

Aerodynamic Electrical Energy: Wind Turbines

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Abstract

Renewable resources such as wind, solar, and water, are important in energy production. This project was to design a wind turbine electricity generation system and gain an understanding of the engineering involved in producing electricity from the wind. Having observed the wind patterns on the campus of Utah State University, it was decided to obtain both a horizontal axis (HAWT) and a vertical axis wind turbine (VAWT) and mount them on the roof of the USU Dean F. Peterson, Jr. Engineering Laboratory Building. The outputs of both turbines were measured and compared. For the low wind conditions of Logan, Utah, the HAWT was found to be the most effective.

1.0 - Introduction

Wind turbine electricity generation is on the rise in the United States, as well as many other nations. The goal in the U.S. is to have 20% of electricity production come from wind turbines by the year 2030 ("20% Wind Energy by 2030 Increasing Wind Energy's Contribution to U.S. Electricity Supply." <http://www.osti.gov/bridge>. Department of Energy. July, 2008. December 7, 2011). Methods were studied for generating electricity with two different wind turbines, a three-blade horizontal axis wind turbine (HAWT) and an Eddy model vertical axis wind turbine (VAWT). Both turbines have a rated capacity of 600 W output. They will charge and maintain a bank of lead-acid batteries using 100-W incandescent light bulbs as loads.

1.1 - Project Overview

This systems engineering design project has been spread over two semesters. In the fall of 2011, a horizontal axis wind turbine was obtained and installed, and in the spring of 2012 semester a vertical axis wind turbine was obtained and set up. The overall goal of the project is to monitor the two different types of turbines and attempt to determine which is more efficient. The two turbines are located on the roof of the Engineering Lab building on the USU campus. To determine the best placement of the two turbines on the roof, the wind speed and direction were sampled using an existing weather station also located on the roof of the building. The data show that the highest wind speeds come from the East out of Logan Canyon between about midnight and 10:00 a.m.

The outputs of the two turbines are monitored by measuring both the line current and

the line-to-line voltage on the outputs. Therefore, the output electrical power is derived from a product of these measurements. The system also monitors and records the wind speed using an anemometer. The measurements are obtained using a National Instruments data acquisition device that sends data to LabVIEW for manipulation and visual display. Along with displaying measurement data in real-time, LabVIEW sends data to a MySQL database for storage. A webserver displays the MySQL data to display wind speed, wind direction, and power outputs on a webpage. The website can be viewed by entering <http://windturbine.ece.usu.edu> in a web browser.

1.1.1 - Vertical Axis Wind Turbine vs. Horizontal Axis Wind Turbine

In order to compare and contrast the two turbines were located in relative proximity to one another. However, to avoid the shielding effects of one turbine on another, they need to be spaced far enough apart. A rule of thumb is to place the turbines a distance of three rotor diameters apart in the crosswind direction. The configuration has the turbines placed approximately 20 feet from one another, which is far enough apart that shielding effects are avoided. The outputs of the two turbines are monitored separately and the monitored data is displayed on the webpage for comparison.

1.2 - Scope

This report will detail the design approach used, how the project was implemented, including component level schematics and specifics, and what the final results show.

2.0 - Design Approach

Using a top-down design approach, the system was design with the turbine itself. The VAWT was purchased from a supplier by the name of Solar Conduit. The HAWT was purchased through Lowe's Home Improvement Store. Once both turbines were acquired, the turbines were installed. The construction of the support towers were then designed. The next step was to design the software including capture, display, and transmit the measurements and metadata. The following sections present the overall system engineering requirements and the design of all the sub-components included in the system.

2.1 - System Requirements

The system requirements are as follows:

1. System shall employ a VAWT and a HAWT rated at 600 W each
2. Installation shall not be permanently mounted to or damage the roof
3. System must be safe
4. System shall have energy storage capability
5. Remote website shall include the following:
 1. Daily, Weekly, and Monthly power readouts

2. Wind speed history
3. Wind direction history
4. Visual webcam time-lapse frame of the wind turbines
6. Real-time system outputs shall include the following:
 1. Voltage
 2. Amperage
 3. Wind speed
 4. Wind direction

2.2 - Design Setup

The physical design and setup of the system can be broken into two parts: placement of the turbines and placement of the control components, including measuring devices.

