WIND TURBINE ANALYSIS AND IMPROVEMENT

A Major Qualifying Project Report
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of the

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by

Chris Catanese

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Justin Linnehan

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Nicholas Vaccaro

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Approved:

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Prof. Alexander Emanuel, Major Advisor

ABSTRACT

The objective of this project was to improve the amount of energy delivered by the wind turbine on Atwater-Kent Laboratories. This was accomplished by adding a monitoring and switching module as well as a second, low power, inverter in parallel to the currently installed inverter. A contactor was used to switch between the two inverters, controlled by the power monitoring circuitry. Information on the turbine's output was also recorded and saved on a computer.

ACKNOWLEDGEMENTS

This project would not have been possible without the support of several people. We would like to thank Professor Alexander Emanuel who helped guide us through the project each step of the way. We would also like to thank Dr. John Bzura and National Grid for sponsoring this project and supplying us with the resources necessary. We would also like to thank Professor McNeill for his advice on some of the analog circuitry and Professor O'Rourke for his assistance in obtaining information on the installed turbine.

EXECUTIVE SUMMARY

The goal of this project is to study and establish a better understanding of the operation of residential sized wind turbines. With growing interest in alternative energy due to environmental concerns and increased energy cost, improvements on small, roof-mount, wind turbines are continuously sought after. This project specifically evaluates power production of a SWIFT Wind Turbine donated by National Grid to Worcester Polytechnic Institute. Interest in further study of energy production of the turbine was initiated after the first year of operation; when readings showed a lower than desired energy production throughout the year.

The focus of study was based on the low power sleep mode used in the system. In order for the turbine's associated grid-tie inverter to become active it requires a minimum power delivered. This project studies the potential amount of energy that can be produced, had this minimum power threshold been lowered.

Various monitoring circuitry, with very specific safety and functionality requirements, and data acquisition hardware was installed in order to obtain a better understanding of the system's functionality. Figure 1 represents a block diagram of the system delivered upon completion of this project. The blue components of the block diagram represent components added to the system throughout the progression of the project. Represented by the LED Module is a possible system to store energy when the turbine is inactive in its low power sleep mode.

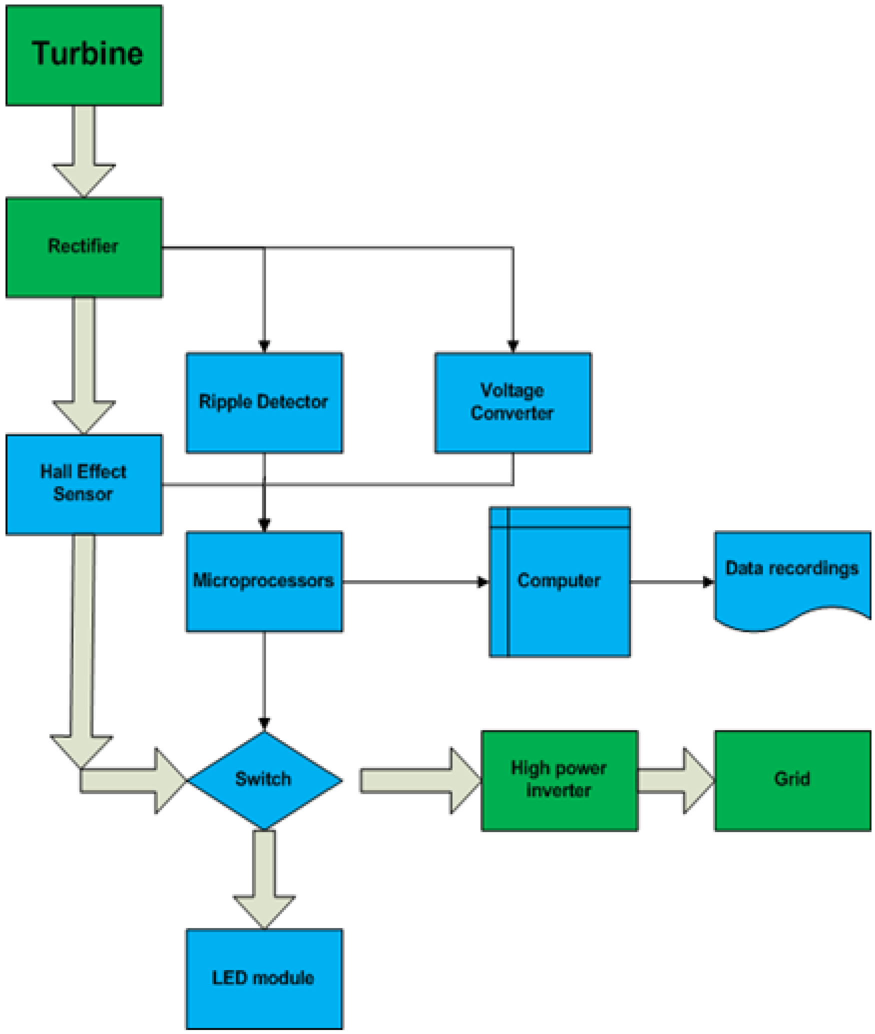

Figure 1: System Block Diagram

After data collection, the information was extrapolated over the previous year in order to estimate the potential energy being wasted by normal operation. The project offers a design for the installment of a low power grid-tie inverter and briefly evaluates the economics of adding this low power inverter. It was found that although the system did increase the overall power delivered by the turbine, the increase was not enough to make installing an inverter cost effective. The following report offers detailed descriptions of the requirements, design, simulation, and testing, as well as the results of our findings.

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1 INTRODUCTION

The main goal of this project was to increase the amount of energy delivered by the wind turbine installed on the roof of Atwater-Kent Laboratories. Our research showed that there was a cut-on voltage of 100V in the originally installed inverter. The attempted solution was to install power monitoring circuitry and a low power inverter to the output of the wind turbine.

The report begins with a background of wind power and specifics of the turbine installed on the roof of Atwater-Kent Laboratories. The methods of energy production by wind turbines as well as the circuitry of the installed turbine and inverter were researched. This information was used to help in developing our design.

Once the overall structure of the design was determined, each individual module was designed and tested. Information on all of the modules is included in this report. Many of the original designs did not meet the requirements of the system, so they were redesigned and tested until the desired outcome was reached. Once the modules were all designed and tested individually, they were tested as an entire unit. To allow for more control and safety, the testing of the entire unit was performed using a three-phase synchronous machine.

After the unit was tested as a whole, a final build was produced and calibrated. Once the calibration process was complete, it was installed into room 317. During the installation process there were grounding issues which damaged the inverters. Due to this we were unable to collect much testing data when connected to the turbine.

The final step of the project was to do a cost analysis of the design. As there are no competitors to this product on the commercial market, return on investment was the metric used to determine whether the system was cost effective.

2 BACKGROUND

This section will give a background on wind power, small wind turbines, and the turbine installed on the roof of Atwater Kent. This information is important in understanding the reason for this project as well how the proposed solution works.

2.1 WIND POWER

With the constantly increasing energy needs, it is important to find means of energy production to meet these needs. Wind power is quickly becoming a very popular option due to the recent change in the public opinion towards protecting the environment. It is also viewed as a safe energy source that does not rely on limited natural resources.

Wind power is a form of power that is renewable as well as a clean alternative to traditional electricity generation. Wind power is harnessed when wind forces turbine blades to rotate. The spinning of the blades rotates the rotor of the motor, which generates electricity through the permanent magnet motor. This motion is then converted into electrical power delivered to households, commercial buildings, or power companies.

Worldwide wind power capacity reached 159,213 MW in 2009, which will create 340 TWh yearly, a monumental increase from the 24,322 MW capacity in 2001.[1] The increasing use of wind power is very prevalent in the United States. The worldwide total capacity for the last decade can be seen in Figure 2.

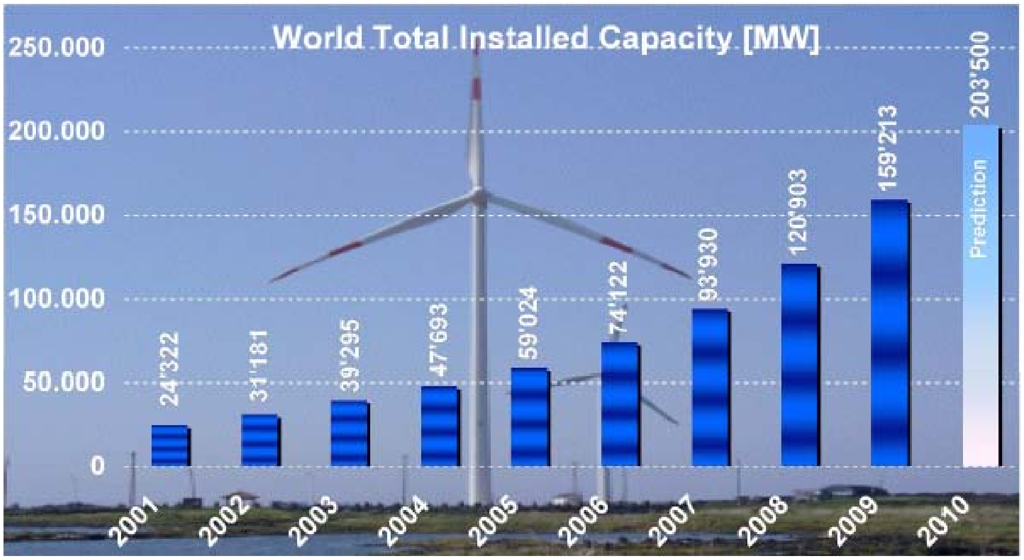

Figure 2: World Total Wind Turbine Capacity[1]

The U.S. Department of Energy outlined a plan for increasing the U.S. wind power to contribute 20% of total energy by the year 2030. In 2009, 1.8% of the total energy produced was produced by wind power.[4] In order to reach this goal the U.S. needs to install numerous wind farms. Most of this power will be produced in large wind farms, but there are also small wind turbines that help to contribute to these totals.

2.2 Small Wind Turbines

Small wind turbines have the potential to produce large amounts of energy. A study by the Carbon Trust found that in the United Kingdom there is the potential for small wind turbines to produce 41.3 TWh annually.[3] Although reaching levels like these will not happen for quite some time, small wind turbines have the potential to greatly reduce the electricity costs for individuals while decreasing the dependence on nonrenewable electricity.

Small wind turbines are typically purchased by individuals and businesses to lower electricity costs. Small wind turbines are defined as wind turbines that have a capacity of under 100kW.[2] Small wind turbines work the same way as the large wind turbines from wind farms, they are simply smaller scale and thus have a smaller energy capacity. A comparison between the small and large wind turbines can be seen in Figure 3.

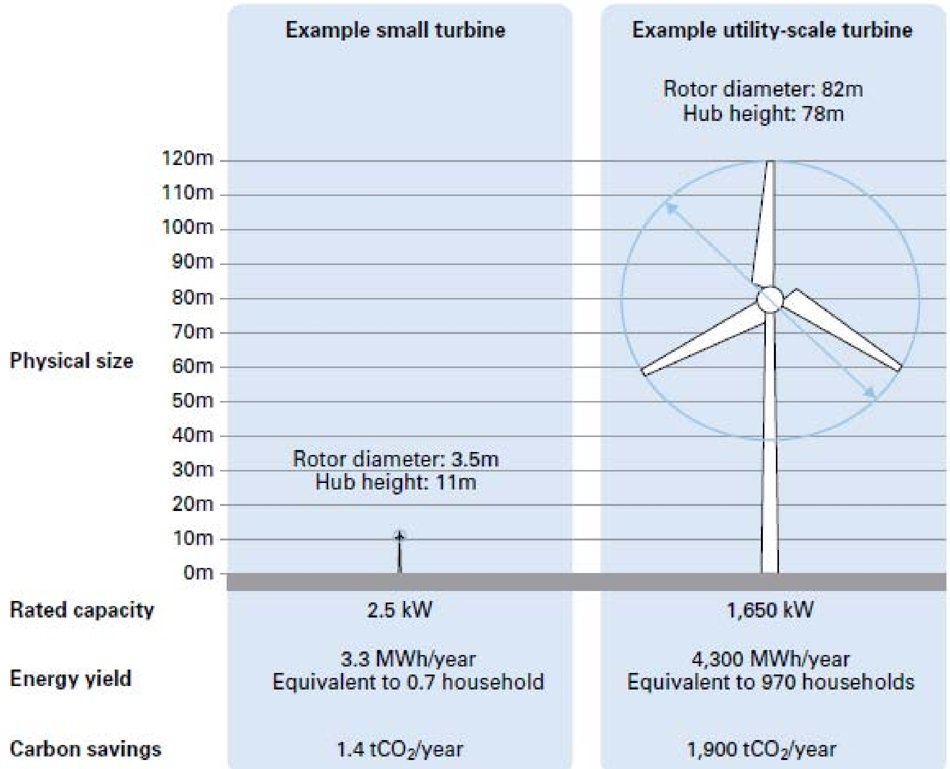

Figure 3: Comparison of Small and Large Turbine[3]

Small turbines are typically connected to the electric grid through an inverter. The inverter is used in order to ensure the produced power is in phase with the grid. The amount of power sent is recorded and the utility company will credit the household with money for the power produced and take the amount off the electricity bill, even paying if the power produced is higher than power used. For very small wind turbines, the turbine is often not connected to the grid. Instead it can be used to charge batteries or power specific equipment. The breakdown of wind turbine size and connection type can be seen in Figure 4.

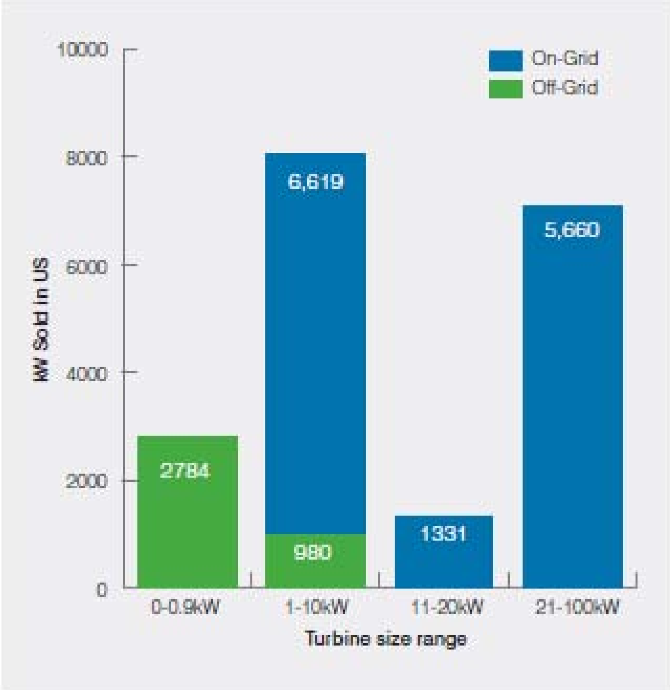

Figure 4: U.S. Small Wind Turbine Market[2]

The small wind market grew 78% in 2009 according to a survey done by the American Wind Energy Association.[2] This extreme growth is thought to have come as a result various contributing factors. These factors include government incentives, decreased zoning issues, the recession, rising electricity prices, public awareness, and improved technology. The government incentives are both federal tax write offs and local and state standardization of the rules and procedures. A few years ago it was very difficult to install wind turbines due to height restrictions, but as they become more common rules regarding their installation become easier to follow.

The recession made wind power more popular because it has smaller initial costs compared to photovoltaic electricity production, the primary alternative for home electricity production. The rising prices and public awareness of the option for home wind power combined to make it more accessible and more cost effective of an option. Finally new technology is making it easier to determine how effective an installed wind turbine will be, allowing for less risky investment. Due to these factors small wind turbine installation has been increasing.

2.3 Turbine on Atwater-Kent Laboratories

As part of an effort to improve small wind turbine energy production, National Grid donated a small wind turbine to Worcester Polytechnic Institute in 2008. It was installed over the summer and connected to the grid through an inverter. The wind turbine donated was a Swift Wind turbine. It can be seen in Figure 5.

Figure 5: Wind Turbine on Atwater Kent

The inverter is a Swift Inverter and was installed in room 317. The inverter works by converting direct voltage supplied by the rectifier into alternating voltage that can be supplied to the grid. It also records total energy as well as instantaneous power. There are eight poles in the turbine motor, and a three phase bridge rectifier at the output.

Over the first year of operation of the turbine, there was a very disappointing power output. The total output for the entire year was approximately 1200kWh. Professor Emanuel felt that this might be due to the inverter's low-power sleep mode.

The goal of the project was to improve this power output. In order to improve the output, we attempted to add a low power inverter to use the power supplied by the turbine when operating below the cut-off voltage. In order for the system to be effective, it needed to know when it was above and below the cut-off voltage. For this purpose power monitoring was necessary. This would allow the system to switch between the two separate inverters depending on the voltage. The power readings would also be recorded on a computer to allow for future research to be done.

2.4 ORIGINAL INSTALLMENT CIRCUITRY

In order to design anything to be installed in conjunction with the original installation, it was necessary to first characterize the original installation. This involved getting a diagram of the wind turbine and already installed inverter. Although it was important to characterize the installation, it was not necessary to get exact schematics for the turbine and inverter, because as long as what would be seen by added components was accounted for no problems should arise. The turbine installment on the roof of Atwater-Kent laboratories is shown in the figure below. This is broken down into three sections.

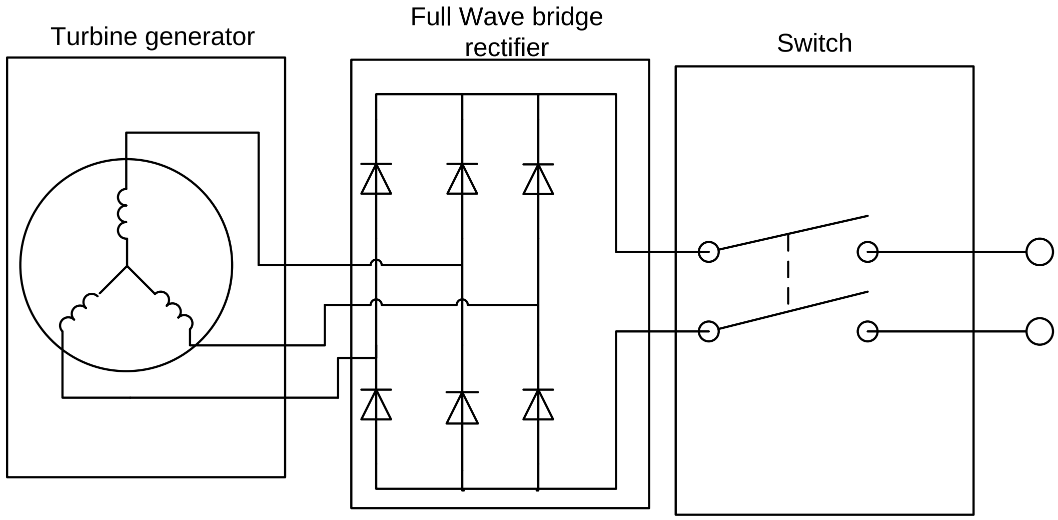

Figure 6: System Setup on Roof of Atwater Kent

The first section is the turbine generator. This converters the wind power into electrical power. The turbine is capable of producing up to 2kW of power at 400V DC, while spinning at maximum speed. Compared to large scale wind turbines, this is a very small amount of power generation. The second stage is a full wave bridge rectifier to convert the AC signal to a DC signal. The rectifier stage is enclosed in the turbine's housing, and cannot be accessed, as it is hermetically sealed. These diodes can pass high currents, on the order of several amps when the turbine produces a high enough voltage. Next there is a service switch to deactivate the unit. It includes both a electrical switch and a mechanical brake. This is used to slow or turn off the turbine if it needs to be serviced or disconnected.

The output of the switch is run down into the building. It is then connected to a Swift inverter located in room 317. This inverter is then connected to a transformer which connects to the grid. The model of the circuitry in room 317 can be seen in Figure 7.

