine is, there exists a small but significant interest in do-it-yourself alternatives for home wind turbines. These are typically open-source projects, with free construction plans and a low-cost requirement. All open-source projects for HAWT turbines involve the traditional shaft generation; we think it is worthwhile to begin an open-source turbine project that makes use of the Blade Tip Power System concept, since this theoretically should not add great expense. The cheaper nature of do-it-yourself systems implies that the gains from having no shaft generation and hence less mechanical resistance...
are even greater, particularly at low wind speeds where a typical do-it-yourself may not even run. We are investigating the proposition that such a system can be built out of common parts like a bicycle wheel and make use of generic components like magnets and inductor coils. The open-source project is the brainchild of Bernhard Zender of the UBC Engineering Physics Project Lab, who is also the project’s sponsor. The name of this open-source prototype is the Breeze Farmer. Bernhard provided an initial SolidWorks prototype of his idea, shown in Figure 2.

![Figure 2: Solidworks rendering of Bernhard Zender’s original vision.](image)

### 1.2 Project Objectives

The ultimate aim of the project is to construct a functional prototype of a wind-powered induction generator. This generator will differ from a wind turbine’s typical construction because it will use magnets instead of a shaft and gear system to transfer energy from the rotor. The prototype will use a horizontal-axis wind turbine (HAWT) configuration, but a rotating base will not be necessary at this development stage. If time permits in the later stages of the project, a
mechanism will be implemented to point the turbine into the wind. The final assembly is expected to be roughly 1.2m in height and 0.9m in width.

Due to the low-friction energy transfer method, the turbine is expected to start producing energy at wind speeds of 3km/hr. It should also continue to operate at higher wind speeds (>50km/hr) without shutting down or experiencing mechanical failure. This will be an improvement over the large commercial wind turbines, which have to shut down in storm conditions to prevent catastrophic failures. It is expected that the wind turbine produce at least 5W of power in optimal wind conditions. The prototype will be used to charge a 12V lead-acid battery, and thus the voltage should be limited to approximately 13.5V (the recommended float charge voltage for a typical automotive battery). A car battery may undergo gassing if a higher voltage is sustained. The current should also be limited to 10% of the battery’s rated power to avoid overheating.

The final assembly is intended to be easily reproducible for any enthusiast attempting to build a similar turbine at home. Thus, the materials to be used in the project should be commonly available - for instance, plywood for the base and bicycle wheel and parts for the rotor. Complex control circuitry will be avoided by limiting the electrical components to wire, diodes, resistors and a few capacitors if necessary. If time permits, an optional circuit to optimize the charging process and battery protection will be added for those capable of implementing it. The proceedings of the project, and the final set of assembly instructions will be documented on a web log to make it available to anyone.

1.3 Scope and Limitations

The scope of this project focuses on what can be built cheaply by a skilled hobbyist following good directions. More professional wind turbines may incorporate specific materials, parts, and construction methods which are beyond the financial limitations of this project. Also, the size of this wind turbine is limited to the order of scale of a bicycle wheel and the type of space constraints typical of a laboratory, workshop, or garage type setting.

A large component of any horizontal-axis wind turbine design is how it handles yaw control for changing wind directions. The scope of this project and prototype ignores these issues, although the addition of a naturally automatic yaw control system (free motion with downwind
blades) is still within the means and abilities of a hobbyist. Another issue is power optimization, which is normally handled using variable blade pitch, ailerons, or spoilers; here the only reasonable option is variable electrical load to adjust the angular velocity for peak power.

The costs incurred during the prototyping phase are expected to be greater than the costs to build the recommended design, due to additional parts being tested. However, there are still some grave restrictions on the prototyping process. Access to a proper wind tunnel is not feasible due to the size of our setup, so the quantitative aerodynamic data collected has very limited accuracy. The construction of the coils is a very time-intensive process, taking over an hour per coil if the coils are made carefully and of good quality. Hence, many of the prototype coils are not made to such exacting standards, and their performance may be slightly diminished.
2.0 Discussion

2.1 Theory

Wind turbine design requires the consideration of several factors, including desired and available power, blade geometry, energy harnessing mechanism and conversion to useful forms of energy.

2.1.1 Available Power

Out of the total energy passing through a HAWT, only a certain percentage of it is theoretically attainable to be converted. To begin, we make some idealized assumptions about the turbine: the rotor is hubless, massless, has an infinite number of blades, the blades have no drag, and the flow is incompressible and purely axial.

The actual power available in the wind is found by combining values of the wind’s density, speed, and cross-sectional area, and using the incremental work method to produce the equation:

\[ P_{\text{wind}} = \rho A v^2 (v_1 - v_2) \]

where \( v_1 \) and \( v_2 \) are the upstream and downstream velocities, respectively, and \( v \) is the velocity at the blades. If a conservation of energy approach is used, the equation is:

\[ P_{\text{wind}} = \frac{1}{2} \rho A v (v_1^2 - v_2^2) \]

Equating the two above equations from incremental work and conservation of energy gives the result that the velocity at the blades is exactly the average of the upstream and downstream velocities. This produces the following equation:

\[ P_{\text{wind}} = \frac{1}{4} \rho A (v_1 + v_2) (v_1^2 - v_2^2) \]
This produces a curve, hitting a maximum at \( \frac{v_2}{v_1} = \frac{1}{3} \). Substituting this value back into the power equation shows that the maximum theoretical power extraction for an ideal turbine is 59.3% of the wind’s actual power. This is known as the Betz limit\(^3\). The power, then, that can be extracted in an ideal case, is as follows:

\[
P_{\text{max, ideal}} = 0.2965 \rho v^3
\]

2.1.2 Blade Design

Ideal HAWT blades are designed on the principle of optimizing lift while minimizing drag. Due to the rotational geometry, the speed of the airstream relative to the blade increases as you move outwards from hub to tip. Therefore the optimal shape is an air foil similar to a wing, but shaped such that it is thick and wide near the hub, and thin and narrow near the tip. This means that the torque generated is uniform along the blade. As mentioned earlier, construction or purchase of these shapes of blades is beyond the scope of this project. We are limited to only two blade shape types based on the materials used. Blades cut from polyvinyl chloride (PVC) pipe have a circular curvature, and blades cut from plywood are flat.

2.1.2.1 PVC Blade Design

The PVC blade design was produced by the following method:

a) Determine the optimal angle of attack \( \beta \) for the blade as a function of radius.

Figure 3 and Figure 4 show the angles and vectors involved. The Reynold's number for this system will be quite low, less than \( 10^6 \), well within the laminar region. Look up the coefficient of lift versus angle of attack curve in Figure 5 to determine a good angle that is below stall for the operational range and past the maximum drag on the drag versus lift curve. (Note: to find the optimal lift/drag ratio graphical analysis is required but the lift and drag curves for this wing shape are nonexistent, so a close approximation was used. Further analysis using the approximate data would be moot.) It was determined that \( \alpha \) is about \( 5^\circ \).
Figure 3: Free body diagram for rotating blades.

Figure 4: Angles of attack for rotating blades.

Figure 5: Coefficient of lift and Coefficient of drag curves.
φ is the angle of the apparent wind to the rotor plane and can be calculated using Betz approximation.

\[ \tan(\phi) = \frac{2v}{3} \left( \frac{\lambda vr}{R} \right) = \frac{2R}{3r\lambda} \]

Therefore, \( \beta(r) = \arctan\left( \frac{2R}{3r\lambda} \right) - 5° \)

where, \( \lambda \) is the tip speed ratio
\( v \) is the free wind velocity along the rotational axis [m/s]
\( R \) is the maximum radius [m]

It can be seen that \( \beta \) changes as \( \arctan(1/r) + \text{constant} \), which approximately decreases linearly.

b) **Determine the Chord as a function of radius (blade planform).**

Using Betz assumption and some algebra to maximize thrust we find that
\[ c(r) = \frac{16\pi R(R/r)}{(9B\lambda^2)} \]
where, \( c(r) \) is the chord as a function of radius [m]
\( B \) is the number of blades

Note that the chord is: inversely proportional to radius, inversely proportional to the number of blades, and inversely proportional to the tip speed ratio squared. For ease of manufacturing the fact that the chord should be inversely proportional to the radius was ignored, and the linear approximation for the optimal angle of attack was favored.

c) **Determine the diameter of the turbine.** This is a physical constraint that we set.

d) **Choose a tip speed ratio \( \lambda \).**

Tip speed ratio is tip velocity / free stream velocity. The tip speed ratio directly effect the rotational velocity and is generally chosen to be between 5 and 8 for high speed rotation. We chose \( \lambda=5 \).
\[ \omega = 2\lambda V/D \quad \text{[rad/s]} \]

e) **Determine the number of blades.**
Considering the effect that the number of blades has on the desired chord, 3 blades were constructed for the final assembly. Earlier 9 blades were tested, but the power output was considerably less. Ideally an infinite number of infinitely thin blades would be used, but would also require exotic materials and an elaborate construction process.

f) **Determine the chord at the tip.**

c(R) = 4D / (Bl^2)

g) **Determine the angle of attack β at the tip.**

Go back to step a) or read from the chart below (Figure 6).

![Blade angle chart](image)

Figure 6: Blade angle. \(^4\)

The final design for the blades is three blades, tip speed ratio of 5, maximum radius of 45.3 cm, chord at inside radius 7.8 cm, β at inside radius of 42.5 degrees, chord at maximum radius of 4.7 cm, and β at maximum radius of 2.5 degrees, with a linear transition of chord and β along the span (tapered plan-form).

**2.1.2.2 Wooden Flat Blade Design**

Since flat blades cannot have the optimal curvature or variable thickness necessary for optimal power capture, the precise shape of the blades is less critical. To make it easier for the would-
be hobbyist, a reasonable wooden blade shape is simply a rectangle, or a quadrilateral that is slightly larger at the outside than the inside.

For flat blades, the optimal angle \( \theta \) between the blade face and the oncoming airstream is theoretically calculated. The force of the wind on the blades is the wind pressure multiplied by the blade area, which is reduced by a factor \( \sin \theta \). However, the component of the force converted into rotational motion is related by a factor \( \cos \theta \). There will also be a drag force as the blades rotate through the airstream, which is proportional to \( \cos \theta \). Therefore, for a given air density, velocity, and drag coefficient, the rotational force is proportional to the following function of blade angle:

\[
F \propto \sin \theta \cos^2 \theta
\]

This function reaches a peak at 35.5 degrees (or 0.62 radians) from the oncoming airstream, as can be seen in Figure 7.

![Figure 7: Percentage of wind force converted vs angle of flat blades](image)

2.1.3 Blade Count

Aerodynamic efficiency theoretically increases with blade count; however, as blades are added, the returns diminish. Increasing the blade count from one to two yields a 6% increase in
efficiency, while from two to three yields only 3%. A larger number of blades provides more symmetry and reduces gravitational stiction, thereby reducing the start-up wind speed. However, it also adds weight to the rotor which can have the opposite effect.6

Generally, adding more blades will increase the torque while reducing angular velocity, placing itself on a different point of the power curve for a given wind speed (recall \( P = T \omega \)).