2.2.1 - Roof layout

The data from the weather station concerning the wind speed and direction was collected and graphed for analysis. The wind direction results can be seen in Figure 1.

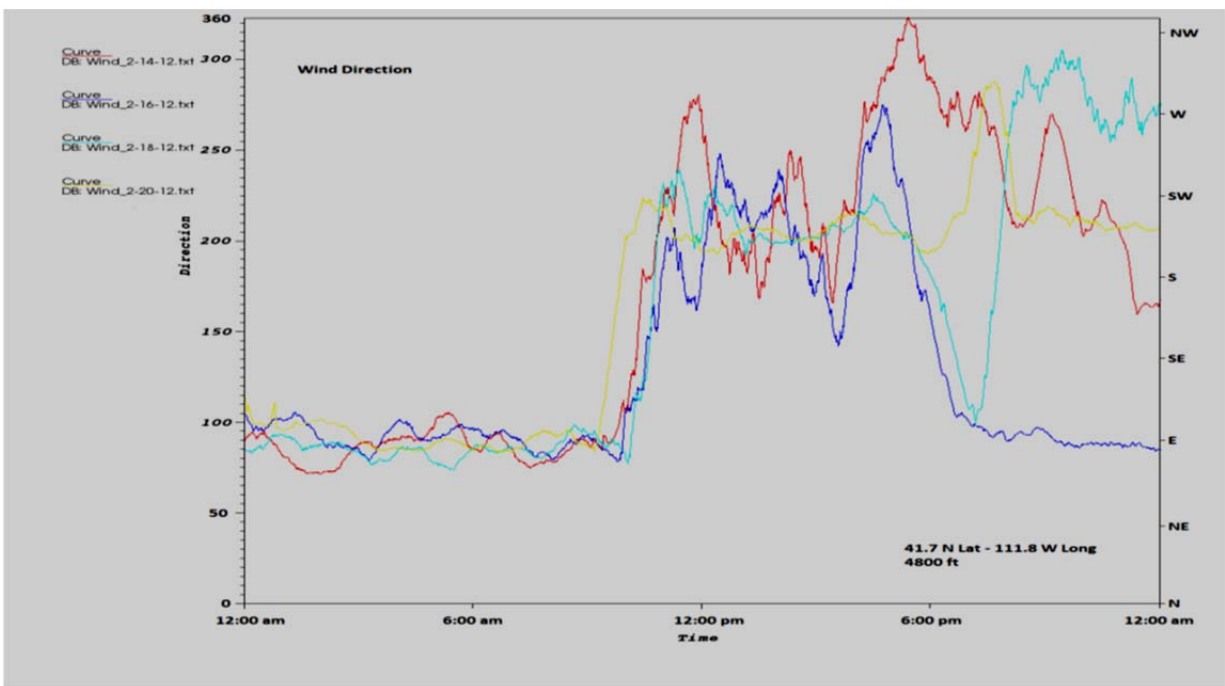


Figure 1: Wind direction over a four day period

The data from each of four days are laid out on top of each other to show the wind direction pattern. From the hours of about midnight to about 10:00 a.m., the wind blows in a steady easterly direction. Figure 2 shows the wind speeds from the same time period as the wind direction.