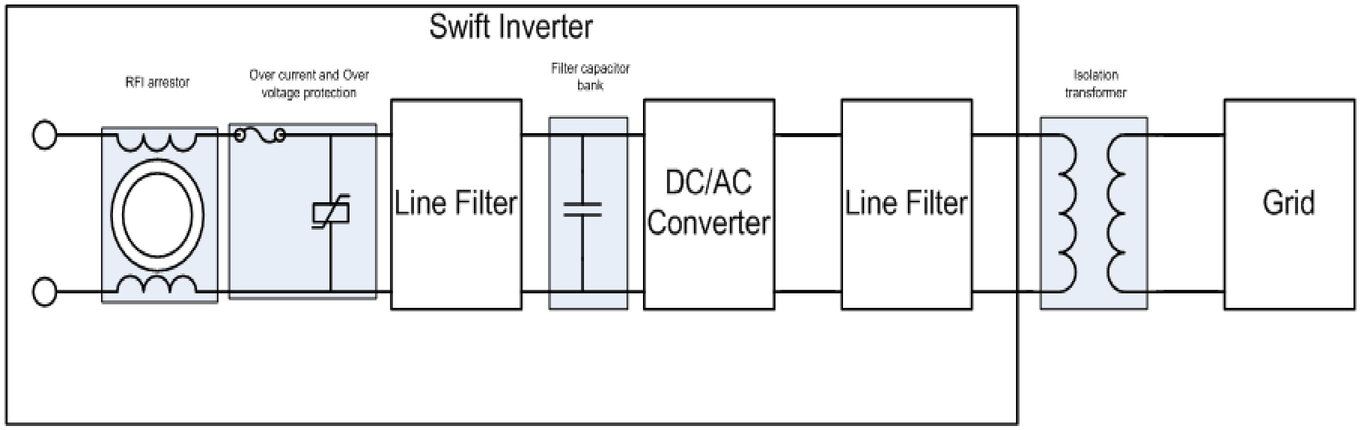

Figure 7: Circuitry Installed in Atwater Kent Room 317

This part of the system involves three main components. The turbine output connects to the inverter, then the inverter connects to an isolation transformer, and finally the secondary of this isolation transformer connects to the grid.

Taking a look inside the Swift inverter, there are a few notable components. Some of these component values and sizes cannot be determined or found, as they are already installed in a professional system, and have proven difficult to reach or measure. Once the turbine output enters the inverter it is filtered through an RFI arrestor. This aids in the removal of stray noise which may be caused by the generator's moving mechanical parts. Next a fuse and a varistor are used for over current and over voltage protection. This fuse is rated at 20A. The varistor is used to prevent large voltage spikes from interfering with the inverter, which could cause damage, or a malfunction.

Then, a line filter is used to further reduce the line noise. This provides for much more attenuation of the signal noise than a single RFI arrestor. This is necessary for the DC/AC converter to work properly, as they commonly contain many sensitive digital components for the driver circuitry. After the line filter is a capacitor bank. This bank is composed of five 560uF capacitors. This part of the circuit provides for the majority of the line filtering, especially the lower frequency ripple caused by the sinusoidal behavior of the rectified voltage.

Once the filtering stages are passed, the next component to this system is the DC/AC converter. This is the heart of the system, as it provides the high power signal to the grid. The DC signal from the turbine is now converted to a dual-phase, 240 volt 60Hz signal. After passing through the DC/AC converter, there is another line filter which eliminates any noise caused by switching in the converter. This filter is a passive filter, composed of capacitors and inductors to short out the switching noises, ensuring a clean sine wave.

After the line filter, the last stage is a 1:2 isolation transformer. This transformer accomplishes three things. The primary use of the transformer is to step down the voltage. The output of the inverter is at 240V. This is too high to attach to the grid so it is stepped down to 120V which is a usable level. The transformer also provides isolation from the grid for a safe power transfer. If there is a transient on the grid it will not damage the inverter. The final benefit is noise filtering. High frequency signals or stray interference on the lines are filtered across the primary winding. This winding is designed for 60Hz operation, and therefore has a relatively large inductance. This filtering is more of a side effect of the design, which works well to the system's advantage. From this transformer, the power is then fed into the grid. By feeding power into the grid, there is a hope to help buy back some of the electrical energy used by the building.

3 SYSTEM DESIGN

Due to the complexity of the wind turbine monitoring design, the components were designed individually to allow each piece to be constructed independently and simultaneously. This ensured an efficient prototyping method. Once each individual component was designed, built and tested it could be inserted into the entire system, and once all components were completed the system was tested as one unit.

Although the sections were designed separately, it was important to take into consideration the requirements of other sections of the design throughout the entire process; in order to ensure proper functionality of the final design. Testing components both separately and as a system was necessary in order to be sure that no unexpected incidents would arise with the installation.

3.1 OVERALL SYSTEM

The goal for the system is to be able to measure and record the voltage, current, and speed of the wind turbine. Additionally it will switch between a low power system and a high power inverter depending on the voltage generated by the turbine. This is important because a portion of power is not being utilized while the wind turbine is rotating slower than its cut-in speed. The high power inverter is tied to the electrical grid in order to deliver power to the rest of the building; if there is a surplus of power generated National Grid purchases the excess power.

The design switches between the new low power system and the original high power inverter. The goal of this is to increase system efficiency by utilizing the low power inverter for the low voltage range, when the high power inverter is not normally activated. The low power inverter does not have to accept a significantly large range of voltages, minimizing the need for a large, bulky, and expensive design. The low power inverter will provide power to light an LED. The block diagram can be seen in Figure 8.

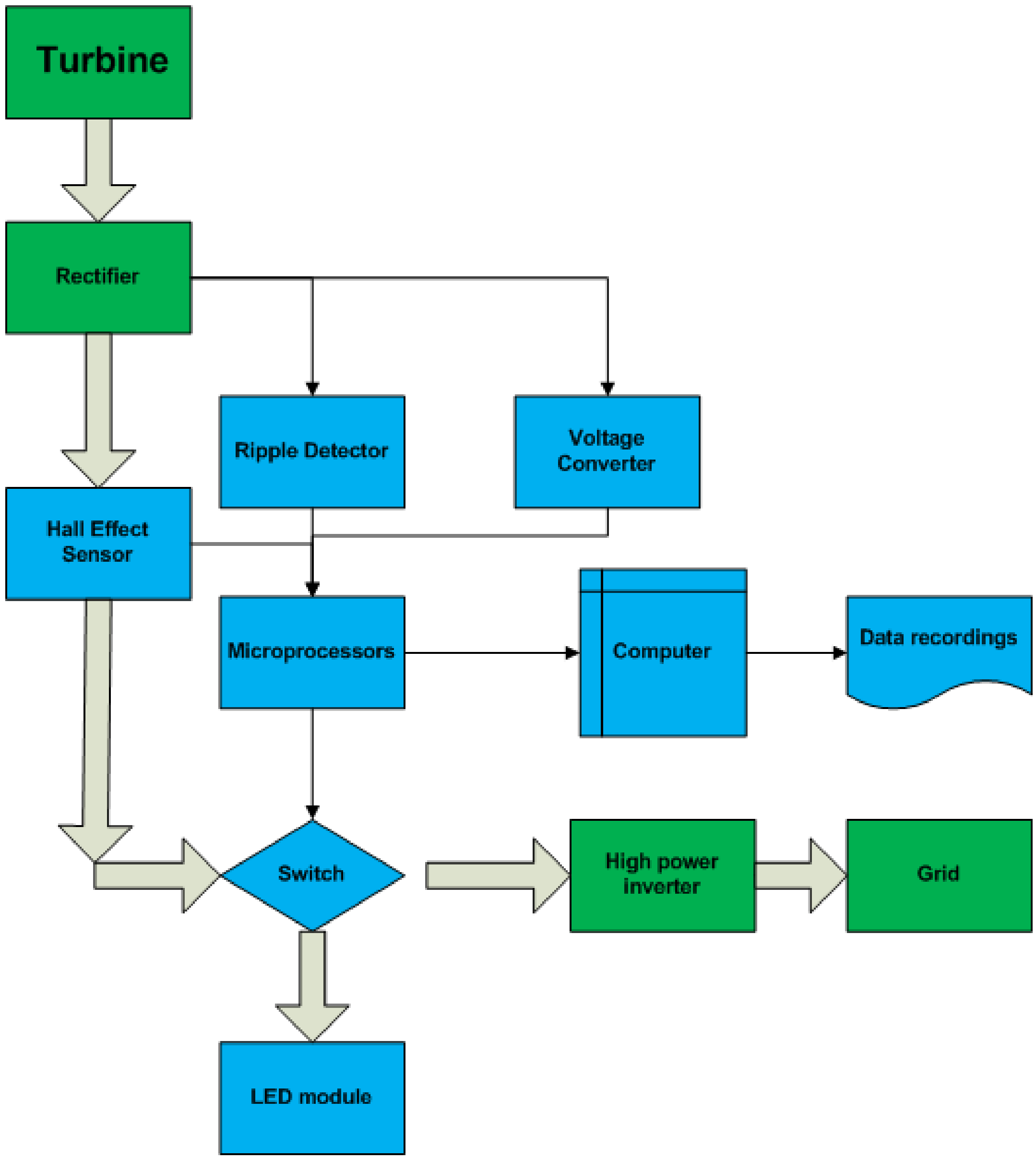

Figure 8: System Block Diagram

The green blocks in the diagram are what were originally installed in 2008 by National Grid. The turbine and rectifier are installed on the roof of the building. The high power inverter and grid connection were installed in room 317. All of our additions are shown in blue in the diagram. The thick beige arrows are the path of the majority of system power. The energy produced by the turbine is sent through the rectifier and then through a Hall Effect sensor. The Hall Effect sensor is used to measure the current produced. The power then goes to the switch, where it is then sent to either the high power inverter or to an LED array. In order to protect the system from rapid switching the system bases its decisions on when to excite the switch following a hysteresis curve.

The ripple detector is used to find the rotations per minute of the turbine based on the small alternating ripple riding on the direct voltage. The voltage converter steps the direct voltage down to a level that can be read by the microprocessor. The microprocessor then sends all of the voltage, current, and RPM data to a computer where data logs are recorded. The microprocessor also controls the switch.

3.2 INPUT CIRCUIT

The rectified power produced by the turbine enters the system via the input circuit. This consists of a 20 amp fuse, an RFI arrestor, and three varistors. Because safety is crucial it was important to use a fuse for over current protection. The high power inverter has a single 20 amp fuse at its input. The varistors were used to protect the system from any large voltage spikes or surges that might occur. The RFI arrestor was fabricated by wrapping wire around a toroidial ferrite core several times. The RFI arrestor helps eliminate high-frequency interference that may occur.

3.3 VOLTAGE CONVERTER

A voltage converter was installed in order to allow the microprocessor to make safe voltage readings. The voltage measurements are evaluated in order to make decisions on the current state of the switch. For this reason accuracy of the voltage measurements is critical to the safety of the two separate systems. This was made difficult because of the large voltage range that needed to be accurately detected. The wind turbine's output varies widely, from 0V to 400V. In order for the microprocessor to remain undamaged, the voltage output from the voltage converter needed to be below 5V. In the case of a surge the voltage converter was designed for an input range of 0V to 670V to be converted to a 0 to 5 V range. In order to accomplish this conversion the converter was designed with a gain of 133:1.

The original design for the voltage converter involved a voltage divider with a 133:1 ratio, Figure 9. Unfortunately, this design posed an issue due to the wind turbines floating reference point. Because the ground of the turbine is floating with respect to earth ground, connecting the two points was potentially catastrophic. In order to use a voltage divider the ground, shown in the following figure, would need to be made up of the direct voltage of the wind turbine and earth ground (representing the systems reference point).

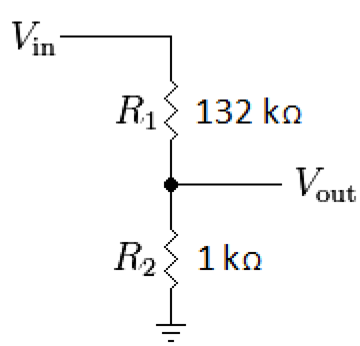

Figure 9: Voltage Divider with 133:1 Voltage Attenuation

The solution to this issue was to use a difference amplifier, shown in Figure 10. For the difference amplifier, a high input-impedance is required for two reasons. First it will ensure that high voltages do not drive too much current through the circuit, and thus destroying it. Second, high input impedance allows for a large attenuation of the signal. This circuit attenuates at a factor of 133, allowing for a robust design that can easily meet the needs of the microprocessor. Considering the turbine's output variations, the signal output from the voltage converter is set below 5V, in order for the microprocessor to remain undamaged.

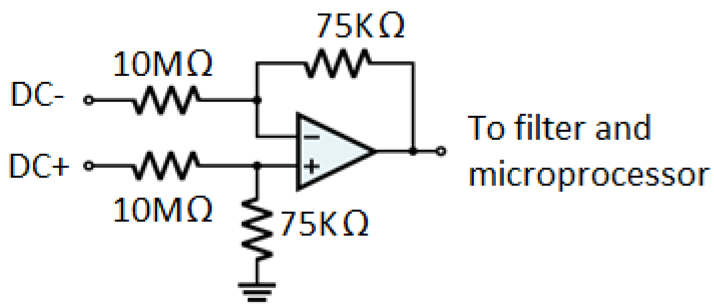

Figure 10: Difference Amplifier

As shown in the previous figure, the system reference point is separated from the DC+ of the turbine a total of 10.75 MΩ. The output of the circuit simply returns the difference of the two inputs amplified a chosen amount depending on the resistor values. The equation for a difference amplifier is shown below:

$$Vout = (DC^{+} - DC^{-}) * \frac{Rf}{Rin} \qquad (1)$$

In the previous circuit R_f is represented by the 75KΩ resistors and R_{in} is represented by the 10MΩ resistors giving the circuit a gain of .0075, or 133:1.

Unfortunately, during initial testing the voltage converter had an issue with 60 Hz noise. In order to solve this problem a Sallen-Key Filter was introduced to the system. The filter designed is a low-pass second order filter meant to cut off frequencies of 60 Hz and higher. Design of the filter can be found in the Filter Design section, section 3.8. The final circuit design, separated into sections, can be seen in Figure 11.

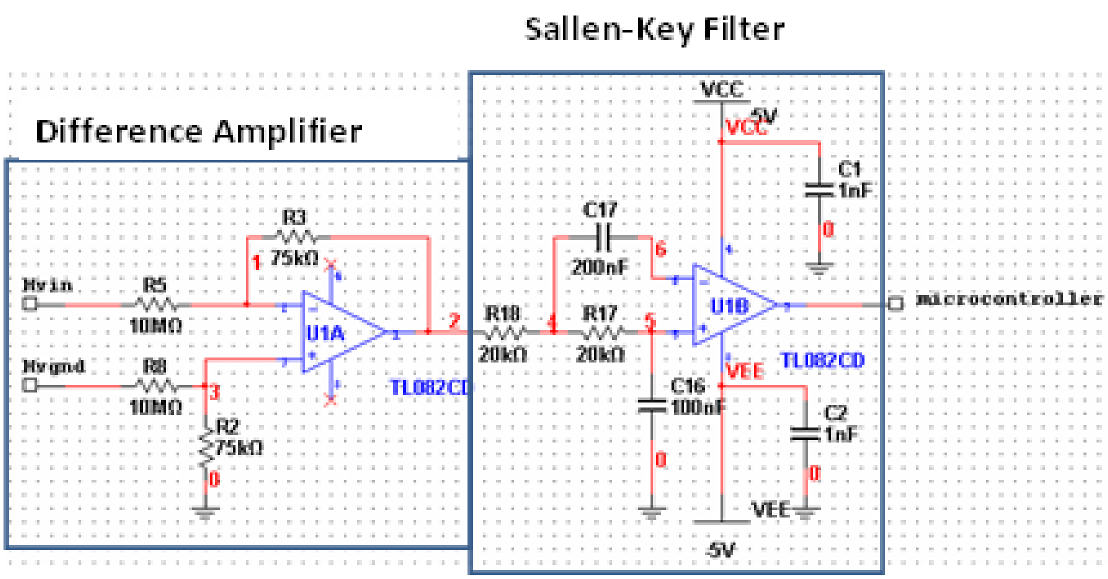

Figure 11: Voltage Converter Circuit Diagram

VOLTAGE CONVERTER SIMULATIONS

Once the values for the parts on the voltage monitor were calculated, simulations of the circuit were completed. Two piecewise linear voltage sources were used to represent the turbine output voltage. This allowed for control of a varying input voltage. The described circuit can be seen in Figure 12.

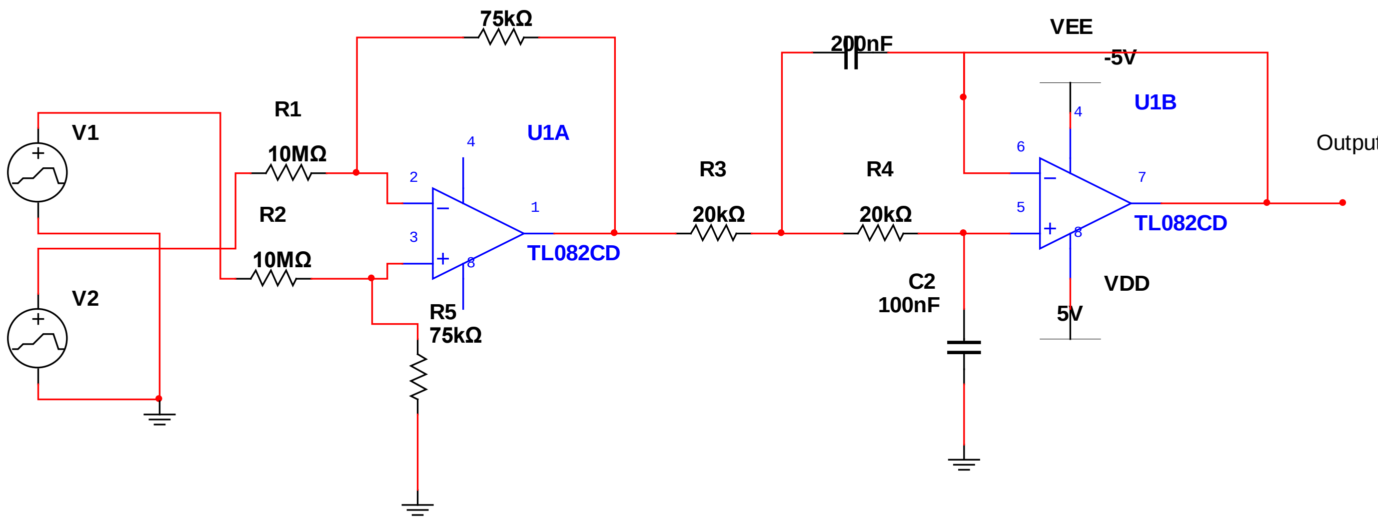

Figure 12: Voltage Monitor Simulation Circuit

Using this model simulations were run to make sure that the circuit worked as expected. The most important factor was that the circuit did not allow for an output voltage to high for the ADC's input range. If there is an overvoltage on the ADC it could easily harm the microprocessor. This means that the voltage at the output of the voltage monitor cannot go above 5V. The output of the turbine is limited to 400V, in case there are spikes, we simulated up to 500V. The simulation results can be seen in Figure 13.

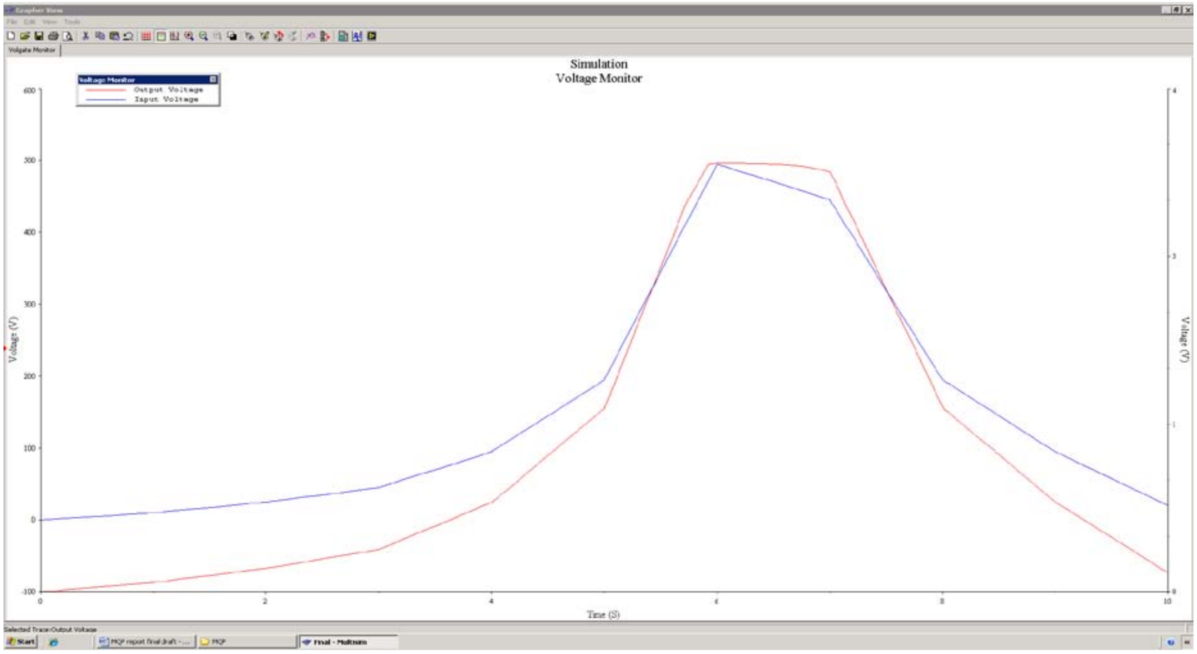

Figure 13: Voltage Monitor Simulation Results

In this simulation the red line, representing the voltage converter output voltage, is plotted relative to the right axis (0 to 4V). The blue line, representing the turbine output voltage, is plotted relative to the left axis (0 to 600V). The figure shows that even when the input voltage reaches 500V the output remains below 4V. Also the correlation between the input and output voltages is very evident, meaning the voltage converter's output can be scaled by the processor to represent the input voltage.