### 2.1.4 Load Optimization for Peak Power Tracking

Given a chosen blade geometry and wind speed, the mechanical power produced will vary with the rotation speed of the rotor. This is because power is equal to the torque multiplied by the angular velocity. There will be zero power produced before the rotor starts moving, and also past the rotor’s stall velocity. Therefore the mechanical power exhibits a maximum somewhere in between (see Figure 8 for sample data). To optimize the system’s performance, the rotor must be set to spin at the optimal velocity for the current conditions. This can be achieved in several ways, such as varying the angle of attack or making use of ailerons or spoilers. For the purposes of this project, the only reasonable way to control the performance is by varying the electrical load on the system, changing the amount of energy extracted and therefore electrical friction on the rotor.

![Figure 8: An example of typical power versus speed characteristics of a wind turbine](image)

Figure 8: An example of typical power versus speed characteristics of a wind turbine.
2.1.5 Coil and Magnet Orientation

Most industrial generator systems use overlapping sets of coils with slots for cores on the stator, completely enveloping the rotating permanent magnets inside (see Figure 9). The offset between each consecutive coil is usually ⅓ of its width, allowing for three-phase power generation.

![Figure 9: An example of and a simplified diagram of coil and core arrangement in a stator.](http://www.gouk.co.nz/images2/stator1.jpg)

From Faraday’s law of induction:

\[
\Delta \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]

Common magnetic core materials used in generators are ferrite and mu-metal, with relative permeability constants of greater that 700 and 20000, respectively\(^8\). However, these are impractical for use by hobbyists, so the scope of the project limits us to common steel alloys, the relative permeability of which rarely exceeds 100.

For systems using cores in their design, it is advantageous to alternate the polarities of magnets on the rotor. Alternating polarities makes use of the residual polarization of a ferromagnetic material\(^9\), forcing the core to become completely demagnetized during each cycle. If the
magnet polarities are not alternated, there is less potential for energy extraction, since there is a smaller change in magnetic field in the core, and therefore less induced voltage. There is no energy lost from the stator movement in completely re-magnetizing the core in the opposite polarity, since this energy goes into generating more electrical power\textsuperscript{10}.

### 2.1.6 Multi-Phase Power

Multi-phase systems have the advantage over single-phase systems of providing a more constant rectified output. Three is the lowest phase count during which the output does not cross zero for sinusoidal waveforms. In the ideal case with three equally-separated phases of sinusoidally oscillating power signals of equal amplitude, the rectified three phase power output will resemble Figure 10.

![Figure 10: Ideal rectified three-phase power.](http://www.allaboutcircuits.com/vol_3/chpt_3/4.html)

Unfortunately, unless the magnets on a rotor are assembled closely together, similarly to a motor magnet array, induction systems only produce a pulsed output. Hence, a greater phase number may be necessary for the power output to consistently remain non-zero. The minimum phase number to avoid non-zero output can be approximated as follows, $D$ being the duty cycle of a rectified output of a single-phase system:

\[
N = \left\lfloor \frac{1}{D} \right\rfloor
\]

### 2.1.7 DC-DC Switching Boost Converter

The output of a wind-powered electrical generator is completely unpredictable, as it depends on wind conditions and the electrical load applied. For this reason, a DC-DC switching converter needs to be implemented to condition the output to a steady value which will be sufficient to charge a 12.6V lead-acid battery, but not exceed its gassing voltage (14.4V). When using a
dedicated chip for the purpose, one needs to be aware of several theoretical guidelines for boost converters, the general design of which is shown in Figure 11.

![Figure 11: Standard design for a switching boost regulator.](image)

A capacitor dielectric material of X5R or better should be used with modern regulators. Both the input and output capacitors in a switching regulator should have low equivalent series resistance (ESR) since ESR increases the output ripple and decreases efficiency. A larger output capacitance also decreases ripple. To approximate the desired value, one can use the standard calculation:

\[
C_{OUT(min)} = \frac{I_{OUT(max)} \cdot D}{f_S \cdot \Delta V_{OUT}}
\]

In the above equation, \( f_S \) is the regulator's switching frequency, and \( D \) is the duty cycle, also approximated as follows using an estimate of 70-80% for efficiency \( \eta \):

\[
D = 1 - \frac{V_{in(min)} \eta}{V_{out}}
\]

Using the parameter \( I_{out(max)} \) as the maximum desired output current, a suitable inductor value can be well estimated by:

\[
L = \frac{(V_{out} - V_{in}) V_{in}^2}{0.3 I_{out(max)} f_S V_{out}^2}
\]

For non-fixed output power supplies, there is a resistive divider feedback network with a specified feedback voltage \( V_{FB} \) (see Figure 12). The relative values of the resistors in the network can in almost all cases be determined with the following equation:
\[
\frac{R_1}{R_2} = \frac{V_{\text{out}} - V_{fb}}{V_{fb}}
\]

Most adjustable-voltage regulators also prefer to have a small picofarad-magnitude capacitor bypass \( R1 \).

![Figure 12: A typical feedback network for any switching regulator.]

Normally, switching regulator chips are extremely sensitive to layout. One often needs to pay close attention to the size and placement of power islands, and to ensure that the feedback loop through the transistor, inductor and feedback resistors is as small as possible. However, ripple and minute accuracy are of little importance for this application, so a through-hole prototype board will be sufficient the regulator.

### 2.2 Methods / Testing Protocol / Equipment

The mechanical and electrical testing procedures are treated separately in this section. The sections describe the development of a laminar, uniform wind column, blade aerodynamics and electrical measurement procedures.

#### 2.2.1 Wind Column

The quality of the wind column is sensitive to parameters such as fan and separator placement, described in the sections below.

##### 2.2.1.1 Laminar Flow

Much work was done attempting to achieve the most laminar, uniform flow possible in absence of a proper wind tunnel. The lab has a couple of axial fans, a box fan and a stand fan, which
produce a very turbulent, rotational flow. The rotation was also in the opposite orientation of the rotation of the turbine, causing poor performance. In order to make this flow more laminar, an air separator was constructed out of folded paper glued together in a wooden frame. This separator, mounted on the fan stand, can be seen in Figure 13.

![Air separator mounted on stand fan.](image)

Figure 13: Air separator mounted on stand fan.

The result of this separator is mostly laminar flow (the perpendicular component of flow is barely measurable using our anemometer, meaning it is less than 1km/hr).

### 2.2.1.2 Velocity Distribution

Although the flow is mostly laminar, the velocity distribution is far from uniform. There is a dead zone in the center and the velocity falls off near the edges. A measurement of the wind velocities coming out of the separator is shown here in Table 1 and Figure 14. Although this data was taken with the box fan, the shape of the stand fan profile is very similar. The velocities measured are in km/hr 1.5” from the separator, and each box covers 2.7” in length.
Table 1: Wind velocities up against box fan running at speed setting 1.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
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<tr>
<td>0</td>
<td>5</td>
<td>6.1</td>
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<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3.8</td>
<td>8.8</td>
<td>7.2</td>
<td>7.7</td>
<td>8.2</td>
<td>2.7</td>
<td>0</td>
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<tr>
<td>0</td>
<td>7.5</td>
<td>8.6</td>
<td>0</td>
<td>0</td>
<td>9.7</td>
<td>7</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>7.2</td>
<td>8.4</td>
<td>4.3</td>
<td>0</td>
<td>8.6</td>
<td>5.6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>9.3</td>
<td>8.8</td>
<td>6.8</td>
<td>8.6</td>
<td>6.3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.8</td>
<td>4.5</td>
<td>4.1</td>
<td>4.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 14: Wind velocity profile of the box fan (vertical scale in m/s).

Although construction of a simple wooden wind tunnel was considered, this idea was abandoned due to time constraints. The stand fan was chosen because it could generate much more powerful wind than the box fan, and a Variac (variable transformer) allows for precise control of velocity.

### 2.2.1.3 Placement of Separator

The question of the separator placement was resolved with some simple data: the variations in wind speed across the plane of interest were measured for two cases. When the separator was placed next to the turbine, the wind speed (at maximum fan power) varied by approximately 12km/hr. When the separator was placed next to the fan, the wind speed varied by
approximately 7km/hr. This can be explained by the fact that when rotational flow propagates, the flow has a tendency to remain rotational and the velocity profile does not become fully developed as a laminar flow will tend to do. It is best to turn it into a laminar flow as soon as possible.

### 2.2.1.4 Placement of Fan

The question of fan placement was resolved by collecting some data on the velocity distribution at three different distances. It was found that for the short distance of 1.25m, the area of significant velocity was too small for our turbine - a whole third of the radial distance around the outside had virtually zero flow velocity. The flow needs more distance to spread out a bit. At the long distance of 5m, the flow was more significant in the outer areas but became more turbulent and varying in time. This is due to the sheer distance required of the airflow, and local lab geometries such as tables make it very difficult to provide an unobstructed path without added turbulence. Therefore it was decided that the middle distance of 2.5m would be the most optimal, providing some velocity in the outer area while keeping a mostly steady-state and laminar flow. Other points of distance were deemed unworkable due to lab space constraints. With this final placement, the velocity profile at the turbine across both the horizontal and vertical axes was tabulated at equal spacing at a particular fan setting, after carefully aligning the fan for maximum symmetry. This data is shown in Table 2. This is for the long 45.3 cm blades.

<table>
<thead>
<tr>
<th>Horizontal Axis</th>
<th>1.1</th>
<th>7.5</th>
<th>10.4</th>
<th>10.4</th>
<th>9.7</th>
<th>5</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Axis</td>
<td>0</td>
<td>7.5</td>
<td>12</td>
<td>10.4</td>
<td>12.7</td>
<td>9.5</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Assuming rotational symmetry, we can make a rough estimate of the average wind speed across the swept area as a percentage of the maximum wind speed by taking the average values for each of the four annuli represented in Table 2, and giving them weight of their area fraction. The result is approximately 41.3% of the maximum wind speed. For the shorter 28cm blades, the result is approximately 76.7% of the maximum wind speed.
2.2.2 Blade Aerodynamic Testing

All aerodynamic testing was performed on our Mechanical Rig, which included magnets on the rotor and three large coils hooked up to our data acquisition module (DAQ). These coils were not optimized for the setup and were leftover from another project; we had hoped to use them to simulate electromagnetic drag, but they were not enough to have any noticeable effect. The same tests were performed for each ‘blade configuration’, that being a particular configuration of blade material, length, and blade count. Not all possible configurations were tested as it became apparent which configurations were most useful in the context of limited time. The five blade configurations we tested were:

- 9-blade PVC 28cm
- 3-blade PVC 28cm
- 3-blade Wood 45cm
- 3-blade PVC 45.3cm 30° (β at ⅔ span)
- 3-blade PVC 45.3cm 15° (β at ⅔ span)

The angles mentioned for the long PVC blades are measured at the point of the rotor rim. Since these blades have a curvature, the chord line (an imaginary straight line connecting the two ends of the curve arc) is used as reference for the angle. The angle is between this chord line and the rotation plane.