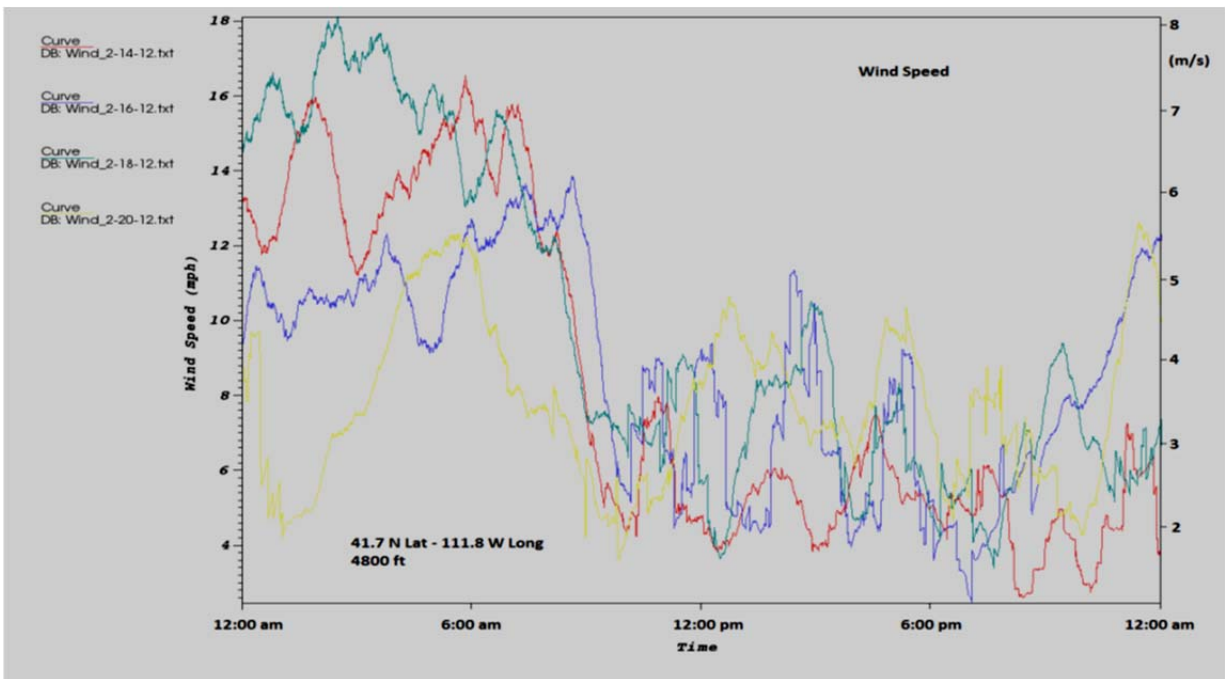


Figure 2: Wind speed over a four day period

Comparing the two graphs shows that when wind speeds are highest, the general direction of the wind is from the East. The wind direction in the afternoon hours is typically from the North. However, the sporadic nature of low wind speeds causes the direction sensor to produce a low signal to noise ratio.

Initial plans for the layout of the VAWT and the HAWT were determined by these data. The turbines were located on the east side of the roof with each turbine located north and south of one another in order to avoid shielding effects with the stronger and more consistent winds coming from the East. However, due to safety concerns with the VAWT, it was decided that it would be better to put it in the center of the roof. With the VAWT in the center, it is far enough away from the HAWT that shielding effects, if any, would be minimal. The layout of the roof is shown in Figure 3.