3.4 RIPPLE DETECTOR

The job of the ripple detector was to create a square wave, representative of the rotational frequency of the turbine, which could be successfully decoded by the microprocessor. Even though the signal is rectified there remains a slight ripple representing magnetic poles of the turbine. As there are eight poles and a three phase bridge rectifier, it is known that for every 48 ripples there is one full rotation. Due to the number of peaks per rotation it had to be accurate over a frequency range reaching 450 Hz. Due to limitations of the microprocessor frequencies higher than 450 Hz cannot be decoded. This is due to the large variance in rotational speeds based on the wind speed. The output of the ripple detector needed to be a square wave, representing rotational speed that could be realized by the microprocessor.

For the ripple detector to function the high direct voltage must be removed. The detector is attempting to make a square wave for each small ripple, so the direct voltage component must be removed while allowing only the ripple to pass through. Two series capacitors, C_1 and C_2, block the high direct voltage, and leave only the remaining ripple. When capacitors are installed in series with circuitry no direct voltage can pass due to the fact that capacitors act as open circuits in steady state, but the ripple, which is alternating voltage, is not caught by the capacitors.

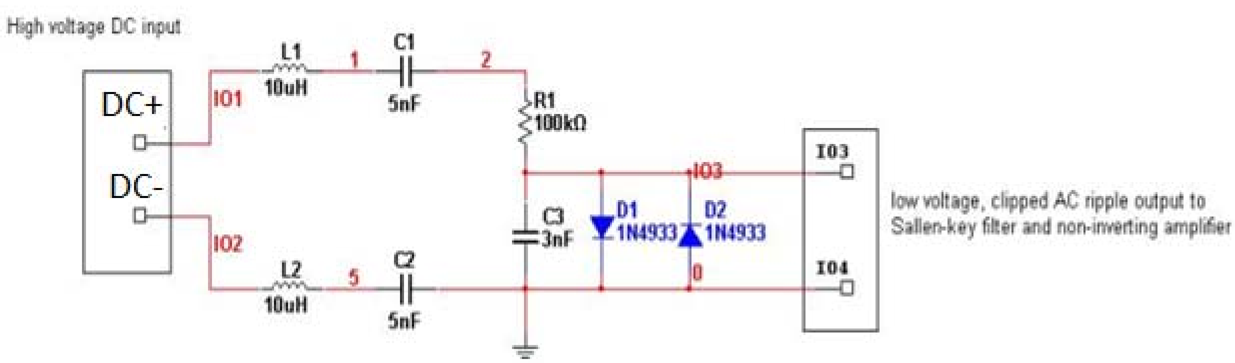

Figure 14: Ripple Detector Input

In order to prevent damage to any op-amps from a large ripple voltage, D_1 and D_2 were used to clamp the voltage to ± 0.7 V.

Because the ripple voltage can be so small, noise within the detector circuit could easily alter readings. To address this issue, three different types of filtering were implemented. In the circuit shown above an RFI arrestor, represented by L_1 and L_2, was installed to remove any environmental noise. A first order filter represented by R_1 and C_3, was installed for any high frequency noise. The equation for cutoff frequency of a first order filter is as follows:

$$f_{3dB} = \frac{1}{2\Pi RC} \qquad (2)$$

Because, the maximum frequency required in this circuit is 450 Hz, higher frequency is undesired. The first order filter was designed to have a cutoff frequency of approximately 500 Hz. In Figure 14 R_1 and C_3 represent the R and C of the Equation 2. Using a 100kΩ resistance and a 3nF capacitance the resulting cutoff frequency is approximately 530 Hz. Cascaded with this filter is a Sallen-Key Filter, Figure 15. This second order filter more accurately removes unwanted noise, with a cutoff frequency of 450 Hz as shown in the Filter Design section, section 3.8.

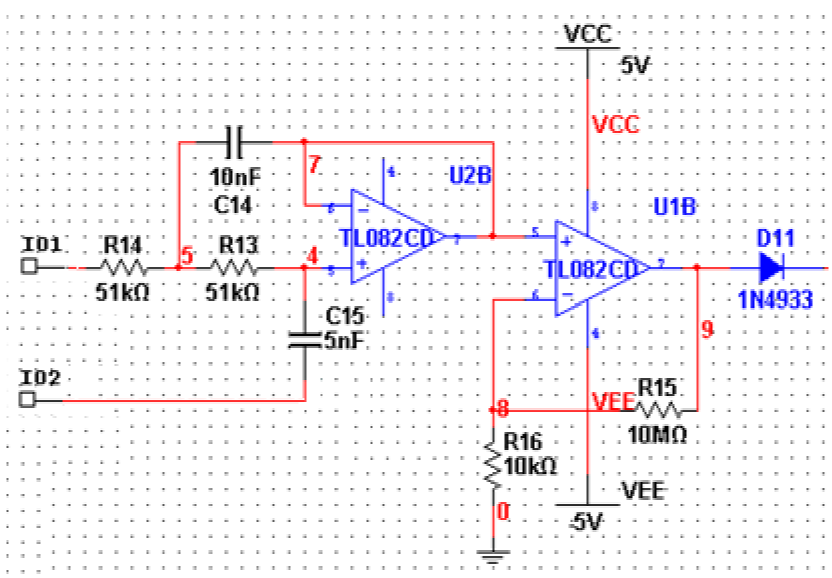

Figure 15: Ripple Detector Filter and Amplifier

After filtering is completed the signal is then amplified in order to obtain a square wave. The equation for gain of a non-inverting amplifier is:

$$\frac{V_{out}}{V_{in}} = (\frac{R_f}{R_{in}} + 1) \qquad (3)$$

The amplifier, represented by U1B, in the figure above has an R_f represented by R_{15}, and an R_{in} represented by R16. The overall gain of this amplifier is approximately 1000V/V. Because operational amplifiers can only output values within their supply, for all input voltages above 5 mV the output is 5 volts. Similarly for all input voltages below -5 mV the output is -5 V creating a square wave, which can be decoded by the microprocessor. Since the input range of the microprocessor is only 0 to 5 Volts, D_{11} was used in order to cut off the negative voltage of the square wave. The circuit now produces a 0 to 5V square wave, with one rising edge per ripple. Finally, in order to aid the aid the microprocessor in successfully reading higher speeds a 4:1 frequency divider was installed. An example of a 4:1 frequency divider is shown in the Figure 16.

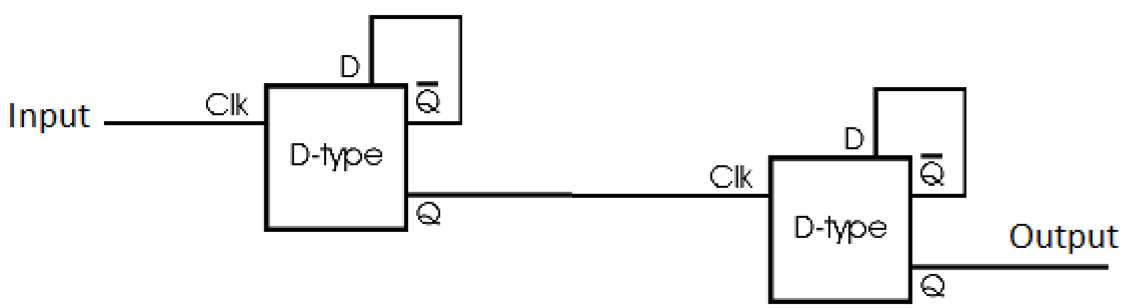

Figure 16: D Flip Flop Frequency Divider

With this circuit composed of two D-type flip flops, for every four rising edges of the input signal the output signal has one rising edge. As demonstrated in the figure below.

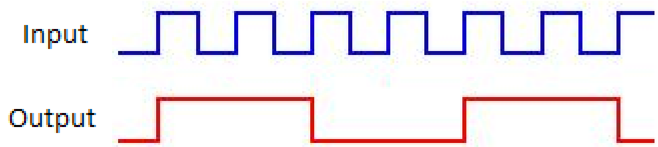

Figure 17: Example Frequency Divider Input and Output

D Flip Flops change state only on a rising edge at the clock input. The output of a D Flip Flop is shown in Table 1.

Table 1: D Flip Flop Response

Clock	D	Q	Q'
Rising Edge	0	0	1
Rising Edge	1	1	0

For every rising edge on the clock pin the D Flip Flop passes the digital value of the D pin to the Q pin and the inverted value to the Q' pin. By connecting the Q' pin to the D pin there is a full cycle delay of the clocks input. For example if D is initially a 0 and the clock ticks (providing a rising edge) Q will become 0 and Q' will be 1. On the following clock tick Q will become a 1, since that was the previous value Q', and Q' becomes a 0 thus dividing the rising edge frequency in half. When cascading D Flip Flops as shown the multiplier becomes:

$$\frac{1}{2^n} = \text{Multiplier} \qquad (4)$$

Where n represents the number of Flip Flops.

Ripple Detector Simulations

In order to test the ripple detector's functionality it was important to vary the frequency and check that the output changes accordingly. This was accomplished by using a voltage controlled AC power supply in conjunction with a piecewise linear voltage supply. This allows for the frequency to be controlled based on the voltage of the piecewise function. The circuit modeled can be seen in Figure 18.

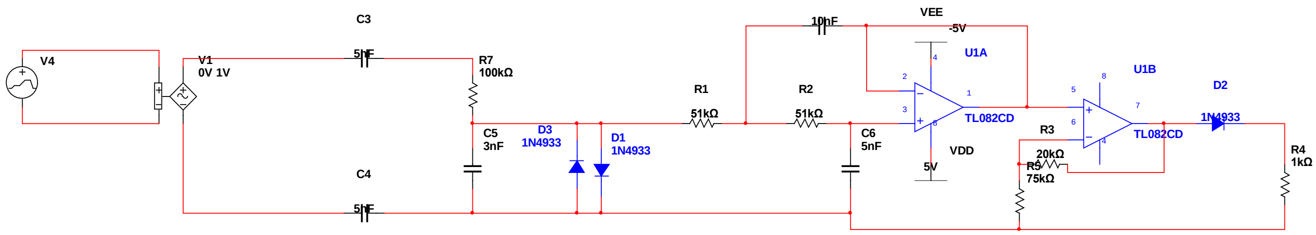

Figure 18: Ripple Detector Simulation Circuit

The results of the simulation can be seen in Figure 19.

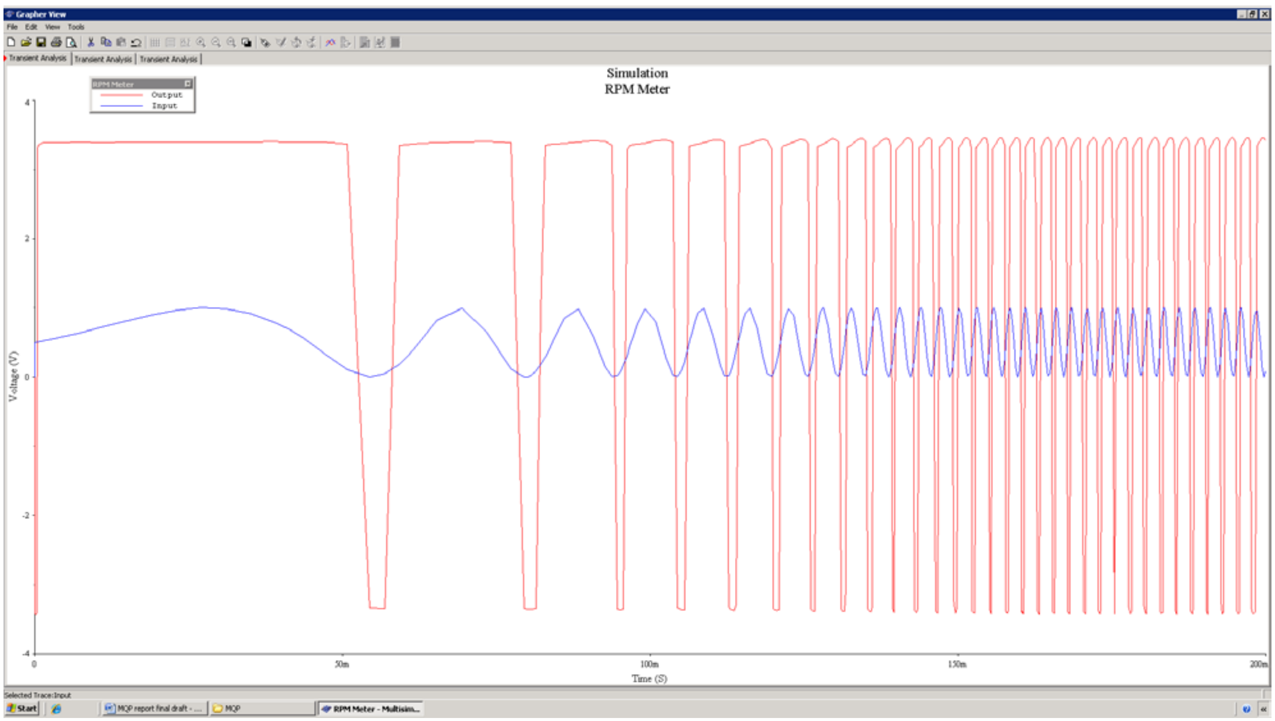

Figure 19: Simulation of Ripple Detector

This simulation shows that the ripple meter is functioning as desired. It is counting every ripple of the simulated turbine, which can be used to calculate the total rotations based on the known number of poles of the turbine. The ripple detector does not double count when the frequency changes. This is important because the wind will be constantly changing speed, which will change the frequency. If there were double counts every time the frequency changed it would cause major errors in the ripple count. This was a problem that presented itself with some other designs. The voltages also stay well within the limits of the microprocessor. Although there is a negative voltage shown in the simulation, this is be blocked out in the final build using a rectifier.

3.5 CURRENT SENSING CIRCUIT

The final monitoring circuit was the current sensing circuit. Current readings are necessary in order to determine the power output by the wind turbine. A Hall-Effect Sensor, Tamura’s S22P015S05, was used to monitor the current produced by the wind turbine. By measuring the strength of the magnetic field surrounding a wire Hall-Effect Sensors obtain a measurement on the amount of current flowing through the wire. Hall-Effect Sensors are the only non-invasive way to measure current, meaning there is no break in the circuit to allow for measurement of current flow. The Hall Effect sensor is simply situated above the point where current measurements are of interest.

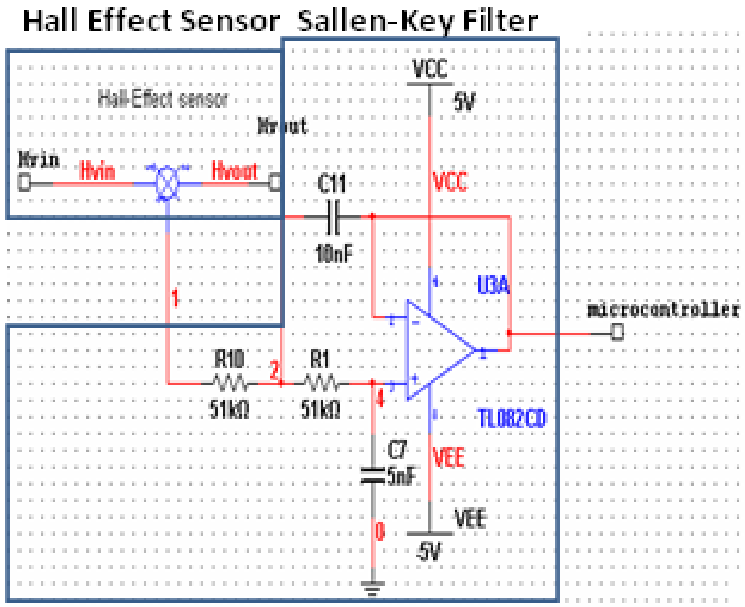

Figure 20: Current Sensing Circuit Schematic

The first part of this circuit is the Hall-effect sensor. This sensor is the heart of this circuit and is set in a small module with a power pin, ground, and a signal output pin. The chosen sensor has an output voltage representative of the current it measures. The output range of the sensor is 0 to 5V, which meets the requirements of the microprocessor. The sensor also has a bias of approximately 2.5 volts to allow for measurements of current flowing in both directions. Input vs. Output characteristics are evaluated and discussed in the Testing section, section 4.4.

This signal is then output to a Sallen-Key filter in the next stage. This filter is the same kind implemented in the design of the ripple counter. This filter is a second-order; low pass filter set to cut off at 450Hz. This eliminates any stray noise which may cause misreading by the microprocessor.

3.6 Power Supply

A power supply was necessary to deliver power to all the components within the system. A few options were considered, using the wind turbine's produced power, battery power, or utilizing power from the nearest outlet. It was decided to use outlet power as it was the most reliable of options. This would prevent the entire system from shutting down or acting undesirably while the turbine is not spinning.

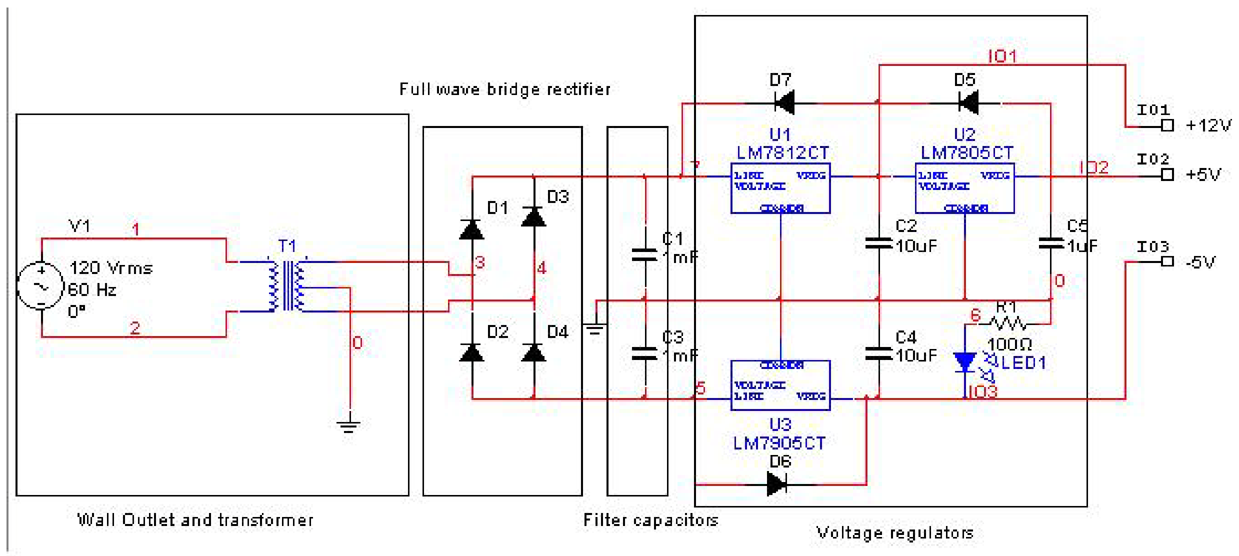

Figure 21: Power Supply Schematic

The design chosen was a standard linear, dual rail supply. This supply can provide power at +/-5 volts to power the op amps, and a +12V line for the contactor and a cooling fan. To obtain the three different voltage levels three voltage regulators were used: LM7812 for 12 V, LM7805 for 5 V, and LM7905 for -5 V. The circuit is built up with a transformer connected to wall power, a rectifier, filter, and voltage regulators. The voltage is stepped down from the wall voltage with the transformer. It is then rectified into direct voltage using the rectifier. The filter capacitors are used to remove ripple from the direct voltage line. This filtered voltage is sent to the voltage regulators which output the desired voltages.