The measurement of the wind speed at the turbine is difficult due to the uneven distribution of velocity across the plane of rotation. However, the maximum speed typically is measured about halfway from the center to the edge of the rim. This midway radial point, on either side along the horizontal central axis of the turbine, is typically where documented measurements of wind speed were taken. All wind speed measurements were taken with the same hand-held anemometer, held as best possible so that it faced the wind axially and with the best attempts made to not let the hand or arm obstruct the flow.

2.2.2.1 Stationary Torque

A digital force meter was used to measure the rotational force at three different radial points along the rotor to determine the stationary torque. These points were the intersections of
spokes, where the force meter hook could easily be placed without sliding. Measurements were made at a variety of wind speeds. The torque was calculated by multiplying the measured force by the radial distance, and an average of the three points of measurement was used for the final data.

2.2.2 Starting Wind Speed

To measure the starting wind speed, the fan power was increased until just at the point where the turbine started to turn. Then the wind speed was measured.

2.2.2.3 Rotation Speed

Finally, measurements of the rotational speed (measured in revolutions per minute {RPM}) versus wind speed were taken for each blade configuration. The electrical load on the test coils was also varied to determine any effect that might have on the rotational speed. The effect, if any, was too small to detect with that rough setup and only three coils.

The RPM was measured using a MATLAB script and the DAQ, described in Section 2.2.3.4.

2.2.3 Electrical Data

Most of the electrical data was logged with a DAQ. The data was acquired and analyzed in MATLAB; the implemented code can be viewed in Appendix A. An oscilloscope was also used for testing and to calibrate the DAQ, and a digital multimeter (DMM) was used to measure resistances.

2.2.3.1 General Data Acquisition Module Information

A 48000 sample per second National Instruments DAQ was used to quantify some of our results. Four differential channels were monitored, recording the voltage and current at the output of the rectifier bridge (channels A01 and A02, respectively), the voltage output from one of the three coil phases before the rectifier (channel A03), and the voltage output of the boost regulator (channel A04). Channel specifications are summarized in Table 3. Whenever the
measurable output voltage exceeds 10V - as is the case when the boost regulator isn’t heavily loaded and can actually produce its desired voltage, or a battery is connected at the output for charging - a 50% resistive divider, and the measurements are doubled in software. Quite often, however, it is sufficient to discharge a battery with a power resistor to bring its voltage below 10V.

Table 3: Summary of differential analog input channels used on the DAQ.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Name</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A01</td>
<td>$V_{\text{rect}}$</td>
<td>[-10 10]</td>
<td>Volts</td>
</tr>
<tr>
<td>A02</td>
<td>$I_{\text{rect,sense}}$</td>
<td>[-1 1]</td>
<td>Volts</td>
</tr>
<tr>
<td>A03</td>
<td>$V_{\text{coil1}}$</td>
<td>[-10 10]</td>
<td>Volts</td>
</tr>
<tr>
<td>A04</td>
<td>$V_{\text{out}}$</td>
<td>[-10 10]</td>
<td>Volts</td>
</tr>
</tbody>
</table>

The maximum sampling rate for analog channels is 12kHz because the DAQ samples channels sequentially. It was limited to 4kHz to keep the measurement and computation cycle in MATLAB to within several seconds.

The measurement voltages of interest were connected directly to the DAQ, which has an input impedance of 144kΩ. This is much higher than the impedances in our circuit, so the measurements should have negligible influence on it. It would be preferred, however, to buffer the measurement connections with an operational amplifier (Op-Amp) to introduce much higher input impedance. This step was omitted due to time constraints.

2.2.3.2 Eliminating Sampling Channel Delay Effects

Because of the sequential sampling, there are slight delays between what should be simultaneous data points from each channel. Channel A03, as well as A04 are independent from the others, so their data remains unaffected. However, the other two channels are voltage and current measurements which are eventually multiplied together, so it is important for them to remain aligned for accurate calculations. Thus we implemented a shifting algorithm using basic digital signal processing (DSP) functions (see Figure 15: Flow diagram for correcting the DAQ's channel delay. for a flow diagram). Channels A01 and A02 were first upsampled to 48 kHz - the maximum sampling rate of the DAQ. Their temporal behaviour is quite similar (there is no phase shift since the impedance seen by the rectifier output is mostly
real), so we take the cross-covariance of the two signals and find the peak. The offset of the peak from 0 (in samples) yields the shift of the current measurement on A02 with respect to the voltage measurement on A01. The current data is then shifted, and the current data then downsampled to its original sampling rate.

Figure 15: Flow diagram for correcting the DAQ’s channel delay.

### 2.2.3.3 Calculating Power and Boost Efficiency

The gathered data was then processed to extract four quantities of interest: rectified power, output power, RPM and boost converter efficiency. Equations used for power and efficiency calculations are provided below:

\[
I_{\text{rect}} = \frac{I_{\text{rect, sense}}}{R_{\text{sense}}}
\]

\[
P_{\text{rect}} = \frac{1}{n} \sum_{n} V_{\text{rect}} I_{\text{rect}}
\]

\[
P_{\text{out}} = \frac{1}{n} \sum_{n} \frac{V_{\text{out}}^2}{R_L}
\]

\[
\eta_{\text{boost}} = \frac{P_{\text{out}}}{P_{\text{rect}}}
\]
2.2.3.4 Extracting Revolution Speed Information

RPM was determined by recording the locations of the voltage peaks in a single phase array of coils, and also counting the peaks. Since the distances between peaks could be slightly irregular due to coil and magnet arrangement inconsistencies, we only used time stamps of peaks spaced an integer number of periods apart. To convert this data to a RPM reading, the following equation was used ($n$ being the number of periods of revolution captured by the DAQ sampling session):

$$RPM = \frac{60 \, n}{t_{(12n+1)th \, peak} - t_{1st \, peak}}$$

2.3 Results

Measured results for blade aerodynamics parameters, as well as performance of various aspects of the electrical system are described in the sections below.

2.3.1 Blade Aerodynamics

This section discusses stationary torque produces, starting speed and rotation speed results.

2.3.1.1 Stationary Torque

The results for the torque provided at start-up versus wind speed (average values) are plotted below for our five blade configurations. The reason for the spread of wind velocity data between the long and short blades is that we had not anticipated the much lower average wind speed for the long blades (due to poor coverage of the swept area by the wind column). Nevertheless, the data can be extrapolated by eye for some simple conclusions.
2.3.1.2 Starting Wind Speed

The values for the starting wind speed (or ‘cut-in velocity’), the speed at which the rotor just begins to turn, are tabulated as follows:

<table>
<thead>
<tr>
<th>Blade Configuration</th>
<th>Max Cut-in Velocity [km/hr]</th>
<th>Avg Cut-in Velocity [km/hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9PVC-28cm</td>
<td>7</td>
<td>5.369</td>
</tr>
<tr>
<td>3PVC-28cm</td>
<td>5.2</td>
<td>3.9884</td>
</tr>
<tr>
<td>3Wood-45cm</td>
<td>3.4</td>
<td>1.4042</td>
</tr>
<tr>
<td>3PVC-45.3cm-30deg</td>
<td>6</td>
<td>2.478</td>
</tr>
<tr>
<td>3PVC-45.3cm-15deg</td>
<td>6.3</td>
<td>2.6019</td>
</tr>
</tbody>
</table>

2.3.1.3 Rotation Speed
The values for rotation speed versus the average wind speed at the turbine are graphed as follows for each blade configuration:

Figure 17: RPM vs average wind speed for five different blade configurations.

2.3.2 Electrical Data

This section details results concerning cores, coil dimensions, unloaded rectifier output and boost regulator performance.

2.3.2.1 Core Size and Positioning

Winding cores were eliminated from the design to eliminate rotational friction by attracting the passing magnets. Closely positioned steel cores increase power production roughly by a factor of 10, but cause massive jerks on the passing magnets. Also, upon stalling, the rotor always stops with its magnets aligned over the cores, causing the starting torque to be impractically high. Displacing the cores further from the magnets reducing their effectiveness approximately
with a $1/r^2$ relationship (see Figure 18). If the core is removed far enough (~12 mm) to decrease the starting torque to roughly 2.4lb-in, it only increases the EMF by 30%. Out of the tested options, only the long PVC blades were able to provide this much torque at low wind speeds - at 2.7 and 3.6 m/s winds for 30 and 15-degree angled mounting, respectively. This would meet our cut-in wind speed design objective marginally, while providing little benefit. Thus, to keep our cut-in velocity to a minimum, the core was eliminated entirely.

![Figure 18: Starting torque vs core spacing.](image)

### 2.3.2.2 Optimal Coil Parameters

Using a fixed length of magnet wire, coils of various diameters were assembled and tested by exposing them to magnets moving at different velocities. The coils thickness and the distance from the magnets kept the same for each trial. The peak induced voltage was recorded in each coil, and processed to extract a useful comparison parameter - the generated EMF per magnet speed ratio in a single turn of wire. This parameter exhibited a clear maximum in the range of 36-44mm (see Figure 19). The data and calculations for these results are provided in Appendix B.

![Figure 19: Change in induced EMF in a turn of coil with increasing RPM vs coil diameters.](image)
Originally, several coils were manufactured with 22-gauge transformer wire, but these generated insufficient EMF so a thinner wire was needed. Ambitiously assuming a maximum electrical power extraction by the coils of roughly 5W (500 mA at 10Vrms), a 166 mA per phase capacity is necessary. 29-gauge wire is the smallest diameter suitable for power transmission at this current, based on the American Wire Gauge standard\textsuperscript{13}. Hence, the coils were assembled with the smallest available size meeting this specification - 28-gauge wire.

### 2.3.2.3 Unloaded Output Characteristics

Three-phase rectifier output was tested with an oscilloscope with no load attached. At a moderate wind speed (roughly 11 km/hr), the system generates relatively evenly spaced peaks mostly around 9V, to a maximum of 13V (see Figure 20). Upon over-clocking the fan with a Variac transformer, and producing wind speeds of roughly 19 km/hr, peaks of 30V are attained. Adding a capacitor to the output maintains the output voltage of an unloaded system at its maximum peak.

![Figure 20: Typical rectifier output with no load attached.](image)

### 2.3.2.4 Boost Converter Performance

A MAX1771 switching DC-DC regulator was tested for use in the design. For an unloaded, or a very lightly loaded boost regulator attached to the output of the rectifier, a typical start-up sequence was recorded (see Figure 21). One can see the mean voltage slowly ramping to its steady-state value, typically 9-10V at these conditions. The start-up sequence takes roughly 3 seconds, and is much much faster and cleaner when the input power is drawn from a power supply.
Upon introducing a load across the output of the boost regulator, the input voltage decreases dramatically due to the increased power consumption (see Figure 22). Unfortunately, tests with a power supply confirmed the diminishing efficiency of the MAX1771 as the gap between input and output voltages increases (see Appendix C).

When sufficient power is supplied, the boost regulator maintains a constant 14.2V output, albeit with 100mV amplitude ripple. The ripple is of no concern as long as the output voltage stays below 14.4V.