Observing power requirements for the circuitry we obtain a measurement for the required power delivered by the power supply. The digital circuitry requires about 15 mW. The voltage regulators, contactor, opto-coupler, and cooling fan, in worst case, require approximately 6 W total. The Hammond Manufacturing's™ 166G30 transformer is 120V, 60Hz, step down transformer providing $30V_{rms}$ at the secondary, capable of providing 15 W exceeds the requirements of the system.

The power supply uses voltage regulators in order to properly clamp the voltage at its required level. The LM7812 was chosen for the +12V supply, the LM7805 chosen for the +5 volt supply, and the LM7905 for the -5V supply. These regulators provide for a ripple rejection between 62dB and 73dB, and can pass currents up to 1 amp over a large range of input values. The output ripple from the regulators is then calculated as so:

$$dB = -10 * log_{10}\left(\frac{V_{out}}{V_{in}}\right) \qquad (5)$$

If we consider the input, V_{in} to be an unknown, assume V_{out} to a peak-to-peak ripple voltage of 5mv at the output, (low enough to maintain functionality of the system) and the regulator is attenuating at 62db, then the output is calculated as so:

$$V_{in} = \frac{V_{out}}{10^{-dB/10}} \qquad (6)$$

Substituting in the values above, the maximum input peak-to-peak ripple is

$$V_{in} = \frac{.005V}{10^{-62/10}} = 7.92kV_{p-p} \qquad (7)$$

This enormous ripple value allows for much flexibility in this design, as the ripple voltage for this power supply could never possibly get to be this high. The filter capacitor values may now be chosen. The filter capacitors are chosen to be 1000uF 35V electrolytic capacitors, and are connected between both rails and ground. This value of 1000uF is something commonly seen in many power supplies, particularly linear supplies.

It is necessary to take into consideration the ripple voltage present at the input of the regulator. The voltage is calculated as follows:

$$I = C * \frac{dv}{dt} \qquad (8)$$

The ripple voltage is dV (peak to peak voltage), the load current is I (amps), and the time for one half cycle of a 60Hz wave is dt (seconds). The load will be set to 457mA, the capacitor is 1000uF and the time for a half-cycle of the 60Hz sine wave is 8.33mS. Substituting in values for our system:

$$dv = \frac{0.457A * .00833s}{.001F} = 3.79V_{p-p} \qquad (9)$$

The ripple voltage calculated is far too cumbersome for digital components to handle, this is where the voltage regulators take over for attenuation of this noise margin. With a worst-case 62dB attenuation, the output ripple is calculated by rearranging equation 5 :

$$V_{out} = V_{in} * 10^{-\frac{db}{10}} \qquad (10)$$

$$V_{out} = 3.79 * 10^{-\frac{62}{10}} = 2.39\mu V \qquad (11)$$

The output ripple from the regulator is calculated to be 2.39uV. A signal this low couldn't possibly interfere with our system. The ripple is so small at this point, there is no need to calculate the ripple voltage at the output of the 5V regulator to the microcontroller.

Next, it is necessary to choose a diode for the full wave bridge rectifier. A standard 1N4007 diode is chosen. This diode has a peak reverse voltage of 1kV and can pass currents up to 1 amp. Further, it can handle a 30 amp current surge for up to 8.33mS. This diode is very well suited for this application. The diodes are also placed in reverse bias fashion across the input and output of the regulators. This is done to prevent a capacitive load at the output from reverse biasing the regulators at power down, which could potentially lead to damaged regulators.

Further, three more capacitors are used to increase the ripple rejection and reduce noise as much as possible. There are two 10uF capacitors, one placed after the +12V regulator, the other at the output of the -5 volt rail; and a 1uF cap placed at the output of the +5V rail.

Now we need to ensure that the voltage regulators are kept cool, and will not over heat. It is necessary to determine power dissipation of the regulators. The majority of the current drawn by our system, travels through the +12V regulator to drive the larger loads. The current draw from the other regulators is not significant enough to produce noticeable power dissipation, and therefore heat sinking can be disregarded. The formula to calculate the power loss is given below

$$P_{disp} = (V_{in} - V_{out}) * I \qquad (12)$$

Substituting in values, V_{in} = (15V)*1.41 = 21.15V_{pk}; I = 0.457A; V_{out}=12volts.

The worst case power dissipation (current draw of 457mA) is calculated below:

$$P_{disp} = (21.15V - 12V) * 0.457A = 4.18W \quad (13)$$

This regulator, the LM7812, will require a heatsink capable of dissipating up to 5W. RadioShack's model: 276-1368, TO-220/TO-202 Aluminum Heat Sink fits these requirements.

Power Supply Simulation

Since the system was powered by an outlet, issues with varying voltages powering the system could be ignored. The model for the power supply can be seen in Figure 22.

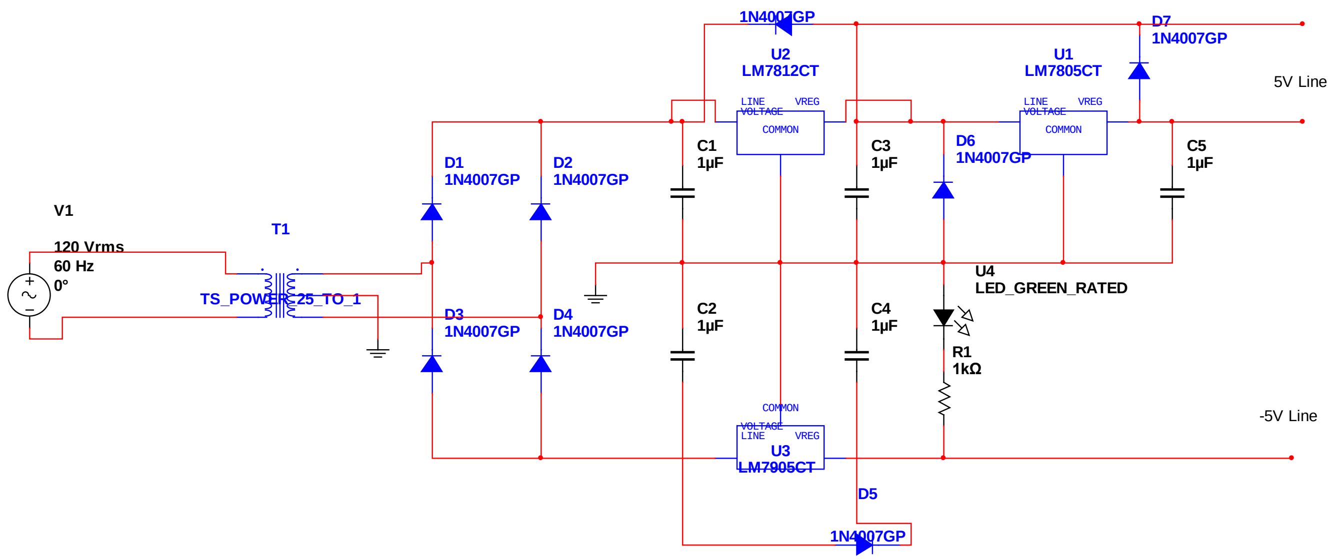

Figure 22: Power Supply Simulation Model

The simulation for this circuit worked perfectly resulting in the exact voltages that we need to power our circuitry. The results can be seen in Figure 23.

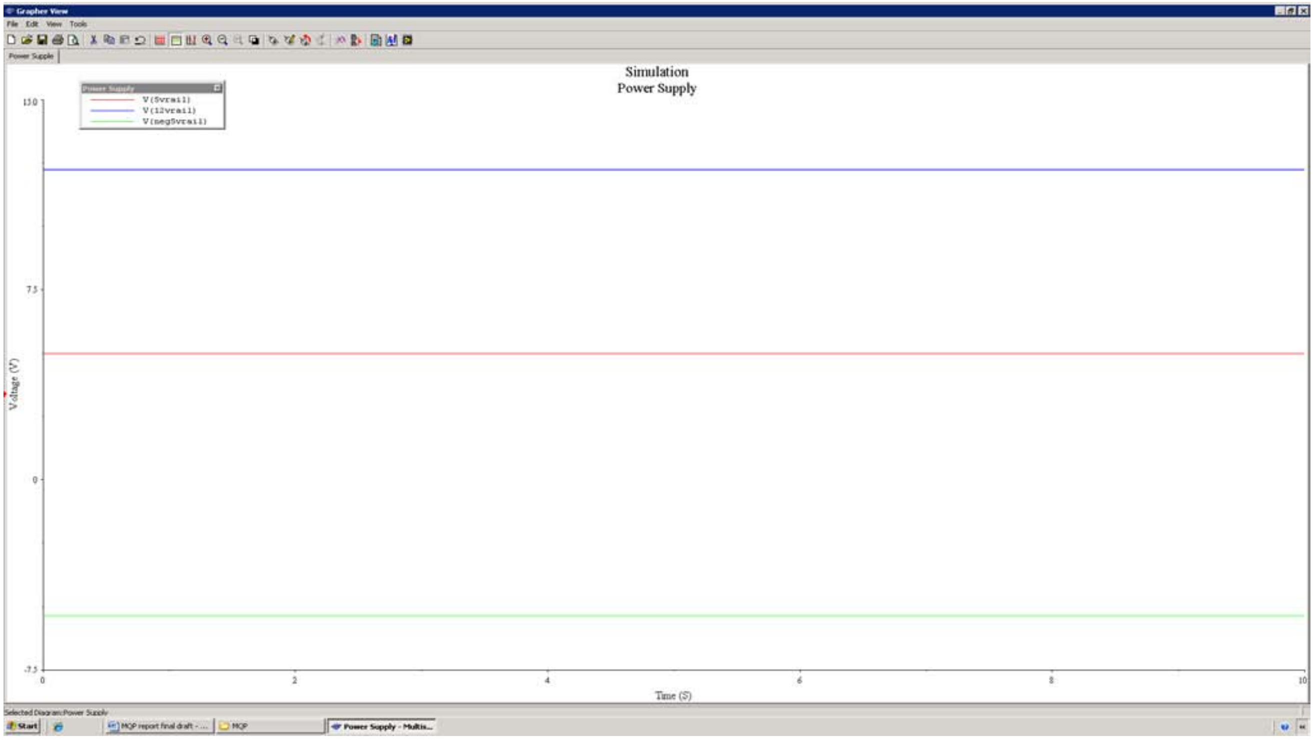

Figure 23: Simulated Power Supply Output

This circuit provides power for all other components. The most important aspect of this circuit is that it allows the system to run at all times; even in low-wind situations.

3.7 Switch

The purpose of the switch is to allow the turbine output to be switched to either a high power inverter, or a low power inverter. This is accomplished with a double-pole-double-throw contactor, driven with a +12Vdc signal. This +12V signal is controlled by a transistor network, seen in Figure 24.

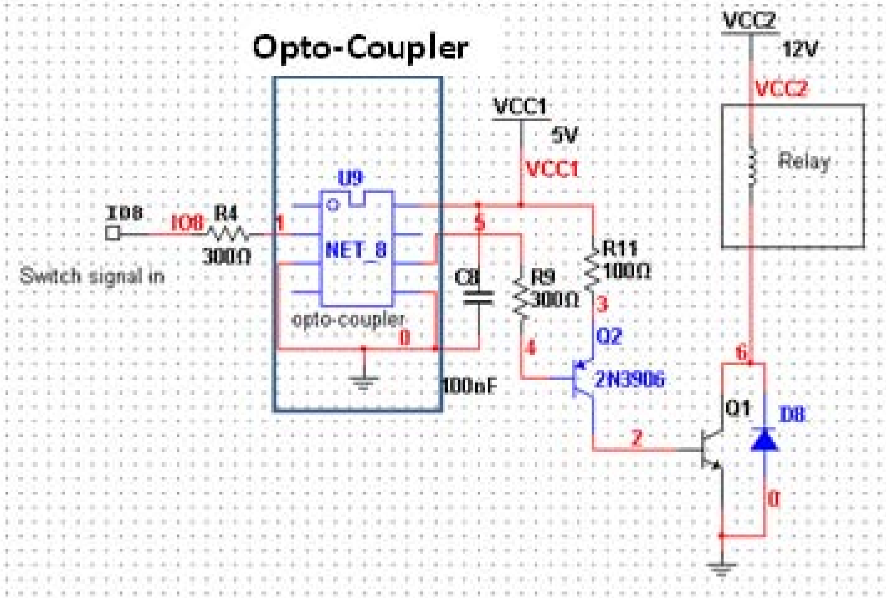

Figure 24: Switch Control Circuit

Because the contactor required an excitation voltage of 12 VDC the microprocessor could not excite the switch alone. In most situations a MOSFET is used as a driver to deliver a voltage or a ground to a given destination. Figure 25 shows an example of this driving circuit.

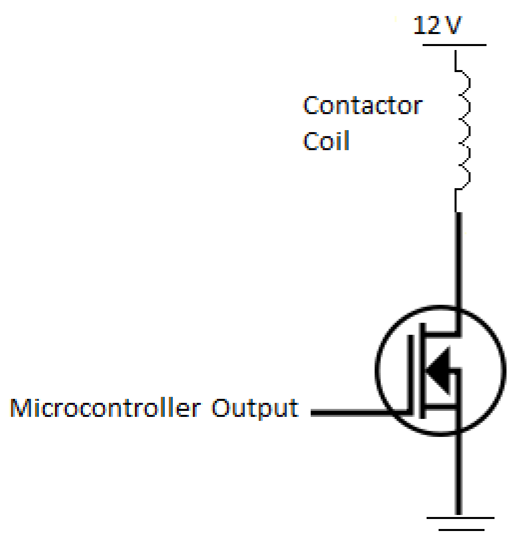

Figure 25: MOSFET Driving Circuit

In this example, in order to excite the coil the microcontroller needs to output a high voltage causing the MOSFET to close and pass current from drain to source.

In order to protect the microprocessor from any hazards, in the rare case of a short or arc across the contactor, an opto-coupler, Figure 26, is used in this design. This device provides isolation for the microprocessor from the contactor. This will prevent any high voltage from driving current backwards through the circuit and destroying the microprocessor.

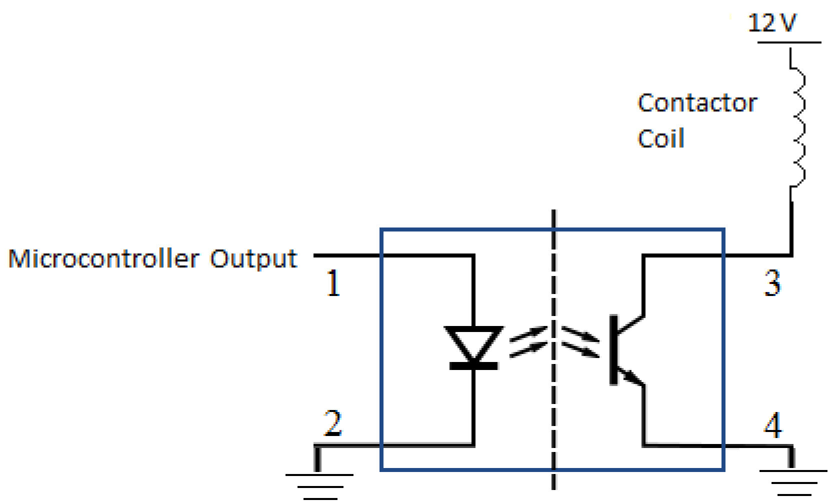

Figure 26: Opto-Coupled Driving Circuit

Opto-couplers make use of an LED and a phototransistor. In this case the microcontroller powers a small LED. Once the LED is on the phototransistor detects the light and allows current to flow from its drain to source. This circuit offers complete isolation from the switch and the microcontroller, thus protecting the microcontroller.

Another important design feature taken into consideration was the state of the switch if wall power was lost. In this state the switch defaults to the high power inverter. This is important should the power supply fail, or a power outage occur. If the high voltage inverter is the only system connected to the turbine, no damage to the system will occur, regardless of the turbines output voltage. If the low voltage inverter is defaulted to though, it could easily become damaged if the voltage range reached the upper limit of the low power inverter.

3.8 Sallen-Key Filters

The design required the use of various low pass filters remove high frequency noise. Sallen-Key Filters were chosen due to their efficiency and versatile design. The filters were designed as second order filters, providing attenuation of -40 dB per decade in the filtered regions, in order to improve the roll-off without drastically affecting the linearity.

The Sallen-Key Filters used were designed with either a cutoff frequency of 450Hz or a cutoff frequency of 50 Hz. The second filter is a 50Hz low pass filter used on the voltage converter. The following figure shows the general design of a Sallen-Key Filter.

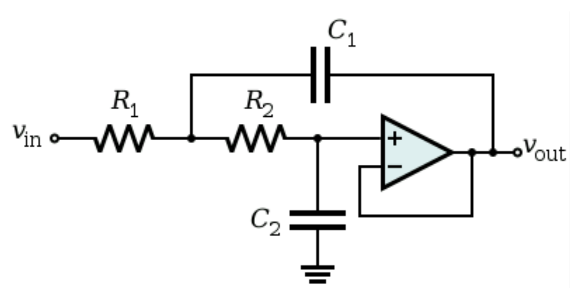

Figure 27: Sallen-Key Filter

The cutoff frequency of a Sallen-Key Filter can be obtained by the following equation.

$$f_{3dB} = \frac{1}{2\Pi\sqrt{(R1)(R2)(C1)(C2)}} \qquad (14)$$

Since each Sallen-Key Filter had only a cutoff frequency requirement, component selection was based predominantly on availability. In designing the 450 Hz filter, two resistors of 51 KΩ were used, and the capacitances chosen were 5 nF and 10 nF. The cutoff frequency using these components was approximately 445 Hz, within 1.1% of the desired value.

The 50 Hz filter was designed using two 20 KΩ resistors, and capacitances of 220nF and 100nF. The cutoff frequency of the second filter was 55 Hz. While this value is higher than the desired 50 Hz, it is sufficient enough to minimize the 60 Hz of noise originally posing an issue.

Sallen-Key Filter Simulations

In order to be sure they are not going to change the desired signal, they were simulated and observed to be designed for cut-off frequencies above the maximum frequency expected. The model of the low pass filter is seen in Figure 28.

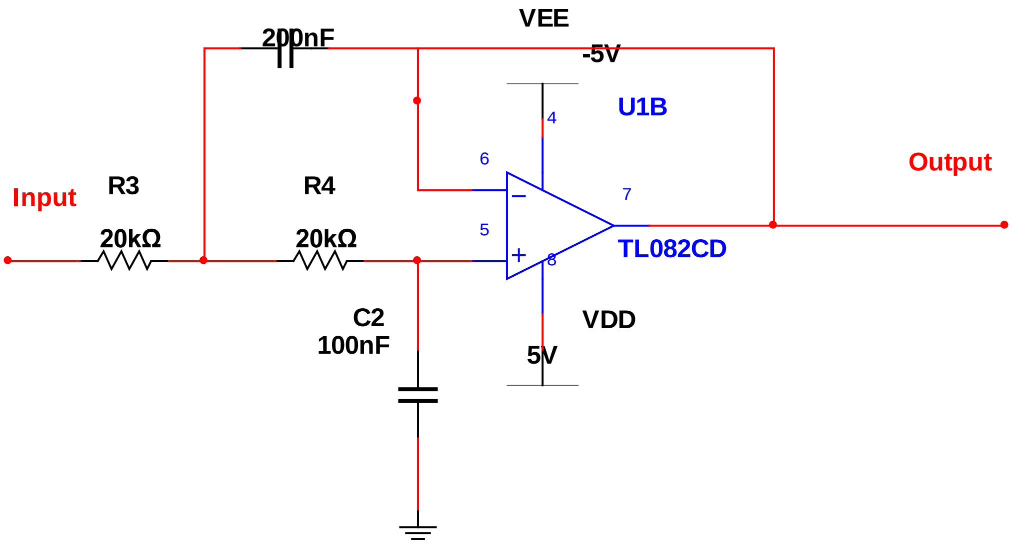

Figure 28: Sallen-Key Filter Simulation Circuit

Using this model a bode plot, Figure 29, was generated to better evaluate the effectiveness of the filter.