2.3.3 Overall System Performance

The power tracking and battery charging performance are described here.
2.3.3.1 Peak Power Tracking at the Rectifier Output

The load was intended to be placed across the output of the boost regulator. However, to determine the optimal load for the system more generally, we tested the optimal equivalent load as seen by the rectifier. Once this is determined, the remainder of the system can be adjusted accordingly to operate at this equivalent load.

For a given wind speed, the load was varied and the rectified power and RPM measured. This produced a rough power curve for each wind speed. Graphs for the rectified power versus load and RPM are given in Figure 23 and Figure 24, respectively for the four different wind speeds measured. Note that the slowest wind speed, 6.1 km/hr, was the cut-in velocity for this final prototype setup. For detailed data, please refer to Appendix D.

![Rectified Power vs RPM](image)

**Figure 23: Rectified power vs RPM for final setup.**

Taking the maximum power of each curve and plotting it against its average wind speed produces the graph in Figure 24.
As a designer, the metric one would use to control the rotor speed would be the electrical load applied. Hence, rectified power versus load data is also presented below.

The power peaks are not as obvious as in the rotor speed data, but a zoomed in linear section of the plot (see Figure 26) yields some indication that the optimal resistive load decreases with increasing wind speeds. This makes sense, since a system generating more voltage (from higher wind speeds) should be able to drive heavier loads (smaller impedances).
2.3.3.2 Peak Power Tracking at the Boost Regulator Output

Power measurements at the output of the boost regulator immediately indicated that voltage boosting through an IC introduced great inefficiencies at such low power rates. The recorded few sets of recorded data (see Appendix D) show tolerable efficiencies of roughly 50-75%, but for most loads the power output is insufficient to power the boost regulator to make it run at all. Hence the power production range decreases greatly. It was also discovered that for medium-to-high wind speeds, as long as the system is able to produce voltage spikes exceeding the instantaneous battery voltage, a boost regulator is unnecessary. For further testing for this application, more emphasis should be put on generating a higher voltage at lower wind speeds rather than boosting it. It is important to note that generated spikes below the battery voltage will not be useful, so one must ensure that there is a sufficient duty cycle of voltage above 12V to charge a battery before a boost regulator is discarded. Also, if system capacities increase to continuous outputs of even 200mA, a boost regulator will again be useful since its efficiency will be greatly increased.

2.3.3.3 Battery Charging Performance

As aforementioned, the boost regulator is not necessary to charge a battery, as long as the system can generate a voltage greater than the battery’s for a satisfactory portion of its
operation. Hence, charging performance was tested with the battery connected across the output of the rectifier. Due to time constraints, the tests were only carried out at optimistic wind conditions of 19 km/hr, and no maximum was observed meaning that more batteries could be added in parallel (see Figure 27). For raw data, please see Appendix D.

![Figure 27: Power delivered to battery vs charging duty cycle.](image)

From the observed maximum of roughly 200mW, we can estimate the time it would take to fully charge a 12.6 1.2Ah lead-acid battery in very optimistic constant-wind conditions:

\[
t_{\text{full charge}} = \frac{E_{\text{capacity battery}}}{P_{\text{delivered to battery}}} = \frac{(1.2\text{Ah})(12.6V)}{0.2W} \approx 75\text{ hours}
\]

Here, we have ignored the fact that the current delivered to a charging battery tails off as the battery approaches full charge. We have also assumed the charging power to always be delivered to 12.6V, whereas discharged battery’s actual voltage is well below this. Nonetheless, this result indicates that it would take a noticeable portion of a car’s lifetime to charge a car battery.

The current delivered by the system was observed to decrease from approximately 30mA with a very discharged battery to about 18mA for an almost charged battery. This is mostly due to the battery’s increasing voltage as it charges. Surprisingly, the result with a single battery connected almost matched the peak power figure measured with a plain resistor. This result could further be optimized in the future by trying more batteries in parallel, pulsed at various charging duty cycles. In addition, slower wind speeds should be tested.
2.4 Discussion of Results

This section details standalone blade aerodynamic system, electrical system results, as well as results of the overall system.

2.4.1 Blade Aerodynamics

Although efforts were of course taken to collect accurate data, the nature of the wind column (not entirely laminar, and certainly not a uniform velocity distribution across the rotation plane) and the lack of significant electrical drag components meant that results can really only be used for relative comparisons and are not indicative of how the final product should perform. That being said, the results are quite conclusive in terms of showing at least what type of blades available to a budget hobbyist are the best for this application.

The least reliable data is in Table 4 for cut-in velocity, since there are certain stationary orientations of the rotor that have more gravitational stiction than others. In particular, there is a blade that sits nearly on top of a magnet, and when this blade ends up pointing straight down behind the vertical support, the cut-in velocity can be higher than normal. Unfortunately, this non-symmetrical effect was only really noticed for the last set of PVC blades (at both angles), so multiple cut-in velocities were measured and the worst-case number was chosen for this table. The first three configurations have only single-valued data and are therefore not as reliable (this is particularly important for the wood blades, since they appear to have the best performance here). The average velocity was then calculated from this based on the 76.7% average for the short blades and the 41.3% average for the long blades. Even with this poor accuracy, it’s somewhat clear from the table that the short blades have a poorer performance for cut-in velocity.

Luckily, the short blades can be discarded based on the other metrics as well. Even without clear experimental power data, the first set of short PVC blades provides only half or less of the theoretical power of the longer blades. There is no real advantage to using shorter blades except for the negligible material cost savings.

The stationary torque graph applies the most when extrapolated back to the cut-in velocity, although torque can be important at higher speeds if the electrical load is high. Of course, these
measurements are for stationary torque and hence cannot be directly correlated to a dynamic torque value. Assuming the average cut-in velocity for the system under any blade configuration is roughly 2-6 km/hr, it is clear that the short PVC blades do not provide enough torque at these low speeds. This makes sense because the area of wind capture is much smaller. There is less weight to turn, but the constant weight of the bicycle wheel, spokes, and magnets diminishes this effect. The graph clearly shows the long PVC blades outperforming the competition. The torque results for the wooden blades are somewhat disappointing.

The rotation speed graph also shows rather disappointing results for the wooden blades. Aside from the fact that they are flat and do not attempt to produce uniform torque along their length, wood is simply denser than PVC and the blades weigh significantly more, increasing frictional losses in the hub. Although the short PVC blades appear to perform well in this metric, the data was collected at higher average velocities and so a little extrapolation shows them to be of poorer performance. The smaller angle from the rotation plane clearly is a boost to rotational speeds for the long PVC blades. However, the torque graph showed that the larger angle provides more torque at low to moderate speeds (taken with a grain of salt - this is stationary torque, which may behave quite differently from torque at speed). Therefore, the tentative winner is the long PVC blades, but the angle to set them at depends mostly on application and local wind conditions. If wind is low, the larger angle of 30° should be used to take advantage of low-speed torque. If wind is typically higher, a smaller angle of 15° should be used to take advantage of boosted high-speed rotation. Other angles may be chosen as well.

### 2.4.2 Electrical Data

#### 2.4.2.1 Coil Parameters

Due to an oversight in original design, the coils were made too large and plentiful. According to AWG standards\(^{13}\), the resistance for 28-gauge wire is 219.2Ω/km. Then estimating 22 windings per row, 22 rows of conductors in a coil, 40mm as the average winding diameter, for six coils wired in series, we get:

\[
R_{series} = 6 \cdot 20 \cdot 22 \cdot \pi \cdot 0.04 \text{ m} \cdot 219.2 \text{ mΩ/m} = 72.7\Omega
\]
This is incredibly high! Also, unfortunately, it is within 5-10% of reality for most sets of coils, according to the laboratory’s DMM. To reduce the miniature heater effect in a wind turbine, either wire thickness should be increased, the coil size should be reduced or less coils connected in a single phase. Use of cores or more diode pairs per coil are good ways of reducing losses in a conductor.

### 2.4.2.2 Assessing the Need for a Boost Regulator

The usefulness of a switching regulator to boost the voltage and keep it stable is questionable in this project. A battery connected for charging acts as a capacitor in parallel with a resistive load which is only active when the charging voltage exceeds the battery voltage. Thus, the regulator can be eliminated as long as the system can generate sufficient voltage at low wind speeds, yet doesn’t provide enough power to raise the battery’s voltage above 14.4V while charging (systems supplying less than 12W should be OK). Lower-power systems do not cause the battery voltage to rise as much because the charges in the battery have more time to distribute themselves within the chemicals instead of accumulating on the surface and spreading out during the trickle charge phase.

### 2.4.2.3 DAQ Measurement Accuracy

The least reliable of all measured quantities in the electrical data is the rotor speed. This result relies on correctly counting voltage peaks which are sometimes different by a factor of two in magnitude. The peak extrema must also be correctly located, although the error from this is in software and DAQ time resolution is significantly smaller. However it is not uncommon for the software to miscalculate a peak or count a false one, so given our setup of 12 magnets on the rotor, the error can be as large as +/- 8.5%. This is a major reason why the power peaks appear much smoother when plotted versus load as opposed to versus rotor speed.

### 2.4.3 Overall System Performance

This section discusses peak power tracking and battery charging results.
2.4.3.1 Peak Power Tracking and Efficiency

The swept area with the chosen set of blades is equal to 0.641m². By the available power theory in section 2.1.1, the ideal power curve appears as in Figure 28. Keep in mind this is assuming that the peak of the power curve (ideal balance of torque/load and angular speed) is used at all wind velocities. This graph is the theoretical version of the experimental data from Figure 24.

![Theoretical Power vs Wind Speed for Final Turbine](image)

Figure 28: Theoretical extractable power vs wind speed for final turbine area 0.641m².

To compare this to our experimental power curve would require a very large graph due to the difference in order of magnitude; the only reasonable plot that can be provided here is how the efficiency of the system varies over wind speed. This is plotted in Figure 29.

![Efficiency vs Average Wind Speed](image)

Figure 29: Efficiency vs wind speed based on rectified power over the Betz power.
There is no clear trend in efficiency, except to say it is all rather poor. There are many contributing factors to this, the underlying one being that the system is insufficiently optimized - factors such as magnet position on the rotor along the radial axis, magnet dimension and count, blade material, coil count, etc. Another obviously noticeable factor is the eddy current damping caused by the aluminum mass in the final design.

Furthermore, the high resistance of our coils in series consumes a substantial amount of power. This effect is especially prominent at lower-resistance loads (<200Ω) in comparison to which the coil resistance becomes substantial and for which we originally expected our peak power production. For some visual representation of how drastic this effect is, we have plotted the roughly projected power production curves for an ideal, lossless conductor to compare with the actual results (see Figure 30). The extrapolations were made by assuming that all of the power in the system output is distributed proportionally between the coil and load resistances, which is clearly not the case in reality. Nonetheless, it is clear that decreasing the coil resistance shifts the apparent power peaks to loads on the order of 100Ω from around 1kΩ, and increases the usable power.