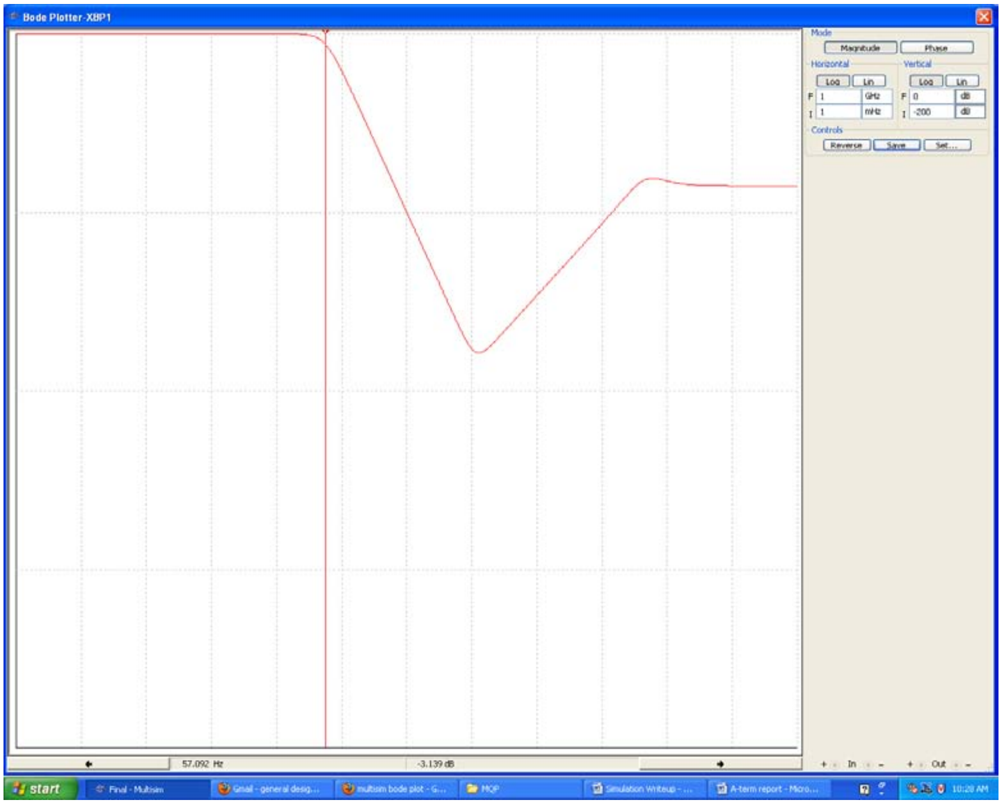

Figure 29: Bode Plot of Low-pass Filter

The filters used are of second-order (-40dB/decade) and have been tuned to -3dB at approximately 57Hz. The lowest value seen on this plot is -89dB at 12.7 kHz. After this value, the filter decreases its attenuation by 20dB/decade until it levels off at -42dB at approximately 16MHz. This behavior is unusual, but does not seem to be problematic for our circuitry.

3.9 MICROCONTROLLER

The microcontroller acted as the brain of our switching circuit. The microcontroller's job was to evaluate and choose which inverter was to be running at any given time. The group chose to use the PIC 16F887 microprocessor because of its availability. The PIC 16F887 offers an option combination of 14 A/D converting inputs, 24 digital I/O ports, and 1 external interrupt, covering each of our essential needs.

In the case of the microprocessor we required two analog to digital converters. One converter was for a reading of the DC voltage produced by the wind turbine at any given time. The second analog to digital converter was used to obtain the speed at which the wind turbine is turning at any given time.

MONITORING VOLTAGE WITH THE MICROCONTROLLER

The A/D converters offered by the PIC 16F887, provided 10-bit accuracy. To be more precise the following calculations show the precision of the analog to digital converter.

$$\frac{Input\ Range}{2^{Number\ of\ Bits}} = \frac{5\ V}{2^{10}\ bits} = 4.88\frac{mV}{bit}\ precision \qquad (15)$$

The meaning of this 4.88 mV value is that for every, approximately, 5 mV of change at the input of the A/D the software will recognize the change and report the voltage to 5 mV of accuracy. When we incorporate the gain of the voltage monitor, shown earlier to be 133:1 we obtain the minimum DC voltage change produced by the wind turbine to be registered by the system, as shown in the following equation.

$$Overall\ Precision = Precision\ of\ Microprocessor * \frac{1}{Gain\ of\ Voltage\ Monitor} \qquad (16)$$

$$Overall\ Precision = 4.88\frac{mV}{bit} * 133 = .649\frac{mV}{bit} \qquad (17)$$

In conclusion, for every 0.65 volts the DC output of the wind turbine changes the PIC 16F887 will be able to read the change and correspond accordingly if need be.

The purpose for recording voltage with the microprocessor was to determine which system, low power or high power, should be active at any given time. Incorporated into software was hysteresis for the switching circuit as a form of protection. If we were to make the circuit switch at exactly 100 V between the two systems, whenever the turbine was producing approximately 100 V there was a large potential, due to noise and/or wind fluctuations on the line, to switch rapidly between the two inverters. Rapid changes like these harm the relay and each inverter, and have the potential to be catastrophic to the system. As explained, we introduced hysteresis to the switching mechanism. The following figure shows how the hysteresis was designed.

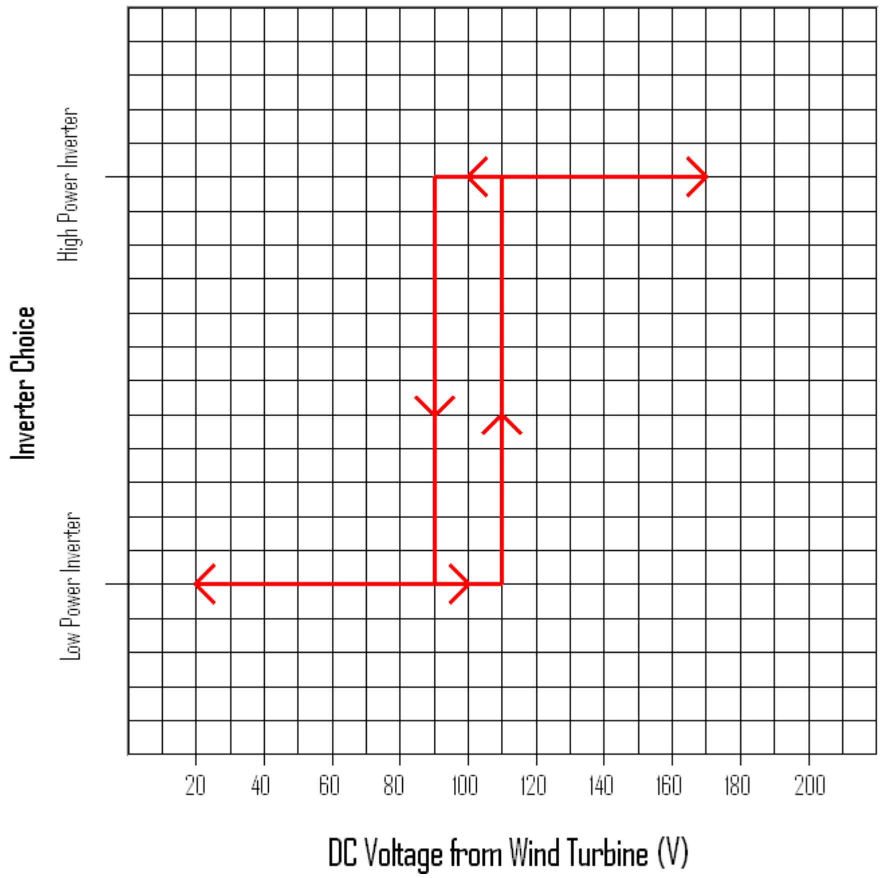

Figure 30: Hysteresis Curve for Switch Control

As seen in the graph above upon startup, provided the DC voltage from the wind turbine is below 110 V, the low-power system will be active. Once the voltage reaches 110 V DC the microprocessor will signal a switch between the inverters and the high-power inverter will be active. From this point, the microprocessor will not switch to the low-power inverter until the voltage falls below 90 V, thus completing the hysteresis loop.

MONITORING RPM WITH THE MICROPROCESSOR

After the ripple detector converts the ripple riding the direct voltage into a square wave with a high value above 3V and a low value below 1V the microprocessor has to read the number of cycles and report the speed the turbine is turning with, at any given time. We used the microprocessors 8 MHz timer and one of the analog to digital converters to record this value.

Software would continuously check the state of the square wave, and compare it to its previous state. If the microprocessor finds a digital high when reading the voltage at the output of the ripple detector, it would compare it to the previous value obtained. If the value previously was a digital high it would ignore it and continue. However, if the software sees a digital high and the previous value was a digital low it will increment the number of cycles. By doing so, the software only reacts to a state change from low to high, meaning one of the teeth of the Turbine were passed. Measurements are taken approximately at a frequency of 13.3 MHz. The following figure depicts how the software interprets a new cycle.

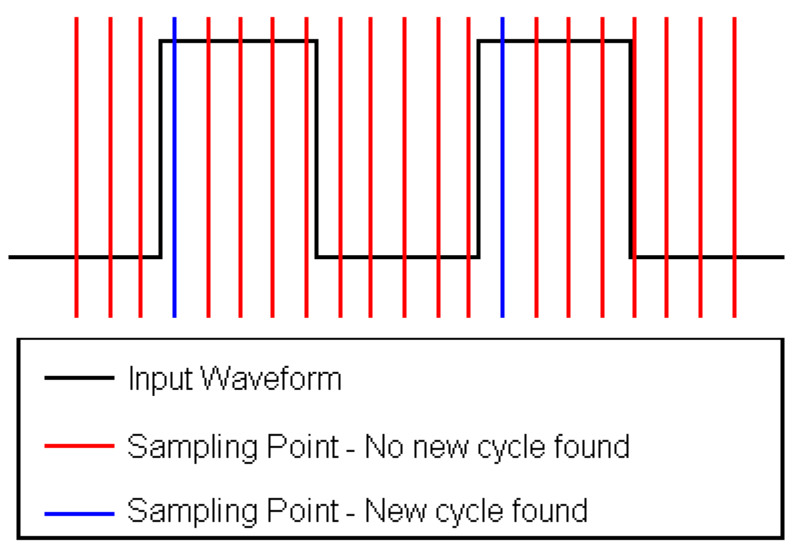

Figure 31: RPM Meter Signal Detection

As shown in the figure the sample immediately following a rising edge is what software looks for in order to increment the number of cycles.

This information is not substantial enough for software to understand how fast something is occurring, in this case the speed at which the turbine is turning. The software relies on an internal clock. Once the software is made aware that the clock has ran for a full second it computes the following equation to report rotations per minute.

$$RPM = \frac{Cycles}{Elapsed\ time\ in\ Seconds} * \frac{Ratio\ of\ Frequency\ Divider}{\#\ of\ Teeth\ of\ the\ Turbine} * \frac{\#\ of\ Seconds}{1\ Minute} \quad (18)$$

The frequency divider refers to the frequency divider mentioned earlier in the ripple detector section, section 3.4. Because software runs this calculation every second the elapsed time is 1 second. The number of teeth contained in the turbine, is 48 (6 poles each with 8 teeth) and the ratio of the frequency divider was designed to be 4:1. With these constants inserted the equation simplifies to:

$$RPM = Cycles * \frac{1}{12} * 60 \quad (19)$$

Once the microprocessor obtains this value, it resets cycles back to zero to start the process over, and it stores the value of RPM in a separate variable which is output to the data-logger.

Inverter Switch Control using the Microprocessor

To actuate the switch between the two inverters we dedicated one pin of the microprocessor to send the command. The pin was set to a digital output. As a failsafe we designed the circuit to use the high-power inverter when the pin was low, and the low-power system when the pin is high. At any given time it is safe to leave the high-power inverter on since it has always been left in said situation. In high-power situations it would be dangerous to leave the low power inverter since it is only designed to run with low power input.

Unfortunately, the microprocessor cannot source enough current to drive the switching relay, so we incorporated a separate driving circuit. Our driving circuit consists of an opto-coupler with a power transistor. We chose an opto-coupler as another form of a failsafe, if the driving circuit ever broke down, the opto-coupler would not be able to power the contactor causing the relay to remain in its high-power inverter state.

3.10 DATA-LOGGER

To log the data we used a USB Bit Whacker. The USB Bit Whacker is a chip designed specifically for data purposes. It has a pre-installed USB interface, and 12 inputs that can be configured to A/D inputs or digital inputs. The USB Bit Whacker communicates with the PC via Hyper-Terminal. Unfortunately, there is no way to write code in Hyper-Terminal to repeatedly obtain data. In order to overcome this obstacle we created a console application using Visual Basic. Using Visual Basic we can open Hyper-Terminal establish communication and send keyboard commands to be sent periodically through Hyper-Terminal to the USB Bit Whacker. Once each command is sent the USB Bit Whacker sends a response to Hyper-Terminal which we then timestamp and save to a data file to be evaluated later. The process is shown in the following figure.

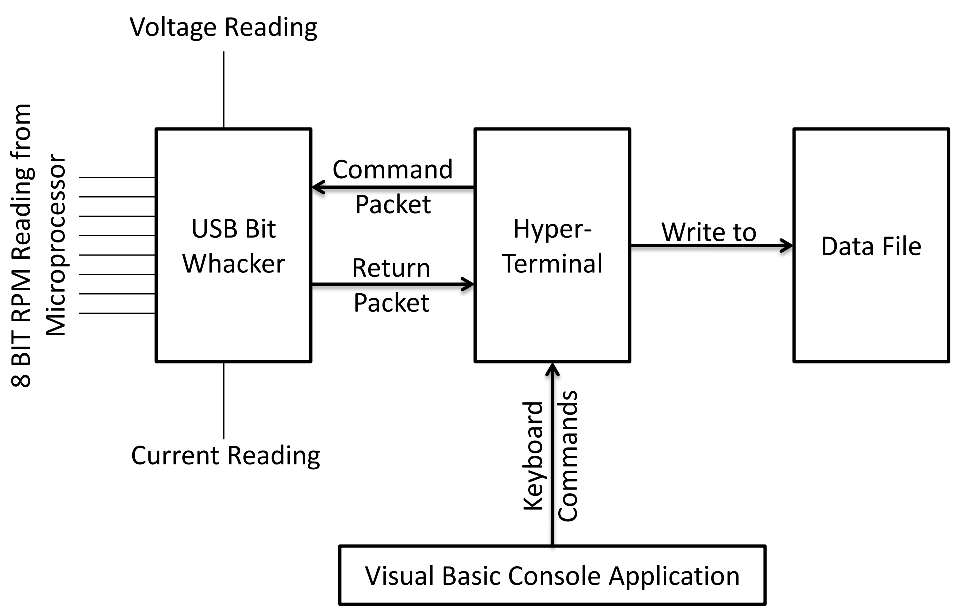

Figure 32: Data-Logger Block Diagram

The Voltage and Current pins are both set to Analog inputs and read directly from the output of the voltage meter and current meter respectively. The RPM reading, however, comes from the microprocessor as an 8-bit number which the USB Bit Whacker then reports its decimal equivalent.

3.11 INVERTER

The new inverter designed is a small DC to AC inverter design originally for solar panels. This inverter was designed and constructed by Enphase™, it is designed to have a nominal 30-50 V DC input, and an output of 240 V 60Hz AC. This inverter, known as a "Microinverter", is used to power a single 240volt, fluorescent light ballast. The formerly unused 0-100 volt margin is now used to power a light, as described earlier.

The major issue with the inverter was being able to find the right one, as well as finding a reliable retailer of inverters. The second issue deals with the input voltage range that we would like to use. The turbine's output is not fully suitable for this particular inverter. In order to supply the input of the inverter with the right voltage, we implemented a DC-DC converter which operates between 30 to 100 volts DC, allowing for more head room.

This converter is a small unit, capable of providing up to 100Wof power at 48V DC at the output. This device is perfect for driving the inverter, and efficiently regulating the turbine voltage. Due to grounding issues during testing, the purchased inverter became damaged. In order to continue with implementation, a LED array was connected in place of the inverter for testing and installation purposes.

4 TESTING

Once the components were designed and simulated, the next step was to test them. A small dynamometer in Atwater-Kent laboratories was used to run the tests and an oscilloscope was used to observe the respective outputs of the system.

This dynamometer has a three-phase synchronous generator driven by a DC motor. The motor is controlled by a variac to vary the voltage across the motor armature and its series field windings. This allows the speed of the machine to be varied, allowing the mimicking of varying wind speeds. The axel of this motor then drives the synchronous generator. This generator has a field winding controlled by a second variac to vary the three phase AC output voltage. This three phase output voltage is developed across three coils which are arranged in a Wye winding. The dynamometer is shown in Figure 33.

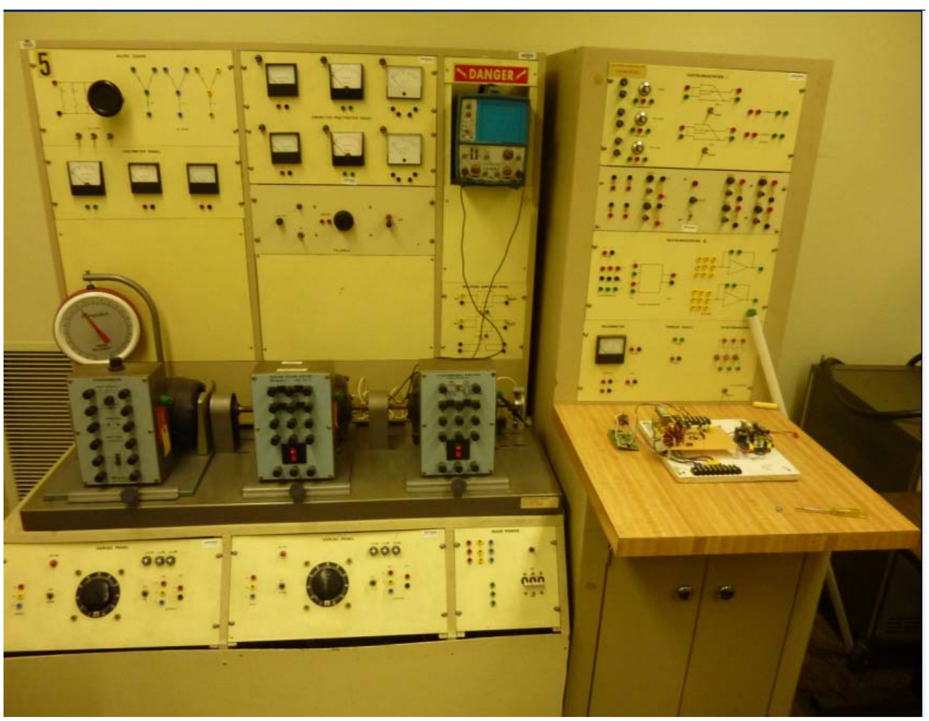

Figure 33: Dynamometer Synchronous Generator Used For Testing

From the output of the synchronous generator, the three phase current is then passed to the front-end circuitry, Figure 34. This front end circuit, modeled after the turbines front end, rectifies the current and filters the signal to achieve a signal which is pure DC. This circuit was a small test circuit, composed of a full-wave bridge rectifier, and a capacitor with a bleed resistor for safety. The front end has a DC output, which mimics the output of the turbine. This output is then connected to the system for testing. The system is tested with an oscilloscope, one circuit at a time.

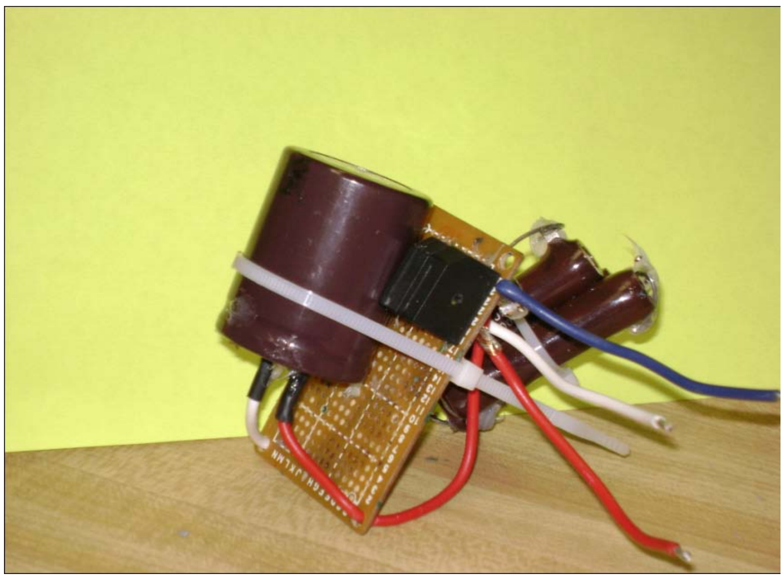

Figure 34: Model Front End Used For Testing

The tests were performed on all circuits of the system. The power supply, voltage converter, ripple detector, current sensor, and switch where the circuits tested. The LED module was tested with the system as well. It was connected to the low power terminals on the contactor

The filters where not individually tested during this phase. The filters were bread boarded and tested with a function generator, the INSTEK GFG-8219A function generator. Because these filters are commonly used in many applications, they do not require any specialized testing.

4.1 POWER SUPPLY TESTING

The first circuit to test in this system is the power supply. The power supply has three outputs, a dual 5V rail, and a 12V rail. The dual 5V rail powers the Op-amps, microcontroller, and hall element. The 12V rail is utilized by a fan for cooling the low-power system and to power the contactor.

Because the power supply is a very basic and straightforward circuit, there is not too much testing to be performed. The noise margin and the voltage stability are the only two things to take into consideration during this testing. Once constructed the rails were tested under normal load conditions. Power supply noise is crucial to eliminate, as it may cause undesired operation, and/or inaccurate readings. The first oscillogram shows the ripple voltage at the input to the +12V regulator, and the output of the regulator.

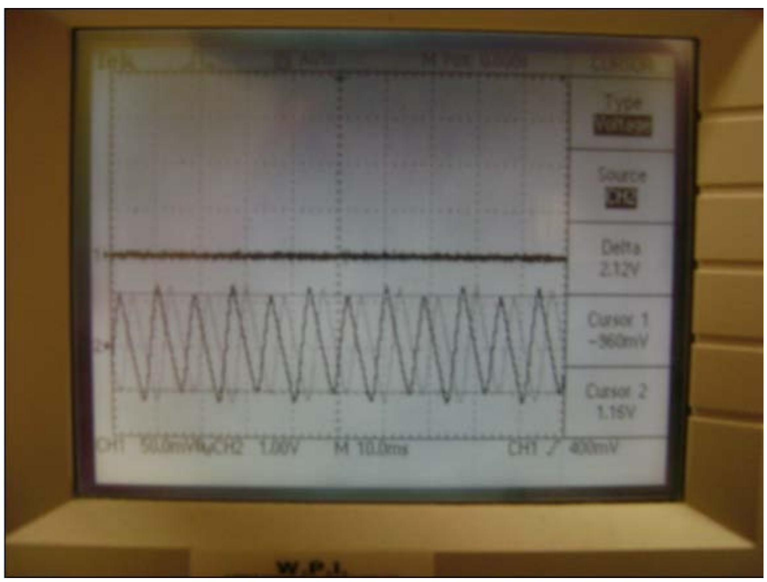

Figure 35: Top Trace: +12V Regulator Output (50mV/div) Bottom Trace: +12 V Regulator Input (1V/div)

The above figure shows the ripple voltage across the filter capacitor (input to the 12V voltage regulator) in the power supply. There is a ripple of $2V_{p\text{-}p}$. The regulator can easily handle this. The top trace shows a near flat-line DC signal, from the output of the 12V regulator. In order get a better view of the ripple present on this channel another oscillogram is shown below.

Figure 36: Output of +12V Regulator (20mV/div)

After a better look at the channel, the ripple is measured to be a signal of 22mV. This is a very low margin of noise, and from experience, it is known that this will not cause undesirable operation of the contactor or fan. Next it is important to check the ripple on the output of the +5V regulator.

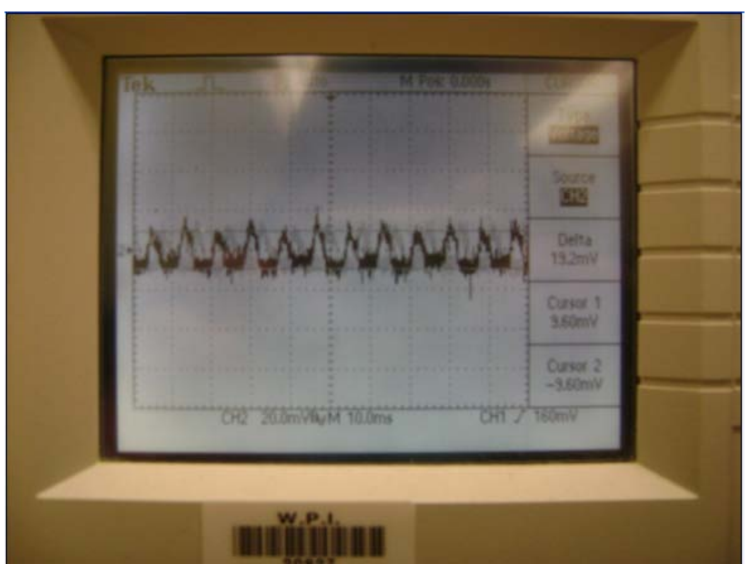

Figure 37: Output of +5V Regulator (20mV/div)

Strangely, the 5volt regulator doesn't appear to attenuate the noise margin at all. Nevertheless, the noise does not interfere with the functionality of the processor.

This testing concludes that the ripple rejection calculation for the voltage regulator is off. This is expected, as the 12V regulator dissipates a few watts of heat. If we are to recalculate ripple rejection, we have 20mV$_{pp}$ output, and a 2V$_{pp}$ input, then the rejection is -20dB$_V$ as calculated below. This is much lower than initially expected.

$$dB = 10 * log_{10}(\frac{0.02V}{2V}) \quad (20)$$

4.2 Voltage Converter Testing

Once the entire system was constructed, the voltage contactor was tested. The primary concern for the voltage converter was the step down would be enough to ensure safe voltages into the microprocessor. The results of the test can be seen in Table 2.

Table 2: Voltage Converter Output Testing

Front-End Voltage Output	Voltage Converter Output
0V	-1.6mV
10V	75mV
15V	109mV
30V	223mV
60V	442mV
90V	655mV
100V	727mV
110V	797mV
150V	1.07V

The table shows a linear response that is safely and properly attenuated, approximately 135:1 for the microprocessor. The readings were taken from two voltmeters. One provided on the synchronous machine, and the other, a standard digital voltmeter.

Oscillograms were taken to ensure that the output was free of noise, and stable. The two pictures below show a reading for a signal just below 30 volts DC. The oscilloscope probe is connected to the output of the voltage converter and the analog voltmeter is connected to the output of the front end module.

Figure 38: Voltmeter Measuring Turbine Output Voltage

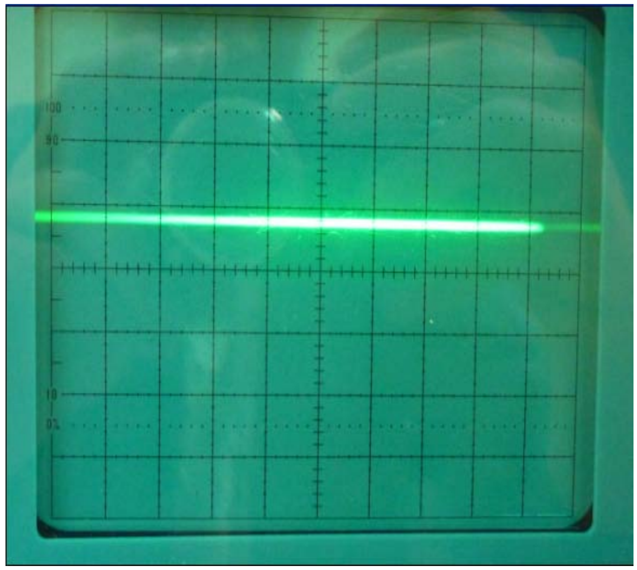

Figure 39: Voltage Reading at Voltage Converter Output

The oscilloscope in the figure above is set to 200mV/Div. According to the oscilloscope the output is approximately 180mV. According to the linear relationship shown in Table 2, this value should be approximately 200mV.

Any noise which may be present on the output can easily be seen with the oscilloscope. This includes any 60Hz noise which may be present in the lab, picked up on the long wires used for connecting the machine, front-end module, and our system. As can be seen in the figure below, there is no significant noise margin. This test also concludes that the Sallen-Key Filter implemented in this circuit is working correctly.

The oscillogram below, Figure 40, shows the response curve of the voltage converter. The generator output, controlled by the variacs, ranges from 0 volts Dc to 150 volts DC. The testing was not able to go above 150 volts, as the synchronous machine's abilities are limited.

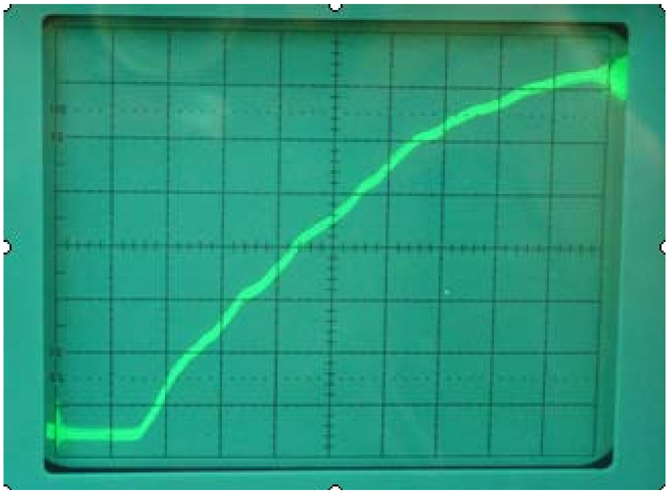

Figure 40: Voltage Converter Oscillogram (0.2V/div, .5 S/div)

4.3 RIPPLE DETECTOR TESTING

The next part of testing involved the ripple detector. The main focus of this test is to ensure that the circuit produces a square wave at a frequency that shares a linear relation to the speed of the synchronous generator. The frequencies measured here are not a good representation of what the turbine's actual speed is. This is due to the difference in generator design. For instance the turbine has 8 poles, and can output up to a maximum of 400Volts DC. This machine has 3 poles and can put out a maximum of 208 volts.

Of course, the behavior of this circuit is similar for both turbine and synchronous generator. This circuit can be tested with the synchronous generator, as it largely involves the signal processing of the AC ripple component which "rides" the high voltage DC current. It is also important to see the output change frequency with varying generator speeds. This will ensure a correct relationship between the voltage generated and the frequency of the square wave. The frequency of the square wave is then read by the microprocessor.

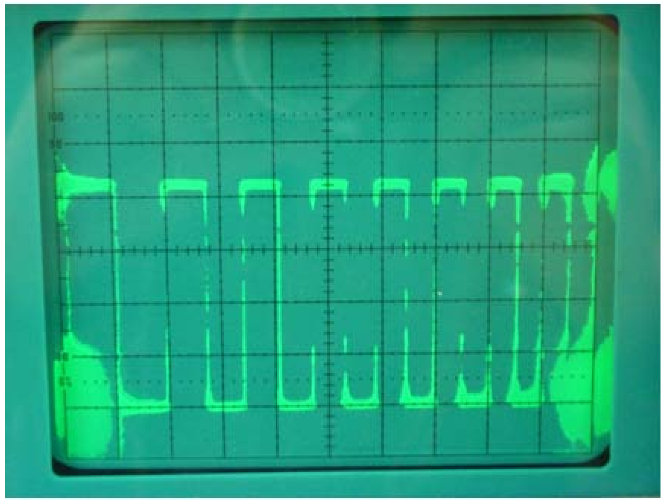

Figure 41: Ripple detector Oscillogram (1V/div, 20mS/div)

The figure above shows the frequency change from a low speed to a higher speed. The difficulty in testing this circuit is due to the slow acceleration of the dynamometer, and the limitations of the oscilloscope. This is why the change in frequency seen above is somewhat limited to a small range of values.

The lowest frequency measured by the oscilloscope in the figure above, is in the left half of the figure, and the highest, in the right. The left most signal is around 25Hz and the rightmost, around 50Hz. The figure below shows a much more clear square wave, but this is only limited to one discrete value of generator speed.

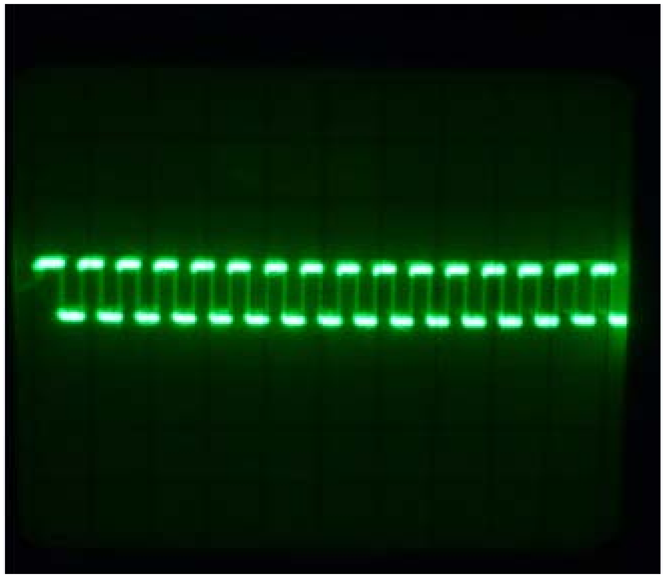

Figure 42: Ripple detector Oscillogram (5V/div, 20mS/div)

Below is a table which indicates a few measurements of the square wave frequency from the ripple detector. A strobe light was used to find the RPM of the synchronous generator. The strobe light used had a very sensitive speed adjust scale, and proved somewhat difficult to get an accurate reading. Furthermore, the sweep time on the oscilloscope made it difficult to read the frequency of the signal. A digital voltmeter was used to measure the square wave frequency. The values given below are approximated, but are the best results found; a more linear relationship was expected.

Table 3: RPM Frequency Measurements

Front End Voltage	Measured RPM (strobe light)	Square wave frequency (measured with DVM)
30V	1200	20Hz
100V	2000	133Hz
120V	2800	163Hz

Again, it should be noted the tolerance of the DVM, and the sensitivity of the strobe light adjustment can give some strange readings. This is apparent with the 100volt reading.

4.4 CURRENT SENSOR TESTING

This was a simple circuit to test as it was simply a hall-effect sensor. This sensor was designed to be compatible with most microcontrollers. The output is biased at 2.5volts, and has an accuracy of approximately 10mA. The testing was done utilizing an analog ammeter in series with the input to our system. This allows for accurate readings during testing, as they can be compared.

A high power resistor bank was connected to the output of our system on the low power terminals of the contactor. This resistor bank can be adjusted with switches, to change the impedance in a piecewise manner.

Figure 43: Resistor bank used for hall-sensor test

The bank was set to an impedance of 12.4ohms, and the voltage was varied to see the behavior of the current sensor. A table of values has been created below.

Table 4: Current Sensor Output Voltages

Input current (read from analog ammeter)	Sensor output voltage
0.0A	2.48V
0.1A	2.49V
0.5A	2.539V
1A	2.599V
1.1A	2.617V
2.0A	2.73V
2.4A	2.777V

Due to the limitations on the synchronous generator, the current drawn by the resistor bank had to be kept under 2.5 amps. This test worked very well, as we are able to test the accuracy of the Hall-Effect sensor itself. This linearity is found by taking the differences in output voltages for two different current draws and comparing them to the other values. For instance, changes in currents of 100mA are seen in the first two values as well as the fourth and fifth values. The difference in output voltage is taken for the first two, as well as the fourth and fifth values. The differences in voltage output for each pair must be exact in order for the reading to be considered accurate. As can be seen, the differences for the two pairs is not the same, this might be due to low current inaccuracies that are common in Hall Effect sensors.

The linear relationship is re-established with high current draws. Differences in 400mA, as can be seen with the difference between the second and third values in the current column in the table, compared to the difference of the last two values. The change in voltage output is the same, and therefore this sensor was concluded to be accurate to current changes of 400mA.

Comparing more values in the table shows that the linear relationship is re-established with higher current draws. For the purposes of this project, the Hall-effect sensor is very well suited for the demands of the turbine. The turbine is unlikely to operate only on small scale current draws, so there will not be any issues with data recording.

A previous test involving a small 12V 4 amp 60 Hz transformer was used to test the sensor to check the response. This was a much less accurate approach, but confirmed, that there was a clean, linear response. A graph was created below with the values plotted with a "best-fit" curve. These measurements show a relationship of 170mV output for every amp drawn.

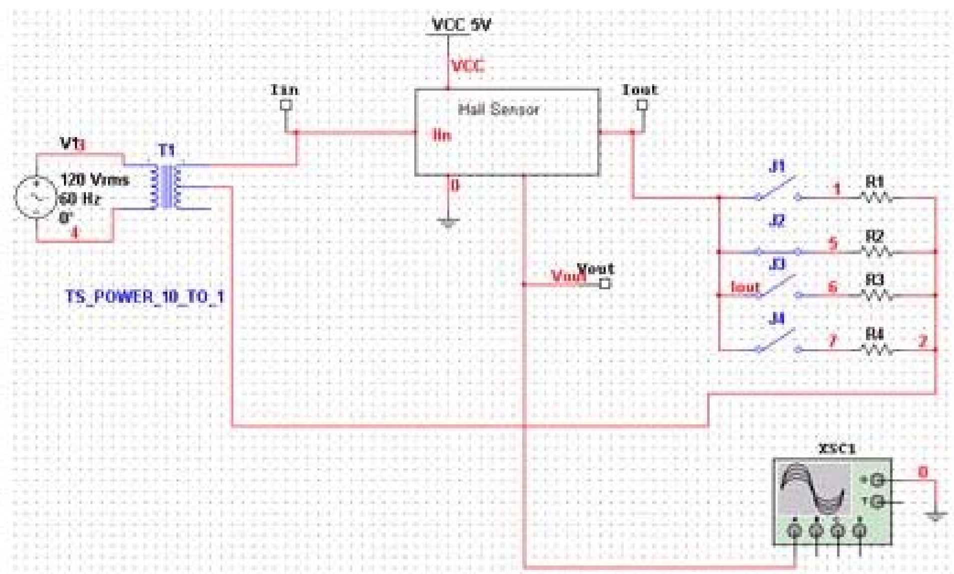

Figure 44: Hall Effect Sensor Testing Setup

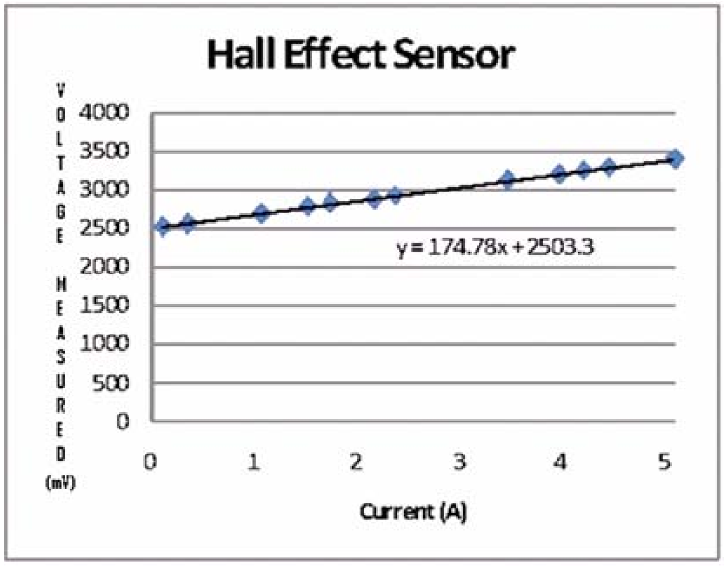

Figure 45: Hall Effect Sensor Best Fit Curve

From the second test, Table 4, the relationship is established as 120mV output for every amp drawn. This 50mV difference in sensor output voltage per amp drawn is very small, and would correspond to changes that can be neglected, as they are too precise for the A/D converter of the microcontroller.

4.5 SWITCH TESTING

The last major part of the system to test was the switch. This switch is a double pole double throw (DPDT) high voltage contactor. The contactor is driven by the microcontroller, through an opto-coupler which drives a transistor network, to activate the contactor coil. When the switch is activated or deactivated along its hysteresis curve, it is necessary to see the response time. This circuit requires no specialized testing as it is just an ON/OFF driver circuit.

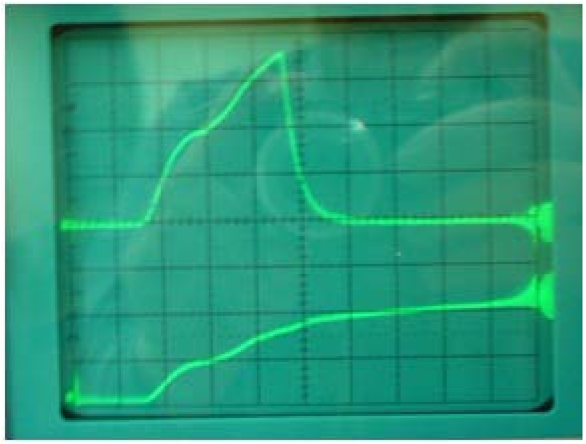

Figure 46: System Switching From Low Power Terminals to High Power Terminals on Contactor

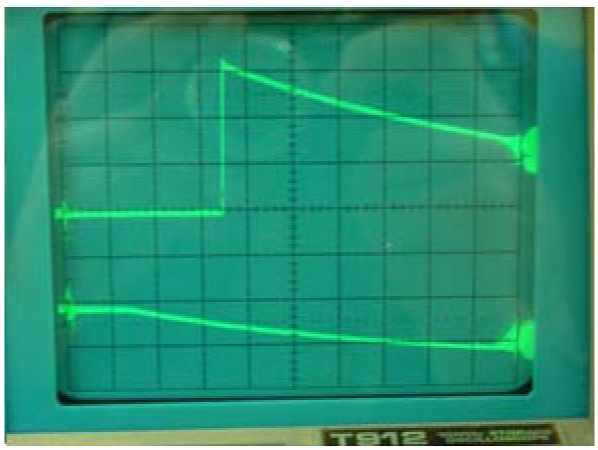

Figure 47: System Switching From High Power Terminals to Low Power Terminals on the Contactor

The upper trace in each figure is connected to the low voltage contactor output though a difference amplifier, then to the first channel. The oscilloscope channel for the top trace is set to 0.2V/div on a 0.5S/div time scale. The oscilloscope channel for the lower trace is 0.5V/div on a 0.5S/div time scale. This second channel is connected to the output from the voltage converter in our system.