![Figure 30: Projected power production with lossless conductors vs actual consumption.](image)

However, the fact the efficiency does not rise significantly is actually rather good, as the turbine will perform with the same efficiency across a wide range of wind speeds, provided that the load is maintained at its optimal value. For further testing, it would be interesting to see how the
efficiency varies with wind speed when a battery is attached to the output for charging, rather than a constant resistive load.

Comparing Figure 8 to Figure 23 also yields an interesting result. In Figure 8 (far more ideal data) all of the curves for the various wind speeds start in roughly the same place. In Figure 23, our data, the starting spots are offset by an increasing amount. At 19km/hr, minimum load, we get zero rectified power even though the rotor spins at roughly 40 RPM. This ‘power offset’ is likely due to the extreme resistive losses incurred in the coils at minimum load (the small load shifts the resistive divider such that the power is lost in the coils rather than put into load).

The cut-in velocity was measured at 6.1 km/hr maximum velocity (2.52 km/hr average velocity), which is a fairly good result, and comparable to the speeds we were getting without the eddy current drag. This is as expected, since eddy currents only take effect when the magnets are already moving.

2.4.3.2 Battery Charging Performance

It is interesting that when charging a single 12V, 1.2Ah lead-acid battery, the power output closely resembled the peak system power at the same wind speed. This is potentially due to the charges building up near the terminals of the battery, so that the current is only delivered to a portion of the battery’s voltage. The charges would diffuse over time, but would accumulate to provide a larger resistance if the charging rate is too high. Thus, this surprisingly good performance will probably deteriorate throughout a long-term test.

Also, no maximum was found by changing the battery’s appearance as a load to the circuit. The positive power slope does look it is leveling out to create a peak, but there is insufficient data to draw any conclusions yet.

To optimize this process across all wind speeds, an automatic power tracking system needs to be implemented. The most effective solution would involve a microcontroller, which is beyond the scope of most hobbyists’ abilities. However, a simple MOSFET switch may be implemented to parallel the manual switching function described in Appendix D.3 of this report. Whether the switch would pulse at a single duty cycle found to be optimal across all operating conditions, or whether the pulse widths would be adjusted by circuitry is up to the abilities of the user.
2.5 Final Design

The Breeze Farmer prototype design is pictured in Figure 31. The following sections outline its particulars.

Figure 31: The Breeze Farmer prototype.

2.5.1 Base, Rotor and Stator

Breeze Farmer is mounted on a solid block of wood. A vertical wooden beam is fastened to this base block. On top of this beam, an L-bracket supports one end of the rotor hub shaft. The rotor and its hub are an aluminum bicycle wheel with all spokes intact supporting the rim. The other end of the hub shaft is mounted with a bracket atop a ½” copper rod, which sits inside a
hole drilled into the base block. The stator rim, which is an aluminum bicycle wheel rim of equal
diameter but without its spokes or hub, is mounted directly behind the rotor on the vertical
wooden beam. The stator rim is supported by a diametric rod which is fastened in the centre to
the L-bracket atop the vertical wooden beam. A notch is cut out of the beam to allow the stator
rim to sit slightly recessed. It is fixed to the wooden beam by a set of brackets with setscrews to
allow for precise distancing of the coils on the stator from the rotor. It is also supported at the
top by a tensioned string fixed to the top of the wooden beam.

2.5.2 Blades
Breeze Farmer utilizes three PVC-pipe blades, cut from 6" diameter pipe using the profile
described in theory. They are 45.3cm long, and begin 3.2cm from the center; this creates a
swept area of 0.641m². The blades are fixed to the edge of the rotor rim by being fastened with
a screw into triangular wooden wedges. These wedges are fastened to the rim by a single
wood screw; this allows us to adjust the angle of the blades at the point of the rim, which is also
⅔ the span of the blade.

Wind testing has shown the optimal angle here to be 15°-30° from the rotation plane at ⅔ span,
depending on if one favours lowest start-up speed or fastest rotation at moderate speeds. This
depends on the geographic wind profile of the area in question, as well as other considerations.

The end of the blade closest to the hub has a hole in the corner through which it is fastened by
zap-strap to the appropriate spoke crossing. This second point of fastening secures the blade
and makes sure it points radially outwards from the hub.

2.5.3 Magnets and Coils
Mounted onto the back of the rotor rim are 12 N48 neodymium 1” disc magnets (depth of 1/4”).
The magnets sit in special magnet cups which are fastened by bolt to the rim. They are spaced
equally, between every third spoke (there are 36 spokes). The magnets were placed close to
the outside of the rotor to take advantage of the faster velocities there.
Mounted onto the front of the stator rim are 36 circular inductor coils. Dimensions vary slightly on a case-by-case basis, but are approximately as follows: inner diameter 31mm, outer diameter 55mm, width 11mm. The coil diameter was chosen so that as many windings as possible fall in the optimal range of 36 to 46 mm, and so that they fill the stator rim circumference. The width was selected arbitrarily by picking the distance from the magnets at which the induced EMF drops off by a factor of 2. Beyond this distance, without the use of a core, coils mostly act as inductors without the benefit of much additional EMF. A photo of some of the coils mounted on the stator is shown in Figure 32.

![Figure 32: Coils mounted on stator.](image)

The coil quantity was chosen based on several factors. Firstly, it is desirable to have the number of coils be divisible by three to accommodate a three-phase power system. They can then be arranged in various ways depending on the coil-to-magnet ratio. To maximize our potential power extraction, we fabricated as many coils as would fit side-by-side on the stator rim (36 in our case). Since wire is a much cheaper material than permanent magnets, and is located on the stator, most industrial many coil windings which normally overlap. To eliminate assembly complexity, the coils used were all assembled in one plane with no overlap.
All of the coils are mounted on a horizontal axis, flat face facing the wind. After decreasing the size to prevent early saturation and increasing the number of coils (to increase power consumption and to compensate for the smaller size), it was necessary to mount them within a close vicinity of the outer circumference of the rotor. Two options for achieving this were mounting both coils and brackets on the radially on the rotor, or both magnets and coils on a horizontal axis. The latter has the major advantages of being able to use a second bike wheel as a stator, as well as reducing drag by utilizing area which is already blocking air flow.

Winding of the coils in a relatively timely fashion was achieved by construction of coil winding guides which mount onto a power drill. These guides consist of two inter-locking circular metal rims with perpendicular fins which bound the edges of the coil as it is being wound. A layer of adhesive tape is applied between layers of coil to assist in keeping the coil together and attempts to make the layers as uniform as possible. A photo of this coil winding guide is shown in Figure 33.

![Figure 33: Coil mounting guides.](image)

### 2.5.4 Electronic Circuits

This section describes various aspects of the circuitry used in the final prototype. The rectifier is the most important one of these, while the boost converter may be optional.
2.5.4.1 Rectifier

The circular arrangement of coils forms the equivalent of a three-phase alternator. It provides an oscillating (resembling smooth spikes more than sine waves) signal to two identical rectifier bridges, each with three Schottky diode pairs with low forward voltages (roughly 0.35V at 200mA). A total of six diode pairs instead of three were used to decouple half of the coils in each phase from the other half. This allows for stator rim alignment errors, such that imperfectly placed coils on opposite sides of the stator will not induce EMF in opposite directions. Of course, one may choose to further increase the number of diode pairs, further reducing the number of coils which need to be aligned with each other, to the point where each individual coil uses its own diode pair. Using less coils per diode, however, increases the total voltage lost across the diodes in the rectifier bridge. In our particular case, six total diode pairs yielded maximum generated power. It is up to the user to find a balance in their setup.

2.5.4.2 Boost Converter

For the boost converter, an integrated circuit (IC) solution was implemented to save on design time and complexity, to ensure reliability and a low supply current. An IC is also much easier for an uneducated user to duplicate than a discrete Maxim’s MAX1771 was used in bootstrapped mode, as referenced from a schematic. Several design parameters were determined or calculated based on recommendations in the datasheet and the considerations outlined in the Section 2.1.7.

For output currents of less than 1A, a bulk capacitor smaller than 100uF is said to be sufficient, in conjunction with a 0.1uF as close to the input pin as possible. Because of their attractive price and wide availability, a 100uF electrolytic capacitor was chosen. 47uF was used at the input. It was also recommended that R6 be bypassed with the lowest stable value above 47pF, so 100pF was used.

According to the datasheet, the inductor used should obey:

\[ L \geq \frac{V_{\text{in(max)}} \cdot 2\mu s}{I_{\text{in}}} \]
In the equation above, 2μs corresponds to the minimum time the FET switch will be shorting the inductor to ground. For a limit of 2A (continuous current) inductor, and the maximum expected input voltage of 10V under load, we calculate that L=10uH will marginally satisfy these requirements. Hence a 22uH inductor was used.

Given MAX1771’s feedback voltage of 1.5V, feedback resistors of 225kΩ and 27kΩ were chosen for R5 and R6, respectively, to set the output voltage to 14.0V, as per the equation below:

\[
\frac{R_5}{R_6} = \frac{V_{out} - V_{fb}}{V_{fb}} = \frac{14.0V - 1.5V}{1.5V} = \frac{225 \text{ kΩ}}{27 \text{ kΩ}}
\]

The feedback values were chosen to be unusually high to keep the wasted power below 1mA. The power dissipation through the chosen resistors is:

\[
P_{R,FB} \approx \frac{14.0V}{225 \text{ kΩ} + 27 \text{ kΩ}} = 0.778 \text{ mW}
\]

The complete schematic is shown in Figure 34.

As discussed before, at higher wind speeds, the circuit performs better when the battery is attached directly to the rectifier output, omitting the boost regulator and greatly simplifying the design. However, due to our main objective to operate at low wind speeds when the circuit normally would not generate 12V, the boost regulator was kept as a part of the design. If a
battery charging voltage is attainable without boost circuitry (even if for a partial duty cycle, and not constantly), it is recommended to exclude the regulator.

2.5.4.3 Additional Circuitry

A simple shutdown circuit was implemented for the MAX1771, consisting of a resistive divider and a bipolar junction transistor (BJT) switch. The transistor is pulled up by default, keeping the controller off, until the resistor divider turns on the BJT, pulling the SHDN pin low and enabling the MAX1771 chip. The circuit serves two purposes. The first is FET protection, letting the input voltage reach roughly 4V before enabling the boost converter. This ensures that the FET is able to turn fully on and fully off when switching. The other, more practical purpose, is preventing the coils from being heavily loaded (by keeping the boost converter off) until they are able to steadily generate about 4V. This allows the blades to accelerate faster to a certain RPM (arbitrarily determined) to reach a point of higher power production.

As a final frontier of protection, several Zener diodes (4 diodes, 3.6V each) were added in series at the output to keep the charging voltage below 14.4V. However it takes a substantial current (~500mA or greater) to increase the voltage drop across a lead-acid battery above this value before it is charged, so there is unlikely to be any useful energy wasted in the Zener diodes.
3.0 Conclusions

3.1 Blade Aerodynamics

3.1.1 Wind Column Performance
The fans available in the project lab are simply not large or powerful enough to provide proper wind for a full range of testing. The three key shortcomings are poor area of coverage, wide variation of wind speed across the area of coverage, and an insufficient top speed.