When viewing the figures above, the switching voltages can be seen. The switching from low power to high power occurs at around 750mV, and the switching from high power to low power occurs around 600mV. It is also important to view the speeds at which the switching occurs. The turn off transient takes about half of a second. This is likely due to capacitance in the load. The turn on is very fast compared to the turn off, taking only a few microseconds. It will not damage the system if both are on at the same time very briefly because both can handle the load and are separate systems.

5 ECONOMICS

Upon completion of the system the group studied the economics on the investment of adding a low-power inverter. To do so, the group collected extensive data on wind speeds over the past year. As a benchmark for wind speed data, the group used information gathered by the National Climactic Data Center. The NCDC records hourly and daily weather information, including wind speed, in various cities across America. It organizes the information into data tables dating back to 1996. The nearest NCDC recording station is at the Worcester Regional Airport, approximately 3 to 4 miles away. Because wind speeds could potentially be different in an open airport compared to the top of Atwater Kent Laboratories at WPI, by being consistent and avoiding the use of any alternate sources of wind data, the evaluation of power delivered compared to wind speed will remain uniform throughout the process.

To begin data on low-power situations was collected. The initial goal of the data collection was to obtain a characteristic curve of power produced by the turbine at various wind speeds. Because the focus was based solely on low-power situations, in which the original inverter is not running, situations where the current wind conditions were below 11 mph were evaluated. Wind speeds greater than 11 mph were seen to produce enough power for the original inverter to come on-line. Because the NCDC rounds all hourly wind speed data to the nearest hour the group obtained multiple points for each of the speeds available from 0 to 11 mph. The data collection designed by the group offers power readings for every 20 seconds; therefore the average power was taken during any given hour and used as the data point for that hour. The following figure shows the characteristic curve obtained of power produced at varying wind speeds.

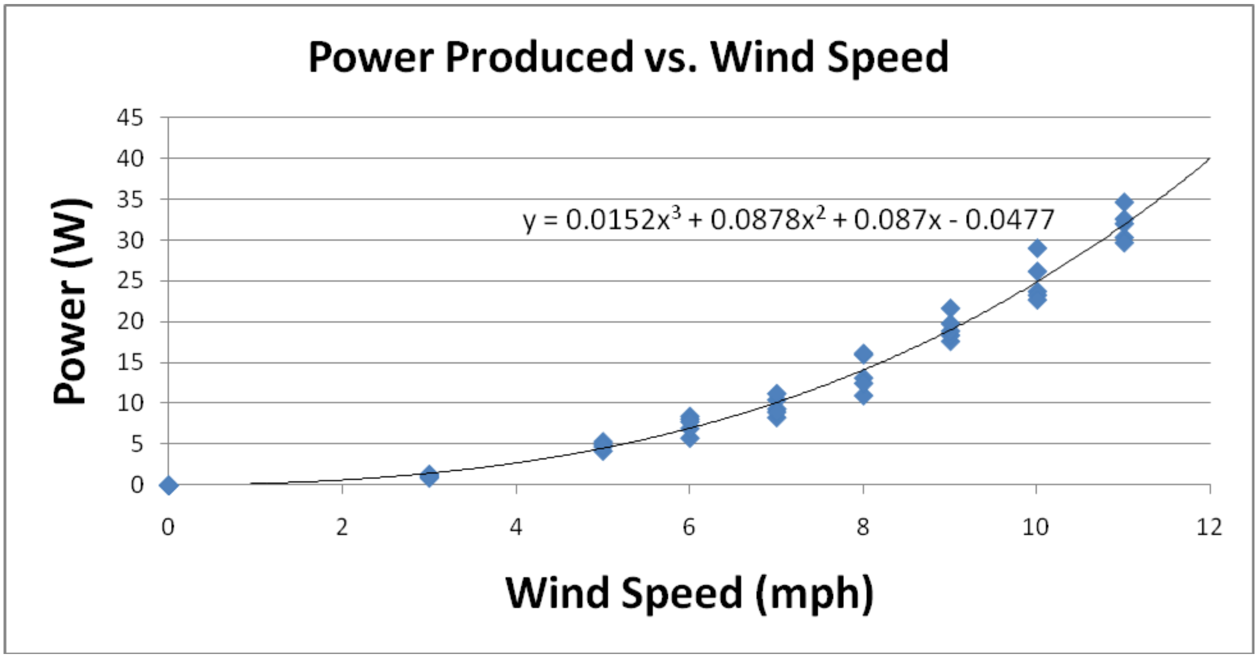

Figure 48: Produced Power vs. Wind Speed

Using a line of best fit tool, the group obtained a third order polynomial shown in the previous figure. This equation would serve as the benchmark for the following calculations to obtain an economic evaluation of the designed system.

By combining NCDC's data for wind speeds throughout the previous year and the previously obtained characteristic curve an estimate of the energy produced by the turbine throughout the previous year which was not placed back on the grid was produced. Using NCDC's daily wind speed averages, speeds rounded to the nearest tenth of a mph, as the variable in the characteristic equation the group obtained a plot of average power produced each day from April 1, 2009 through March 31, 2010.

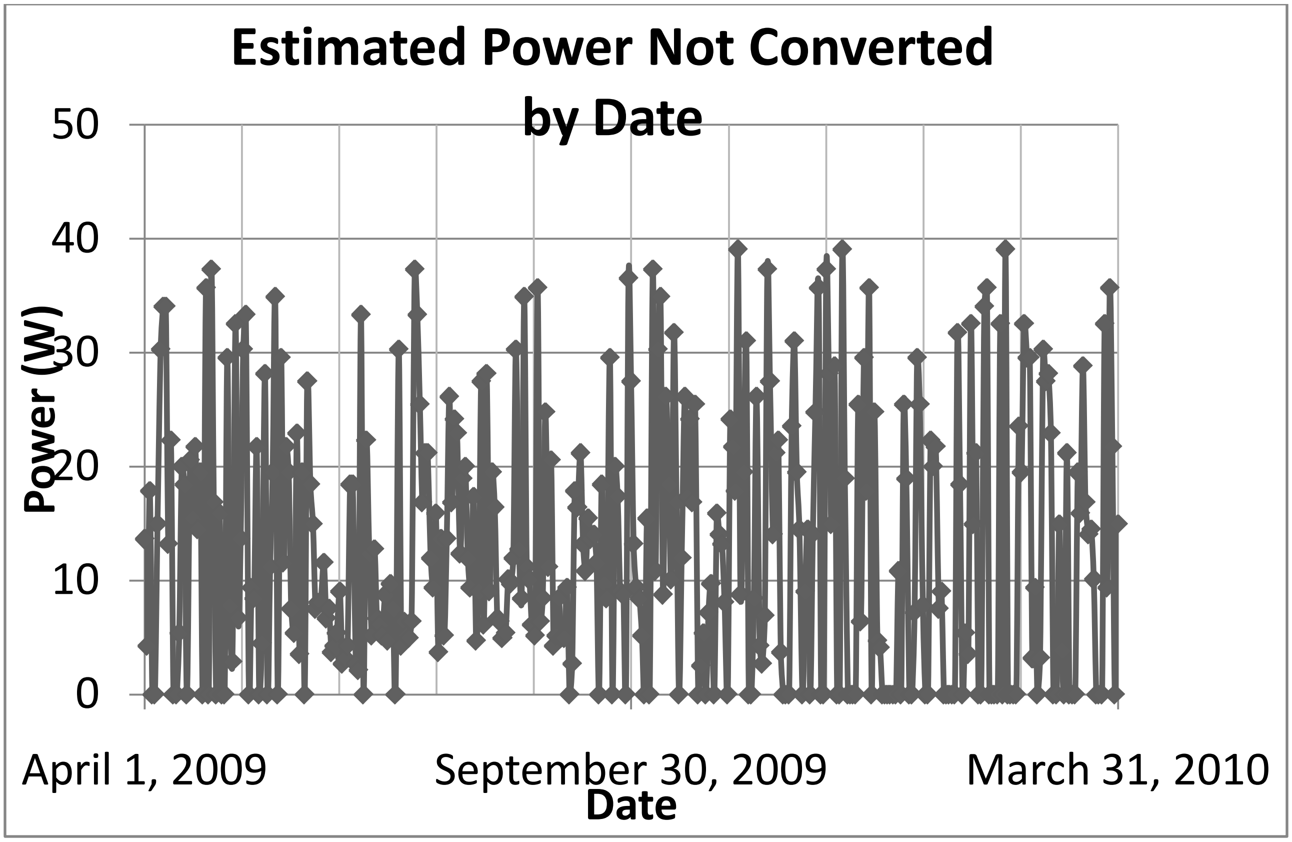

Figure 49: Estimated Power Low Power Inverter, April 2009-April 2010

Unfortunately, because a graph of all 12 months contains 365 data points, one for each day, the graph is cluttered and difficult to evaluate without expanding it beyond the confines of this document Due to this Figure 50 shows the month of April 2009 to better show the information.

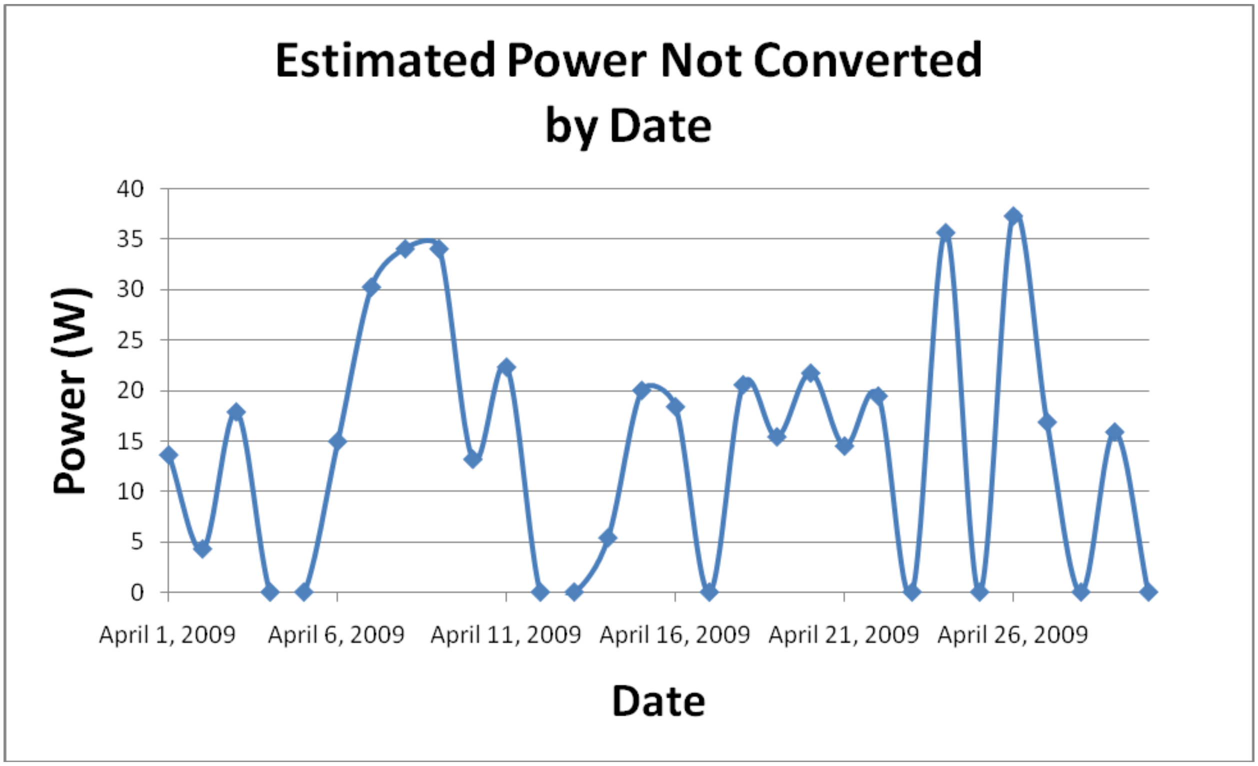

Figure 50: Estimated Power of Low Power Inverter, April 2009

An important item to note is that not all points with a value of 0 W produced represent a day of no power production. As stated earlier this graph does not display values where the original inverter is on-line, therefore in some situations the average wind speed was so high that the power produced was actually placed on the grid by the original inverter. April 23rd and April 25th are two examples of this occasion. Similarly, because the inverter setup designed for low-power conversion also has a minimum cut-in voltage power produced at wind speeds lower than 4.5 mph were also ignored in calculations.

The final piece of information needed is energy produced over the year. By integrating daily power estimates we obtain an estimate of energy produced each day which can then be summed up to a final value. The following equation was used obtain each days energy produced:

$$\frac{P(X)+P(X+1)}{2} * 24 * \frac{1}{1000} \qquad (21)$$

In the previous equation P(X) represents the average power produced on day X. Because energy is most often measured in kWh and the estimates were average power in watts throughout each day scaling factors were incorporated. The scaling factor of 24 in the previous equation is used because there is 24 hours in each day. The scaling factor of 1/1000 is used to convert Watts to Kilowatts. The following graph shows energy produced by the turbine, but not used throughout the previous year.

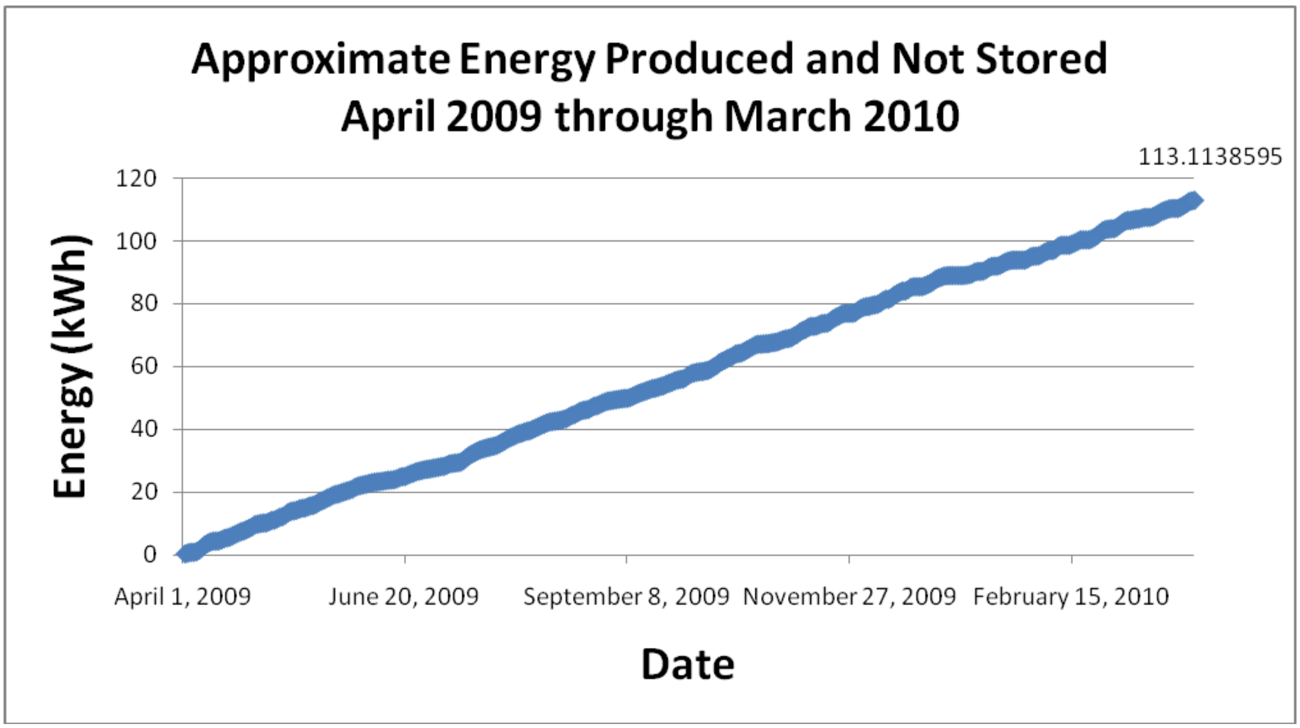

Figure 51: Total Energy Gained with Low Power Inverter, April 2009 - April 2010

As shown in the previous figure the energy produced by the turbine that was not used summed up to approximately 113 kWh throughout the year. If this energy had been stored using the designed low-power inverter, which involved the following two components, there would be loses based on the efficiency of each of the two main components Vicor's DC to DC converter's with 80% efficiency and Enphase’s MicroInverter's with 90% efficiency. The new calculation of power lost is approximately:

$$113kWh * 80\% * 90\% = 81.36kWh \tag{22}$$

Looking at an example National Grid bill, the charge for 1 kWh costs approximately $0.16575, meaning a total estimated savings of:

$$81.36kWh * \frac{\$0.16575}{kWh} = \$13.49 \tag{23}$$

After a full year of running without a low-power inverter installed the wind turbine atop Atwater Kent Laboratories lost a possible $13.49 in energy savings.

By evaluating the cost of the low-power inverter designed, Vicor DC to DC converter and Enphase Inverter, and the returns on energy produced we obtain an economic analysis of the low-power inverter investment. Ignoring the time value of money we can create an estimate on the time it would take to recoup the original investment. With a total of approximately $425 for the low power inverter it would take approximately:

$$\frac{\$425}{\$13.49/Year} = 31.5\ Years \tag{24}$$

An investment that takes over 30 years to offer return of initial profits would seem to be not beneficial. Unfortunately, the idea of installing a low-power inverter seems to be a poor investment.

6 CONCLUSIONS

With the conclusion of the project, the wind turbine system of WPI's Atwater-Kent Laboratories now offers data logging hardware and software, which records information regarding power created at any given time and rotational speed of the turbine. Because the original inverter had a low-power sleep mode tests were performed on the power lost and the economics on storing said energy. Unfortunately, when installing a low power inverter, grounding issues occurred. Because of this, there is currently an LED array installed in place of the secondary inverter.

After analyzing the amount of energy obtained with the low power inverter, a cost analysis was done, determining that it would take over 30 years for return on investment of the inverter. In the future cost and benefit studies should be done on alternative forms of power storage, including rechargeable batteries which can be used to power portable devices. Studies should also be done on the environment surrounding the turbine and why overall power production seems disappointing as we feel that the 100V cut-off frequency is not the cause of the disappointing power production.

Additionally, in the future the log files created should be organized and displayed via the internet seamlessly. In the current configuration a user would have to display that information manually, but the PC should on its own feed the information to a web page.

7 WORKS CITED

1. *World wind energy report 2009*(2010). World Wind Energy Association. (1)
2. *Small scale wind energy - policy insights and practical guidance*(2008). Carbon Trust.
3. *AWEA small wind turbine global market study*(2009). American Wind Energy Association.
4. *AWEA U.S. wind industry annual market report*(2010). American Wind Energy Association.