3.1.2 Blade Performance and Selection
Based on an estimation of the torque delivered and the angular velocity performance, the best choice for blades for this application is PVC piping, cut significantly longer than the radius of the bike wheel (our prototype of 45.3cm seemed to work well). It is also competitive cost-wise and in terms of labour required for preparation. The number of blades is still up in the air - 3 works well but further testing could be done on additional blade counts.

3.2 Electrical Performance

3.2.1 Coil Performance
Resistance losses in the coils are too high due to a combination of too small a wire thickness, the coils being too large, and too many coils connected in a single phase. Use of cores or more diode pairs per coil would assist to remedy this issue; however if using a core, one must be careful to choose the size and position so as not to increase the cut-in wind speed beyond the desired value. Otherwise, the coils performed their function as expected and generated consistent power from their interaction with the magnets. Sturdier mechanical constraints on the rotor and stator, as well as more precise alignment of the coils to magnets will further improve this performance. In the future it would also be necessary to ensure that the coils do not saturate at higher wind speeds.
3.2.2 Boost Regulator

It has been determined that a switching regulator to boost the voltage is not crucial for this application, providing several constraints are met. Firstly, measures must be taken to keep the battery voltage below 14.4V - either by limiting the current delivered to the battery, or by sinking or storing the potentially large quantities of excess energy. Secondly, the system must be able to generate above 12V for a substantial portion of its operation cycle at low wind speeds. Otherwise, a boost regulator is necessary. However, with our design, the natural capacitance of the battery is sufficient to tame excessively high voltage peaks and the generated power is high enough to charge the battery.

3.3 Overall System Performance

3.3.1 Eddy Currents

In our prototype, there is very significant electrical drag caused by eddy currents in the aluminum stator rim and associated aluminum coil brackets. This causes overall poor performance since this drag sucks up a lot of rotor’s power that would otherwise be delivered as current in the coils.

3.3.2 Efficiency

Our efficiency is hovering around 0.08%. The roughly constant efficiency across various wind speeds is a good result and shows that the prototype performs equally as well (or as badly) across a variety of speeds, but the load must be optimized at all times to maintain this efficiency. Eddy currents and conductor losses are two major contributors to this poor result. Other factors include insufficient phase number, blade and coil count optimization.

3.3.3 Cut-in Velocity

The final cut-in velocity for the prototype is 6.1 km/hr maximum velocity (2.52 km/hr average velocity over the swept area), or 1.7 m/s maximum (0.7 m/s average). This result did not change much from the no-load case because electromagnetic drag from eddy currents and coil induction do not affect the rotor at start-up, only once it is in motion.
4.0 Project Deliverables

4.1 List of Deliverables

The prototype at the time of completion consists wind powered generator constructed from salvaged bicycle parts, three sets of hand crafted blades, 12 magnets on the rotor, 36 hand wound coil inductors stator, and a rectifying (possibly voltage limiting ) circuit that can charge a 12 V lead acid battery safely. The cut-in velocity is 6.1 km/hr (short of the desired cut-in velocity of 3 km/hr), but has not been tested for wind speeds greater than 20 km/hr. The total cost to reproduce the prototype for a hobbyist is about $50.

4.2 Financial Summary

The following is a table of costs incurred while building a final version of the Breeze Farmer prototype. The final cost of $124, we believe, is within reason for a dedicated hobbyist.

<table>
<thead>
<tr>
<th>Table 5: Bill of materials for the Breeze Farmer prototype.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Part</strong></td>
</tr>
<tr>
<td>Bike wheel</td>
</tr>
<tr>
<td>Bike rim (no hub/spokes)</td>
</tr>
<tr>
<td>Magnet cups for disc magnets</td>
</tr>
<tr>
<td>Wooden base and beams</td>
</tr>
<tr>
<td>PVC pipe</td>
</tr>
<tr>
<td>Nuts &amp; Bolts, misc. brackets</td>
</tr>
<tr>
<td>Neodymium magnets</td>
</tr>
<tr>
<td>28AWG magnet wire</td>
</tr>
<tr>
<td>Schottky diodes (1N5822)</td>
</tr>
<tr>
<td>Zener diodes (1N5227)</td>
</tr>
<tr>
<td>Capacitors (47uF, 100uF)</td>
</tr>
<tr>
<td>Boost Converter (MAX1771)</td>
</tr>
<tr>
<td>Inductor (22uH)</td>
</tr>
<tr>
<td>BJT &amp; small passive cmpnts</td>
</tr>
<tr>
<td>Boost reg component taxes</td>
</tr>
<tr>
<td>Other taxes</td>
</tr>
<tr>
<td>Shipping</td>
</tr>
</tbody>
</table>

**Total System Cost:** $124.45
By choosing the solution without a boost regulator, there is a savings of ~$7.00. It is also worth noting that the recommended design changes (reduced magnet wire, potential elimination of boost regulator) and a reduction in magnet count by 4 will decrease the project cost to approximately $87.
5.0 Recommendations

5.1 Further Blade Tests

Unfortunately due to time constraints, we were not able to run fully satisfactory aerodynamic performance tests on the type of blade variety we would have liked. Specifically, measurements of the power coefficient when all of the electrical equipment is in place (coils, circuit, and a dynamic load) should ideally be tested with different types and numbers of blades in a proper wind tunnel environment. This would allow very high wind speeds above 20 km/hr to be tested as well. The only real definitive conclusion we made was that longer blades are better than shorter ones. Although a lot of aerodynamic data was taken, it was all taken in a no-load scenario and hence has limited applications to the actual prototype. The loaded measurements were only taken for a single configuration of blades, due to time constraints.

We had hoped to test a wide range of blade materials and designs, but didn’t get to them. One option would be a smaller diameter PVC so that a similar angle of attack range could be achieved with a smaller chord allowing more blades to be mounted efficiently. Different planforms may have higher aerodynamic efficiencies (eg. a chord that is proportional to 1/r as section 2.1.2.1 suggests, an elliptical wing is the most efficient plan-form for fixed wing applications). Blade constructed from fabric would have the advantages that they are light weight, could cover most of the area available, and have reduced noise (even though noise was not a problem in the lab with a fan only two feet away). However fabric blades pose several engineering difficulties especially when trying to mount them inside a bicycle rim, while maintaining the correct shape. Carbon fiber blades would have all the advantages of fabric blades while maintaining their shape without elaborate mounting, but would likely require rebuilding the bicycle wheel with the blades integrated into the spokes.

5.2 Wind Tunnel

Essential to any accurate aerodynamic data collection is a proper wind tunnel, one that can provide near-uniform velocities across the entire swept area. The laboratory fans are just not powerful or uniform enough, so the data they provide is rather sketchy and doesn’t offer much quantitative insight into the performance of various blade sets.
5.3 Improvement of Coil Alignment System on the Stator

Power generation is most effective when moving magnets pass infinitesimally close to the coils on the stator. In the current version of Breeze Farmer, the distance is as large as 3mm during some magnet passes. If both the rotor and stator are firmly constrained to strictly planar positioning, and the coils again independently aligned, this distance can easily be decreased to 1mm by a dedicated, manually dexterous hobbyist with sufficient time and tools. This should provide better system performance across all wind speeds.

5.4 Stator Material Change

A key failure of the Breeze Farmer prototype was the introduction of eddy currents in the aluminum stator rim and other aluminum components not on the rotor. Therefore, an obvious recommendation is to use a far less conductive material for the stator. However, this is not as simple as it sounds. We used a bicycle wheel rim for our stator but these rims are typically made of either aluminum or steel. While steel has a far lower electrical conductivity, it is more magnetic, and therefore would interfere with the magnetic induction. So a different solution must be found for a mounting base for the coils which is sturdy yet sufficiently thin as to not overly disturb the airflow.

5.5 Coil Improvements

Coils or their configuration should be modified to reduce power losses through heat. This can be done by making the coils smaller, or with a slightly larger wire thickness (between 22 and 28AWG), or by connecting less coils together in series for a given phase. Cores or more diode pairs per coil would also assist. Since the coils take a very long time to construct en masse, the favorable improvement would not require re-making the coils.

5.6 Implementation of Automatic Peak Power Tracking

So far, generated power has been tested by manually placing known resistance values at the system’s output. With the current configuration, the optimal loads were all in a very close range across the tested wind speeds. Thus, it is sufficient for the current system to simply find the
optimal load and set the battery to appear as that particular load. With the recommended
design changes, however, and for anyone attempting to reproduce the system (especially if
power output is improved), this is unlikely to be the case. Thus, either a microcontroller system
could be installed for peak power tracking, or a simple anemometer-controlled pulse-width
modulator to increase the battery charging duty cycle with increasing wind speed.

5.7 Additional Functionality of Battery Management Circuitry

Full-charge tests have not been run with the Breeze Farmer mostly due to the lengthy time
required to complete given the current system capacity. Because of this and the small power
output, the only battery protection function in place is voltage limiting. A battery disconnect
function should be implemented to decouple the lead-acid battery from the circuit when it
reaches a certain voltage. This could easily be done with a MOSFET switch (it can be
combined with peak power tracking pulse-width modulated charging) and can eliminate the
need of the slightly more expensive Zener diodes.

In addition, a current limiting system should be implemented. This would be most easily done
with either a dedicated current sensor, or measuring voltage across a sense resistor with a
differential amplifier. With the introduction of additional electrical components, however, one
should be careful to choose parts and operating points which consume little supply current to
avoid taking away substantial charging power from the battery. If the capacity of the system is
increased, this is less of a concern.
APPENDIX A: Data Acquisition and Analysis Program in MATLAB

function RT_ACQ(sampleRate, sampleLength, sampleInterval, numMagnets)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ---------------- *** FILL OUT THESE CONSTANTS!!! *** ------------------ %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sampling rate for DAQ
sampleRate = 2000;
% Sampling time per sample (s)
sampleLength = 4;
% How many magnets are in use?
umMagnets = 8;
% How long to wait between measurements
sampleInterval = 1;
R_SENSE_RECT = 10.1;
R_SENSE_OUT = 46.5 + R_SENSE_RECT;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                          DAQ INITIALIZATION                             %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear ai
% Create a device object using a NI-DAQ
ai = analoginput('nidaq','Dev3');
set(ai,'InputType','Differential');
CH_V = 5;
% Add a hardware channel to ai
chans = addchannel(ai,0); % MATLAB's AI channel 1: DAQ's AI0
ai.Channel(1).ChannelName = 'Vrect'; % Name the channel
chans = addchannel(ai,1); % MATLAB's AI channel 2: DAQ's AI1
ai.Channel(1).InputRange = [-CH_V CH_V]; % Change the range
ai.Channel(2).ChannelName = 'Irect'; % Name the channel
ai.Channel(2).Units = 'Amps'; % Change the units
ai.Channel(2).InputRange = [-1 1];
chans = addchannel(ai,2); % MATLAB's AI channel 3: DAQ's AI2
ai.Channel(3).ChannelName = 'Vcoil1'; % Name the channel
ai.Channel(3).InputRange = [-CH_V CH_V]; % Change the range
chans = addchannel(ai,3); % MATLAB's AI channel 4: DAQ's AI3
ai.Channel(4).ChannelName = 'Vout'; % Name the channel
ai.Channel(4).InputRange = [-CH_V CH_V]; % Change the range
ai.Channel(4).Units = 'Volts'; % Change the units
chans = addchannel(ai,4); % MATLAB's AI channel 5: DAQ's AI4
%ai.Channel(5).ChannelName = 'Iout';     % Name the channel

% List channels
ai.channel
pause(1);

% Declare unchanging vars
MAX_DAQ_RATE = 40000;                   % Max sampling rate: 40 kHz
MAX_VECTOR_LENGTH = 1000000;            % Max data entries: 1000000

% If specified sampling rate exceeds DAQ capabilities, decrease it
if sampleRate > MAX_DAQ_RATE
    sampleRate = MAX_DAQ_RATE;
end

% Pre-emptively truncate excessively long vectors
if sampleRate*sampleLength > MAX_VECTOR_LENGTH
    sampleLength = MAX_VECTOR_LENGTH/sampleRate;
end

% Configure the DAQ's sampling rate and duration of acquisition
set(ai,'SampleRate',sampleRate);
set(ai,'SamplesPerTrigger',round(sampleLength*sampleRate));
sprintf('Sampling rate set to: %i Hz
Sampling time set to: %d s', sampleRate, sampleLength)
pause(2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%
%                              START DATA ACQUISITION                           %
%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

kill = 0;
while kill==0
    start(ai)
    data = getdata(ai);

    shift = zeros(size(data,2),1);
    VrectUpsampled = resample(data(:,1),40,1);
    dataUpsampled = [];
    resampledData = [];
    for i = 1:2
        dataUpsampled(:,i) = resample(data(:,i),40,1);
    end
    Z = [];
    Z(:,1) = xcov(VrectUpsampled, VrectUpsampled);
    Z(:,2) = xcov(dataUpsampled(:,2), VrectUpsampled);
    for i = 1:2
        shift(i) = length(VrectUpsampled) - find(Z(:,i)==max(Z(:,i)),1);
        if shift(i) > 0
            resampledData(:,i) = resample([zeros(shift(i),1);
                                            dataUpsampled(shift(i)+1:length(dataUpsampled(:,i)),i)],1,40);
else
    resampledData(:,i) = resample([dataUpsampled(-shift(i)+1:length(dataUpsampled),i);
        zeros(-shift(i),1)],1,40);
end
end

Vrect = resampledData(:,1);
Irect = resampledData(:,2)/R_SENSE_RECT;
Vcoil1 = data(:,3);
Vout = data(:,4);
lout = data(:,4)/R_SENSE_OUT;

N = size(data,1);
deltaT = 1/sampleRate;
t = deltaT:deltaT:deltaT*N;

VoutRMS = sqrt(sum(Vout.^2)/length(Vout));
loutRMS = sqrt(sum(lout.^2)/length(lout));
Pout = VoutRMS*loutRMS;
Prect = sum(Vrect.*Irect)/length(Vrect);

% Extract RPM from Vcoil1
Vcoil1(find(Vcoil1<0.05)) = 0;               % Flatline all noise and stuff below 50mV
Vcoil1(find(Vcoil1<0.4*max(Vcoil1))) = 0;    % Keep data > threshold
k = 1;
markers = [];
% Locate all rising edges of positive voltages, make markers for them
while k<N
    while k<N && Vcoil1(k)>0 ;              % Skip through non-zero data
        k=k+1;
    end
    while k<N && Vcoil1(k)<0.1*max(Vcoil1);  % Skip through zero-data
        k=k+1;
    end
    if k<N && Vcoil1(k+1)>=0.1*max(Vcoil1) & Vcoil1(k+1)>=0.02;
        markers = [markers k];
    end
end

timeStamps = t(markers);              % Convert markers to time stamps
if length(timeStamps)<numMagnets+1   % If less than one cycle, not enough data!
    freqCoil = 0;
elseif length(timeStamps) < 2*numMagnets+1
    freqCoil = 1/(timeStamps(numMagnets+1)-timeStamps(1));
else
    freqCoil = 2/(timeStamps(2*numMagnets+1)-timeStamps(1));
end

RPM = 60*freqCoil;                   % Convert to RPM

Load = 0;
if length(markers)<=1
Load = 9999999;
else
    for j=1:length(markers)-1;
        maxVrectIndex = find(Vrect(markers(j):markers(j+1)) == max(Vrect(markers(j):markers(j+1))));
        Load = Load + Vrect(markers(j)+maxVrectIndex-1)/Irect(markers(j)+maxVrectIndex-1);
    end
    Load = Load/(length(markers)-1);
end

sprintf('Output Voltage: %3.1f V RMS
Output Current: %3.3f mA RMS
Output Power: %3.3f mW',
        VoutRMS, 1000*IoutRMS, 1000*Pout)

sprintf('Power rectified: %3.1f mW at %3.1f RPM
Load: %3.1f Ohms
Boost efficiency: %2.1f%%',
        1000*Prect, RPM, Load, 100*Pout/Prect)

plot(t, Vout)
pause(sampleInterval);
APPENDIX B: Determining the Optimal Coil Diameter

Using a 3-meter length of 22-gauge magnet wire, several small coils of various diameters were assembled and tested by exposing them to magnets moving at different velocities. The coils thickness was standardized at 11mm, and the distance from the magnets kept the same at 2mm. The eight magnets were housed on the outer edge of a rotating bike wheel; hence velocity was measured on an oscilloscope by finding the time delta between every 8th consecutive peak. An RPM value was only extracted from this for convenience. The peak induced voltage was then divided by the number of turns in the coil, and plotted for several RPM values in Figure 35. The data is tabulated on the following page.
Table 6: Coil geometry testing data.

<table>
<thead>
<tr>
<th>ID (mm)</th>
<th>N</th>
<th>$V_{\text{motor}}$</th>
<th>$\Delta T (1/f)$</th>
<th>RPM</th>
<th>$V_{\text{out}}$</th>
<th>$V_{\text{ind/turn}}$</th>
<th>Fitted $V_{\text{ind}}$</th>
<th>(Error)$^2$</th>
<th>$\Sigma$(Errors)</th>
<th>Slope fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>46</td>
<td>~2V 2220 ms</td>
<td>27.0</td>
<td>130 mV</td>
<td>2.83 mV</td>
<td>3.028</td>
<td>0.041</td>
<td>0.091</td>
<td>0.1120</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1200 ms</td>
<td>50.0</td>
<td>250 mV</td>
<td>5.43 mV</td>
<td>5.602</td>
<td>0.028</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 640 ms</td>
<td>93.8</td>
<td>490 mV</td>
<td>10.65 mV</td>
<td>10.504</td>
<td>0.022</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>40</td>
<td>~2V 2350 ms</td>
<td>25.5</td>
<td>110 mV</td>
<td>2.75 mV</td>
<td>3.121</td>
<td>0.138</td>
<td>0.394</td>
<td>0.1222</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1320 ms</td>
<td>45.5</td>
<td>215 mV</td>
<td>5.38 mV</td>
<td>5.557</td>
<td>0.033</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1140 ms</td>
<td>52.6</td>
<td>245 mV</td>
<td>6.13 mV</td>
<td>6.434</td>
<td>0.096</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 630 ms</td>
<td>95.2</td>
<td>480 mV</td>
<td>12.00 mV</td>
<td>11.643</td>
<td>0.128</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td>36</td>
<td>~2V 2250 ms</td>
<td>26.7</td>
<td>135 mV</td>
<td>3.75 mV</td>
<td>3.666</td>
<td>0.007</td>
<td>0.068</td>
<td>0.1375</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1350 ms</td>
<td>44.4</td>
<td>215 mV</td>
<td>5.97 mV</td>
<td>6.111</td>
<td>0.019</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1130 ms</td>
<td>53.1</td>
<td>260 mV</td>
<td>7.22 mV</td>
<td>7.300</td>
<td>0.006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 670 ms</td>
<td>89.6</td>
<td>440 mV</td>
<td>12.22 mV</td>
<td>12.312</td>
<td>0.008</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 620 ms</td>
<td>96.8</td>
<td>485 mV</td>
<td>13.47 mV</td>
<td>13.305</td>
<td>0.028</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.6</td>
<td>30</td>
<td>~2V 2490 ms</td>
<td>24.1</td>
<td>95 mV</td>
<td>3.17 mV</td>
<td>3.638</td>
<td>0.222</td>
<td>2.280</td>
<td>0.1510</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~2V 2250 ms</td>
<td>26.7</td>
<td>115 mV</td>
<td>3.83 mV</td>
<td>4.026</td>
<td>0.037</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~2V 2000 ms</td>
<td>30.0</td>
<td>125 mV</td>
<td>4.17 mV</td>
<td>4.530</td>
<td>0.132</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1160 ms</td>
<td>51.7</td>
<td>200 mV</td>
<td>6.67 mV</td>
<td>7.810</td>
<td>1.307</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 700 ms</td>
<td>85.7</td>
<td>395 mV</td>
<td>13.17 mV</td>
<td>12.942</td>
<td>0.050</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 650 ms</td>
<td>92.3</td>
<td>440 mV</td>
<td>14.67 mV</td>
<td>13.938</td>
<td>0.531</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38.1</td>
<td>23</td>
<td>~2V 2340 ms</td>
<td>25.6</td>
<td>95 mV</td>
<td>4.13 mV</td>
<td>4.023</td>
<td>0.012</td>
<td>0.446</td>
<td>0.1569</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~2V 2230 ms</td>
<td>26.9</td>
<td>100 mV</td>
<td>4.35 mV</td>
<td>4.221</td>
<td>0.016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~2V 1930 ms</td>
<td>31.1</td>
<td>110 mV</td>
<td>4.78 mV</td>
<td>4.878</td>
<td>0.009</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1170 ms</td>
<td>51.3</td>
<td>195 mV</td>
<td>8.48 mV</td>
<td>8.046</td>
<td>0.187</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>~5V 630 ms</td>
<td>95.2</td>
<td>335 mV</td>
<td>14.57 mV</td>
<td>14.943</td>
<td>0.142</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 530 ms</td>
<td>113.2</td>
<td>405 mV</td>
<td>17.61 mV</td>
<td>17.762</td>
<td>0.023</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 510 ms</td>
<td>117.6</td>
<td>430 mV</td>
<td>18.70 mV</td>
<td>18.458</td>
<td>0.056</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48.3</td>
<td>19</td>
<td>~2V 2480 ms</td>
<td>24.2</td>
<td>64 mV</td>
<td>3.37 mV</td>
<td>3.361</td>
<td>0.000</td>
<td>0.105</td>
<td>0.1389</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~2V 2250 ms</td>
<td>26.7</td>
<td>72 mV</td>
<td>3.79 mV</td>
<td>3.704</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1170 ms</td>
<td>51.3</td>
<td>140 mV</td>
<td>7.37 mV</td>
<td>7.124</td>
<td>0.060</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 635 ms</td>
<td>94.5</td>
<td>250 mV</td>
<td>13.16 mV</td>
<td>13.126</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 595 ms</td>
<td>100.8</td>
<td>265 mV</td>
<td>13.95 mV</td>
<td>14.008</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 540 ms</td>
<td>111.1</td>
<td>290 mV</td>
<td>15.26 mV</td>
<td>15.435</td>
<td>0.029</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 530 ms</td>
<td>113.2</td>
<td>300 mV</td>
<td>15.79 mV</td>
<td>15.726</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60.45</td>
<td>15.25</td>
<td>~2V 2130 ms</td>
<td>28.2</td>
<td>55 mV</td>
<td>3.61 mV</td>
<td>3.757</td>
<td>0.023</td>
<td>0.224</td>
<td>0.1334</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~2V 2100 ms</td>
<td>28.6</td>
<td>56 mV</td>
<td>3.67 mV</td>
<td>3.811</td>
<td>0.019</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1180 ms</td>
<td>50.8</td>
<td>102 mV</td>
<td>6.69 mV</td>
<td>6.782</td>
<td>0.009</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3V 1120 ms</td>
<td>53.6</td>
<td>105 mV</td>
<td>6.89 mV</td>
<td>7.145</td>
<td>0.068</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 620 ms</td>
<td>96.8</td>
<td>200 mV</td>
<td>13.11 mV</td>
<td>12.908</td>
<td>0.043</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 575 ms</td>
<td>104.3</td>
<td>210 mV</td>
<td>13.77 mV</td>
<td>13.918</td>
<td>0.022</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5V 550 ms</td>
<td>109.1</td>
<td>225 mV</td>
<td>14.75 mV</td>
<td>14.550</td>
<td>0.041</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Each curve in the previous graph is linear, as expected, since the rate of change of magnetix flux varies linearly with speed of the magnets. This also indicates that the coils are not saturating so we can safely compare the curves. By linearly fitting each curve with an intercept at the origin (data shown in the previous table), we extract a $\Delta EMF/\Delta RPM$ parameter for each coil size. The induced EMF per turn versus magnet speed parameters exhibited a clear maximum at a diameter slightly greater than that of the disc magnet used (see Figure 36).