APPENDIX A: NETLIST VOLTAGE CONVERTER SIMULATION

```
** Voltage Converter **
*
* National Instruments
*
* This file was created by:
*   Multisim to SPICE netlist routine

* TL082 OPERATIONAL AMPLIFIER "MACROMODEL" SUBCIRCUIT
* CREATED USING PARTS RELEASE 4.01 ON 06/16/89 AT 13:08
* (REV N/A)      SUPPLY VOLTAGE: +/-15V
* CONNECTIONS:   NON-INVERTING INPUT
*                | INVERTING INPUT
*                | | POSITIVE POWER SUPPLY
*                | | | NEGATIVE POWER SUPPLY
*                | | | | OUTPUT
*                | | | | |
.SUBCKT TL082__OPAMP__1    1 2 3 4 5
*
  C1   11 12 3.498E-12
  C2    6  7 15.00E-12
  DC    5 53 DX
  DE   54  5 DX
  DLP  90 91 DX
  DLN  92 90 DX
  DP    4  3 DX
  EGND 99  0 POLY(2) (3,0) (4,0) 0 .5 .5
  FB    7 99 POLY(5) VB VC VE VLP VLN 0 4.715E6 -5E6 5E6 5E6 -5E6
  GA    6  0 11 12 282.8E-6
  GCM   0  6 10 99 8.942E-9
  ISS   3 10 DC 195.0E-6
  HLIM 90  0 VLIM 1K
  J1   11  2 10 JX
  J2   12  1 10 JX
  R2    6  9 100.0E3
  RD1   4 11 3.536E3
  RD2   4 12 3.536E3
  RO1   8  5 150
  RO2   7 99 150
  RP    3  4 2.143E3
  RSS  10 99 1.026E6
  VB    9  0 DC 0
  VC    3 53 DC 2.200
  VE   54  4 DC 2.200
```

```
  VLIM  7  8 DC 0
  VLP  91  0 DC 25
  VLN   0 92 DC 25
.MODEL DX D(IS=800.0E-18)
.MODEL JX PJF(IS=15.00E-12 BETA=270.1E-6 VTO=-1)
.ENDS
```

APPENDIX B: NETLIST RIPPLE DETECTOR SIMULATION

```
** RPM Meter **
*
* National Instruments
*
* This file was created by:
*   Multisim to SPICE netlist routine

* TL082 OPERATIONAL AMPLIFIER "MACROMODEL" SUBCIRCUIT
* CREATED USING PARTS RELEASE 4.01 ON 06/16/89 AT 13:08
* (REV N/A)      SUPPLY VOLTAGE: +/-15V
* CONNECTIONS:   NON-INVERTING INPUT
*                | INVERTING INPUT
*                | | POSITIVE POWER SUPPLY
*                | | | NEGATIVE POWER SUPPLY
*                | | | | OUTPUT
*                | | | | |
.SUBCKT TL082__OPAMP__1    1 2 3 4 5
*
  C1   11 12 3.498E-12
  C2    6  7 15.00E-12
  DC    5 53 DX
  DE   54  5 DX
  DLP  90 91 DX
  DLN  92 90 DX
  DP    4  3 DX
  EGND 99  0 POLY(2) (3,0) (4,0) 0 .5 .5
  FB    7 99 POLY(5) VB VC VE VLP VLN 0 4.715E6 -5E6 5E6 5E6 -5E6
  GA    6  0 11 12 282.8E-6
  GCM   0  6 10 99 8.942E-9
  ISS   3 10 DC 195.0E-6
  HLIM 90  0 VLIM 1K
  J1   11  2 10 JX
  J2   12  1 10 JX
  R2    6  9 100.0E3
  RD1   4 11 3.536E3
  RD2   4 12 3.536E3
  RO1   8  5 150
  RO2   7 99 150
  RP    3  4 2.143E3
  RSS  10 99 1.026E6
  VB    9  0 DC 0
  VC    3 53 DC 2.200
  VE   54  4 DC 2.200
```

```
  VLIM  7  8 DC 0
  VLP  91  0 DC 25
  VLN   0 92 DC 25
.MODEL DX D(IS=800.0E-18)
.MODEL JX PJF(IS=15.00E-12 BETA=270.1E-6 VTO=-1)
.ENDS

.MODEL D1N4933__DIODE__1 D (
+   IS =  2.211e-10
+   RS =  0.03188
+   CJO =  2.879e-11
+   VJ =  0.75
+   TT =  2.164e-07
+   M =  0.43
+   BV =  100
+   N =  1.7
+   EG =  1.11
+   XTI =  3
+   KF =  0
+   AF =  1
+   FC =  0.5
+   IBV =  0.0001
+   TNOM =  27
+ )
```

APPENDIX C: NETLIST POWER SUPPLY SIMULATION

```
** Power Supply **
*
* National Instruments
*
* This file was created by:
*   Multisim to SPICE netlist routine
*



.SUBCKT LM7805CT__VOLTAGE_REGULATOR__1 3 1 2
**************************************
*      Model Generated by MODPEX     *
*Copyright(c) Symmetry Design Systems*
*         All Rights Reserved        *
*    UNPUBLISHED LICENSED SOFTWARE   *
*   Contains Proprietary Information *
*      Which is The Property of      *
*     SYMMETRY OR ITS LICENSORS      *
**************************************
*node 1: VREG (OUTPUT)
*node 2: Ground (Common)
*node 3: Line Voltage
ECCX 131 2 135 2 1.0
VXX 133 2 DC 0
FSET6 2 135 VSENS2 1
FPP 3 2 VXX 1.0
R_YY 31 2 1e6
R_XX 15 2 1e8
R_ZZ 36 2 1e6
R_QQ 65 2 1e8
RXX 1 2 1e8
VSENS1 10 1 DC 0
ISET 2 15 DC 1e-3
DON1 15 16 DMOD1
VSENS2 16 19 DC 0
DON2 15 17 DMOD1
EON2 18 2 3 2 1
FYY 3 2 VSENS1 1
DON3 15 27 DMOD1
VDROP3 28 27 DC 2
EON3 28 2 3 2 4
ELINE 13 42 66 2 1
FSET2 2 36 VSENS2 1
DSC1 36 35 DMOD1
```

```
RCL1 36 37 10
DSC2 37 38 DMOD1
ESCCON 38 39 30 2 1
VSCCON 39 40 DC 0
FSC 19 2 VSCCON 1
FSET3 2 31 VSENS2 1
DOV1 31 32 DMOD1
EOV1 32 2 3 1 1
DOV2 31 33 DMOD1
ISET4 2 30 DC 1e-3
ELOAD 41 2 77 2 -1
ERIPPLE 42 41 72 2 1
EREF 12 13 19 2 1
E3 52 2 3 2 1
CBYPS 54 2 0.001
VORB 54 60 DC 0
RB 60 2 1e3
RBR 72 2 1000
CBS2 52 71 1
RSTEP 77 2 1
FRB 2 65 VORB 1
DRB2 65 67 DMOD1
VXRB 67 68 DC -1
EXRB 68 2 1 2 1
DRB1 65 66 DMOD1
RB1 66 2 1000
.MODEL DMOD1 D
*-- DMOD1 DEFAULT PARAMETERS
*IS=1e-14 RS=0 N=1 TT=0 CJO=0
*VJ=1 M=0.5 EG=1.11 XTI=3 FC=0.5
*KF=0 AF=1 BV=inf IBV=1e-3 TNOM=27
EXX 132 131 3 131 0.0444444
RST6 135 2 10000
RIQX 133 132 RQIX 2222.22
.MODEL RQIX R TC1=-0
RSET 19 2 RSET 5000
.MODEL RSET R TC1=1e-05 TC2=-1.5005e-06
RS1 10 12 0.0075
VDROPX 18 17 1.46
HSENSE1 35 2 VSENS1 4.16667
RISC 30 2 RISC 10000
.MODEL RISC R TC1=-0.0025
ROV 34 2 20000
VOV 33 34 10
EOV2 2 40 34 2 0.291667
FIQD 3 2 VSENS1 0.0003
```

```
RY 52 54 5e+06
RA 72 73 2162.75
RYR 71 72 9.999e+06
CRA 52 73 1.59136e-11
HSTEP 76 2 VSENS1 1
CSTEP 76 77 6e-06
.ENDS

.SUBCKT LM7812CT__VOLTAGE_REGULATOR__1 1 2 3
* POSITIVE 3 TERMINAL VOLTAGE REGULATOR
* PIN 1 = VOLTAGE INPUT
* PIN 2 = VOLTAGE REF (USUALLY GND)
* PIN 3 = VOLTAGE OUTPUT
* OUTPUT VOLTAGE = V1 - 1.3v
R1 5  3 50
R2 1  4 10000
R3 3  2 10000
V1 4  2 dc 13.3
Q2 1 4 5 CNTL_NPN
Q1 1 5 3 POWER_NPN
*
.MODEL CNTL_NPN NPN(Is=6.734f Xti=3 Eg=1.11 Vaf=74.03 Bf=416.4 Ne=1.259
+           Ise=6.734f Ikf=66.78m Xtb=1.5 Br=.7371 Nc=2 Isc=0 Ikr=0 Rc=1
+           Cjc=3.638p Mjc=.3085 Vjc=.75 Fc=.5 Cje=4.493p Mje=.2593 Vje=.75
+           Tr=239.5n Tf=301.2p Itf=.4 Vtf=4 Xtf=2 Rb=10)
.MODEL POWER_NPN NPN
+IS=3.41639e-13 BF=405.26 NF=1.03507 VAF=120.176
+IKF=10 ISE=8.44498e-12 NE=3.47601 BR=0.1
+NR=1.04536 VAR=1.10398 IKR=2.5029 ISC=5.50017e-13
+NC=3.93748 RB=1.80955 IRB=6.50293 RBM=1.80955
+RE=0.0001 RC=0.13777 XTB=0.1 XTI=1
+EG=1.05 CJE=6.36056e-10 VJE=0.4 MJE=0.479146
+TF=7.91835e-08 XTF=463.212 VTF=62107.5 ITF=1000
+CJC=2.70642e-10 VJC=0.95 MJC=0.406578 XCJC=0.128859
+FC=0.8 CJS=0 VJS=0.75 MJS=0.5
+TR=8.186e-05 PTF=0 KF=0 AF=1
.ENDS

.SUBCKT LM7905CT__VOLTAGE_REGULATOR__1 1 2 3
* NEGATIVE 3 TERMINAL VOLTAGE REGULATOR
* PIN 1 = VOLTAGE INPUT
* PIN 2 = VOLTAGE REF (USUALLY GND)
* PIN 3 = VOLTAGE OUTPUT
* OUTPUT VOLTAGE = V1 - 1.3v
R1 5  3 50
R2 1  4 10000
```

```
R3 3  2 10000
V1 4  2 dc -6.3
Q2 1 4 5 CNTL_PNP
Q1 1 5 3 POWER_PNP
*
.MODEL POWER_PNP PNP
+IS=9.22554e-15 BF=7026.13 NF=0.875675 VAF=121.334
+IKF=1 ISE=4.16599e-14 NE=1.16082 BR=0.1
+NR=1.5 VAR=0.840001 IKR=10 ISC=4.16599e-14
+NC=1 RB=1.16529 IRB=0.1 RBM=1.16529
+RE=0.0001 RC=3.25699 XTB=0.1 XTI=1
+EG=1.206 CJE=1.98647e-10 VJE=0.4 MJE=0.85
+TF=1.6698e-09 XTF=1000 VTF=1.23886 ITF=13.7503
+CJC=4.56014e-11 VJC=0.95 MJC=0.463492 XCJC=0.84185
+FC=0.1 CJS=0 VJS=0.75 MJS=0.5
+TR=1e-07 PTF=0 KF=0 AF=1
.MODEL CNTL_PNP PNP
+IS=6.28714e-14 BF=386.157 NF=1.04671 VAF=10
+IKF=0.189462 ISE=1.92795e-13 NE=1.41391 BR=0.1
+NR=1.14919 VAR=1.3773 IKR=0.853995 ISC=1.92795e-13
+NC=2.83982 RB=18.4538 IRB=0.1 RBM=0.1
+RE=0.0561856 RC=1.23424 XTB=0.251412 XTI=1
+EG=1.05 CJE=2.79854e-11 VJE=0.718974 MJE=0.375151
+TF=5.18862e-10 XTF=1.5 VTF=0.999999 ITF=1
+CJC=1.98079e-11 VJC=0.4 MJC=0.393215 XCJC=0.8
+FC=0.649759 CJS=0 VJS=0.75 MJS=0.5
+TR=1.16047e-06 PTF=0 KF=0 AF=1
.ENDS

.MODEL D1N4007GP__DIODE__1 D (
+   IS =  6.698e-07
+   RS =  0.04255
+   CJO =  1.949e-11
+   VJ =  0.3909
+   TT =  4.933e-06
+   M =  0.3577
+   BV =  1000
+   N =  2.412
+   EG =  1.11
+   XTI =  3
+   KF =  0
+   AF =  1
+   FC =  0.5
+   IBV =  0.005177
+   TNOM =  27
+ )
```

```
.SUBCKT TS_PWR_25_TO_1__TRANSFORMER__1 1 2 3 4 5
* EWB Version 4 - Transformer Model
* n= 25 Le= 0.001 Lm= 5 Rp= 1e-006 Rs= 1e-006
   Rp   1  6 1e-006ohm
   Rs1 10  3 1e-006ohm
   Rs2 11  5 5e-007ohm
   Le   6  7 0.001H
   Lm   7  2 5H
   E1   9  8  7  2 0.02
   E2   8  4  7  2 0.02
   V1   9 10 DC 0V
   V2   8 11 DC 0V
   F1   7  2 V1 0.04
   F2   7  2 V2 0.04
.ENDS
```

APPENDIX D: MICROPROCESSOR CODE

```
#include <htc.h>
#include <time.h>
#include <math.h>
#include <stdio.h>
#include "turbine.h"

__CONFIG(WDTDIS & HS & UNPROTECT);


int Voltage = 0;
int j = 0;
int k = 0;

int inverter_choice = 0;            // Lead off with Old-Inverter Powered On
unsigned int cycles = 0;            // 0 = 0ld      1 = New
unsigned int RPM;
unsigned int tmrs;
int was = 0;


void init();
void record_data ();
int record_voltage ();
int record_current ();
void waitforAD ();
void eval_voltage ();
void switch_inverters();
void fixMyIssue();
void handleCycles();


void interrupt TMR_1(void)
{

        if ((TMR1IE)&&(TMR1IF)){
                tmrs++;
                if(tmrs == 10){
                        RPM = cycles * 15 / 48;
                        cycles = 0;
                        tmrs = 0;
                }
        TMR1IF = 0;
        }
}
```

```
void main (void)
{
        init();
        while(1)
        {
                record_data();
                eval_voltage();
                switch_inverters();
        }
}

void init(void)
{
        fixMyIssue();
        T1OSCEN = 1;
        T1CON = 0x01;                       // Enables Timer1
        ADCON1 = 0x8B;                      // Sets Clock choice and ref as Vdd
Vss for A/D converter
        TRISB = 0xFF;                       // Sets PortB as outputs except RB0
& RB1 to be set as Interrupt on Change's
        ANSEL = 0xDF;
        ANSELH = 0x00;
        TRISC = 0x00;                       // Set PortC to Digital Outputs for
Cycles Output to UBW (Upper -- 4 Only)
        PORTC = 0x00;                       // Initialize PortC to low outputs
        TRISD = 0x00;                       // Set PortD to Digital Outputs for
Cycles Output to UBW (Lower)
        PORTD = 0x00;                       // Initialize PortD to low outputs
        TRISE = 0xFF;                       // Set PortE to all Inputs
        TRISA = 0x00;                       // Set PortA to all Outputs PORTA
Pin 0 RA0 = Switch Control
                                        // Enables External interrupt on RB0
                                        // And Interrupt on Change RB1 for Cycles
Timer?
        WPUB = 0x00;
        PIE1 = 0x01;
        INTCON = 0x40;
        GIE = 1;

}
void record_data (void)
{

        handleCycles();
        Voltage = record_voltage();
```

```
		handleCycles();
		PORTC = RPM;

	}
	int record_voltage (void)			// AN6
	{
		ADCON0 = 0x99;				// Enable A/D conversion of Pin
AN6
		if(1){k=0;}
		ADCON0 = ADCON0 | 0x02;
		waitforAD();
		j = ADRESL + (ADRESH << 8);
		j = (float) j*.6585;
		k = 0;
		return j;
	}
	void waitforAD(void)
	{
		while(ADCON0 & 0x02) {}			// Wait until GO/DONE = 0 (DONE)
		ADCON0 = 0x00;				// Turn A/D Off
	}

	void eval_voltage(void)				// Decides when to switch between
inverters
	{
		if ((inverter_choice == 0) && (Voltage < 90))
		{
			inverter_choice = 1;
		}
		else if ((inverter_choice == 1) && (Voltage > 110))
		{
			inverter_choice = 0;
		}
	}
	void switch_inverters(void)			// Switches RA0
	{						// 0=Old 1=New
		if (inverter_choice == 1)
		{
			PORTA |= 0x01;
		}
		else
		{
			PORTA &= 0xFD;
		}
	}
	void fixMyIssue(void){
```

```
	int z;
	z = j;
	z = k;
	z = RPM;
}

void handleCycles(void){
	if ((was == 0) && (RE0 == 1)){cycles++;}
	was = RE0;

}
```

APPENDIX E: COMPUTER RECORDING CODE

```
Imports System.IO

Module Module1

    Private Declare Sub Sleep Lib "kernel32" (ByVal dwMilliseconds As Long)

    Public Class SendKeys

    End Class

    Public Function AppendText(ByVal path As String) As StreamWriter

    End Function

    Sub Main()

        Dim RetVal

        Dim objStreamReader As StreamReader

        Dim objStreamWriter As StreamWriter

        Dim strLine As String

        Dim voltage As String = "0"

        Dim current As String = "0"

        Dim cycles As String = "0"

        Dim voltageValue As Integer

        Dim currentValue As Integer

        Dim cyclesValue As Integer

        Dim voltageOutput As String

        Dim currentOutput As String

        Dim cyclesOutput As String

        'Loop so program runs continually

        Do While 1
```

```
RetVal = Shell("C:\Program Files\Windows NT\HYPERTRM.EXE /d
C:\Documents and Settings\Administrator\Desktop\Turbine.ht", 1)

My.Computer.Keyboard.SendKeys("%(t)c", True)

Sleep(50)

My.Computer.Keyboard.SendKeys("C:\Documents and
Settings\Administrator\Desktop\testht.txt", True)

Sleep(50)

My.Computer.Keyboard.SendKeys("" & vbCr & vbCr & vbCr, True)

'reports version of firmware installed

My.Computer.Keyboard.SendKeys("V" & vbCr & vbCr & vbCr, True)

'configures device to have 2 analog outputs

My.Computer.Keyboard.SendKeys("C,3,255,0,2" & vbCr & vbCr & vbCr, True)

' starts to record data collected

'My.Computer.Keyboard.SendKeys("%TC" & vbCr, True)

' samples analog ports and reports data

My.Computer.Keyboard.SendKeys("A" & vbCr & vbCr & vbCr, True)

Sleep(50)

' samples digital ports and reports data

My.Computer.Keyboard.SendKeys("I" & vbCr & vbCr & vbCr, True)

Sleep(50)

'stops collection of data

My.Computer.Keyboard.SendKeys("%TCS" & vbCr & vbCr, True)

'Pass the file path and the file name to the StreamReader constructor.
```

```
objStreamReader = New StreamReader("C:\Documents and Settings\Administrator\Desktop\testht.txt")

'Read the first line of text.

strLine = objStreamReader.ReadLine

'Continue to read until you reach the end of the file.

Do While Not strLine Is Nothing

    'Write the line to the Console window.

    Console.WriteLine(strLine)

    If strLine.StartsWith("A") Then

        'gets voltage and current values in string form

        voltage = strLine.Substring(2, 4)

        current = strLine.Substring(7, 4)

    End If

    If strLine.StartsWith("I") Then

        'gets cycle value in string form

        cycles = strLine.Substring(6, 3)        'SCR 3 Read Status B not A

    End If

    'Read the next line.

    strLine = objStreamReader.ReadLine

Loop

'writes string to integers

voltageValue = Val(voltage)

currentValue = Val(current)

cyclesValue = Val(cycles)
```

```
'Close the file.

objStreamReader.Close()

'converts the values into strings

If voltageValue > 20 Then
   voltageOutput = voltageValue * 0.16235
Else
   voltageOutput = "0"
End If

currentOutput = (currentValue - 2048) * 10 / 1.43

cyclesOutput = cyclesValue

'adds comma and time to string so that it can be used in CSV file

voltageOutput = voltageOutput

currentOutput = currentOutput

cyclesOutput = cyclesOutput + "," + DateString + " " + TimeString

'WRITES THE CSV

'Pass the file path and the file name to the StreamWriter constructor.

objStreamWriter = File.AppendText("C:\Documents and
Settings\Administrator\Desktop\VCuCy.csv")     'SCR 4

'Write a line of text.

objStreamWriter.WriteLine(voltageOutput + "," + currentOutput + "," +
cyclesOutput)  ' SCR 1 all on one line

'Close the file.

objStreamWriter.Close()

File.Delete("C:\Documents and Settings\Administrator\Desktop\testht.txt") 'SCR
6 removed folder Turbine Test\ and added ht
File.Create("C:\Documents and Settings\Administrator\Desktop\testht.txt") 'SCR
6 removed folder Turbine Test\ and added ht
```

```
            Sleep(19800)
        Loop
    End Sub
End Module
```