![Figure 36: Change in induced EMF in a turn of coil with increasing RPM vs coil diameters.](image)
APPENDIX C: MAX1771 Efficiency Testing

Efficiency of Maxim’s boost regulator IC was tested only for a rough idea of the performance of the chip and the optimal input voltage. An input voltage was provided with a power supply, with a sense resistor in series to measure input current. The load was held constant at 102.3Ω, and the input and output voltages recorded. The data and calculation results are summarized in Table 7 and depicted in Figure 37. Efficiency was calculated as follows:

\[
\eta_{\text{boost}} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{V_{\text{out}}^2}{R_L} \cdot \frac{R_{\text{sense,in}}}{V_{\text{in}}V_{\text{sense,in}}}
\]

Table 7: MAX1771 efficiency data.

<table>
<thead>
<tr>
<th>( V_{\text{in}} )</th>
<th>( V_{\text{out}} )</th>
<th>( V_{\text{sense,in}} )</th>
<th>( R_L )</th>
<th>( R_{\text{sense,in}} )</th>
<th>( I_{\text{in}} )</th>
<th>( I_{\text{out}} )</th>
<th>( P_{\text{in}} )</th>
<th>( P_{\text{out}} )</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.25</td>
<td>12.04</td>
<td>0.444</td>
<td>102.3</td>
<td>1.0</td>
<td>0.444</td>
<td>0.118</td>
<td>1.887</td>
<td>1.417</td>
<td>75.1%</td>
</tr>
<tr>
<td>4.97</td>
<td>13.81</td>
<td>0.487</td>
<td>102.3</td>
<td>1.0</td>
<td>0.487</td>
<td>0.135</td>
<td>2.420</td>
<td>1.864</td>
<td>77.0%</td>
</tr>
<tr>
<td>6.02</td>
<td>14.82</td>
<td>0.446</td>
<td>102.3</td>
<td>1.0</td>
<td>0.446</td>
<td>0.145</td>
<td>2.685</td>
<td>2.147</td>
<td>80.0%</td>
</tr>
<tr>
<td>6.44</td>
<td>15.29</td>
<td>0.442</td>
<td>102.3</td>
<td>1.0</td>
<td>0.442</td>
<td>0.149</td>
<td>2.846</td>
<td>2.285</td>
<td>80.3%</td>
</tr>
<tr>
<td>7.29</td>
<td>14.77</td>
<td>0.356</td>
<td>102.3</td>
<td>1.0</td>
<td>0.356</td>
<td>0.144</td>
<td>2.595</td>
<td>2.132</td>
<td>82.2%</td>
</tr>
<tr>
<td>8.93</td>
<td>14.72</td>
<td>0.282</td>
<td>102.3</td>
<td>1.0</td>
<td>0.282</td>
<td>0.144</td>
<td>2.518</td>
<td>2.118</td>
<td>84.1%</td>
</tr>
<tr>
<td>10.29</td>
<td>14.71</td>
<td>0.245</td>
<td>102.3</td>
<td>1.0</td>
<td>0.245</td>
<td>0.144</td>
<td>2.521</td>
<td>2.115</td>
<td>83.9%</td>
</tr>
<tr>
<td>4.22</td>
<td>11.52</td>
<td>0.416</td>
<td>102.3</td>
<td>1.0</td>
<td>0.416</td>
<td>0.113</td>
<td>1.756</td>
<td>1.297</td>
<td>73.9%</td>
</tr>
<tr>
<td>4.73</td>
<td>13.57</td>
<td>0.500</td>
<td>102.3</td>
<td>1.0</td>
<td>0.500</td>
<td>0.133</td>
<td>2.365</td>
<td>1.800</td>
<td>76.1%</td>
</tr>
<tr>
<td>5.91</td>
<td>14.69</td>
<td>0.447</td>
<td>102.3</td>
<td>1.0</td>
<td>0.447</td>
<td>0.144</td>
<td>2.642</td>
<td>2.109</td>
<td>79.8%</td>
</tr>
<tr>
<td>5.26</td>
<td>14.04</td>
<td>0.479</td>
<td>102.3</td>
<td>1.0</td>
<td>0.479</td>
<td>0.137</td>
<td>2.520</td>
<td>1.927</td>
<td>76.5%</td>
</tr>
</tbody>
</table>

Figure 37: MAX1771 efficiency vs input voltage.
The results show a peak performance at an input voltage of approximately 9V. Unfortunately, most of the time our generates around 4-5V continuous voltage for the input. Moreover, the currents produced are substantially smaller than the 100mA tested with here, so the performance of the MAX1771 is expected to deteriorate further. For a better understanding of the chip's performance at low currents, more testing needs to be done by varying the load resistance.
APPENDIX D: Power Generation Data

APPENDIX D.1: Power Production at the Rectifier Output

To determine the equivalent optimal load as seen by the rectifier, various resistor combinations were used at the rectifier’s output. The data was captured by a National Instruments DAQ and analyzed in MATLAB, as per the procedure outlined in the Methods section. Wind speed was varied by changing the speed setting on a fan and the AC voltage provided by an adjustable transformer. The data for several different wind speeds, and the necessary loads to show both near-zero value ends of the power production curve, is tabulated below.

<table>
<thead>
<tr>
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<th>$V_{rotor}$ [RPM]</th>
<th>$P_{rectified}$ [mW]</th>
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<th>Load [Ω]</th>
<th>$V_{rotor}$ [RPM]</th>
<th>$P_{rectified}$ [mW]</th>
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Table 8: Power generation data for loads across the rectifier output.
APPENDIX D.2: Power Production at the Boost Regulator Output

A similar test was attempted for the output of the boost regulator (see table below). However, the testing was not as extensive since it was immediately obvious that voltage boosting through an IC introduced great inefficiencies at such low power rates. By this point, it was also already known that the system performs better without the regulator.

Table 9: Power generation data for loads across the boost regulator output.

<table>
<thead>
<tr>
<th>$V_{\text{wind}}$ [km/h]</th>
<th>Load Across Regulator [$\Omega$]</th>
<th>$V_{\text{rotor}}$ [RPM]</th>
<th>$P_{\text{rectified}}$ [mW]</th>
<th>$P_{\text{reg output}}$ [mW]</th>
<th>Apparent Load at Rectifier [$\Omega$]</th>
<th>Boost Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1000</td>
<td>65.2</td>
<td>115.4</td>
<td>54.2</td>
<td>63.1</td>
<td>47%</td>
</tr>
<tr>
<td>19</td>
<td>552</td>
<td>59.1</td>
<td>115.4</td>
<td>87.6</td>
<td>58</td>
<td>76%</td>
</tr>
<tr>
<td>19</td>
<td>116</td>
<td>58.6</td>
<td>126</td>
<td>93</td>
<td>21</td>
<td>74%</td>
</tr>
</tbody>
</table>

APPENDIX D.3: Power Delivery to a 12V Lead-Acid Battery

Finally, the system’s power production was tested with a 12V lead-acid battery connected to the output of the rectifier and measured as shown in Figure 38. The power figure was extracted by taking:

$$P = V_{\text{in}}(V_{\text{in}} - V_{\text{sense}})/R_{\text{sense}}$$

Figure 38: Measurement setup for power delivered to a lead-acid battery.
A typical voltage output to a charging battery is shown in Figure 39.

![Typical Power Output to a Charging Lead-Acid Battery](image)

**Figure 39:** Typical output to a charging lead-acid battery.

To vary the load, the battery connection was manually switched at a rate of approximately 3 Hz (see Figure 40) and the duty cycle varied. The noisy “low” data around 8V represents the time when a battery is connected for charging, while the clipped data above 10V represents the system’s output voltage when the battery is disconnected.

![Manually Pulsed (-50%) Output Waveform to a Charging Battery](image)

**Figure 40:** Voltage output of a typical manually-switched system.
The battery charging data is summarized and graphed in the table and figure below.

Table 10: Battery charging performance data.

<table>
<thead>
<tr>
<th>$V_{\text{wind}}$ [km/h]</th>
<th>Load Across Rectifier</th>
<th>Duty Cycle</th>
<th>$V_{\text{rotor}}$ [RPM]</th>
<th>$P_{\text{rectified}}$ [mW]</th>
</tr>
</thead>
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<td>0%</td>
<td>83</td>
<td>0.0</td>
<td></td>
</tr>
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<td>19 Battery</td>
<td>20%</td>
<td>69</td>
<td>20.0</td>
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<td>19 Battery</td>
<td>50%</td>
<td>66</td>
<td>94.9</td>
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<tr>
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<td>70%</td>
<td>63</td>
<td>159.2</td>
<td></td>
</tr>
<tr>
<td>19 Battery</td>
<td>100%</td>
<td>61</td>
<td>204.2</td>
<td></td>
</tr>
<tr>
<td>19 Battery (discharged)</td>
<td>100%</td>
<td>60</td>
<td>221.6</td>
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7.0 References


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    Cross-Sectional Areas of AWG Sizes of Solid Round Wires Used as Electrical
    Conductors.