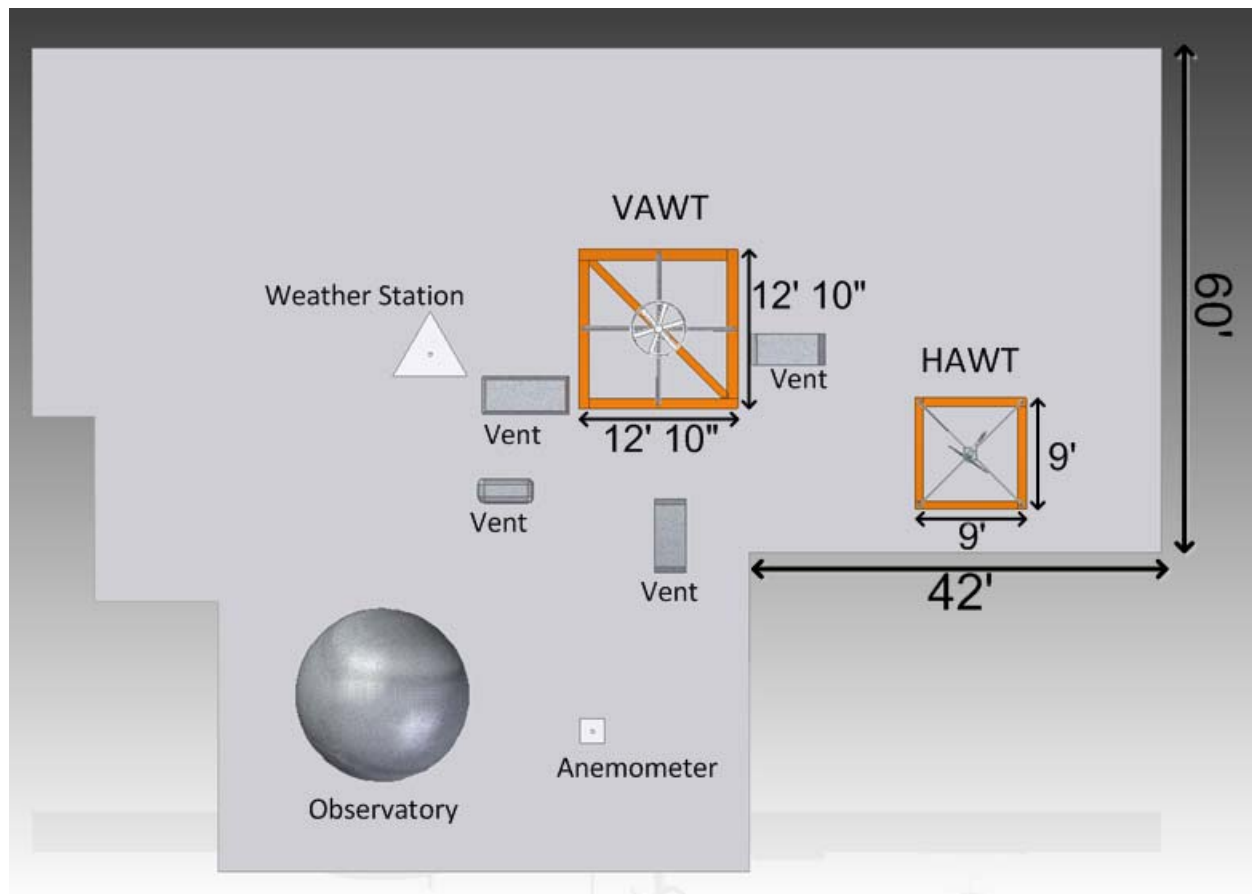


Figure 3: Roof Layout

2.2.2 - Controls layout

The output of the turbine's generators is three-phase power. The frequency of the current and voltage depends on the rotational velocity of the turbines. Variable-frequency AC is unsuitable for powering either AC or DC devices. Consequently, each turbine has a controller, supplied with the turbine, which rectifies the three-phase variable-frequency AC current and voltage into DC power. The VAWT controller supplies 24 VDC and the HAWT controller provides either 12 or 24 VDC depending on the energy storage system needs.

For the VAWT, if the energy storage system is fully charged and the turbine is producing power, any excess power that is not used is routed to a diversion load which dissipates the power as heat. For the HAWT, if the energy storage system is fully charged and the turbine is spinning, an automatic brake is engaged on the turbine which stops it from rotating to protect the battery from overcharging. This safety brake also protects the HAWT from mechanical damage induced by high winds.

All the controls are inside the laboratory building to facilitate ease of use and monitoring. Having the controls inside greatly reduces the need for personnel to be on the roof creating a safer environment.

2.3 - Design Solutions

The following section discusses the design specifications of the subsystems.

2.3.1 - Tower design

Many factors were considered in designing the tower for the VAWT. It had to support the 200-lb turbine that must stand with the midpoint of the turbine at 11 ft. The tower could not be physically attached to the roof, and it also needed to be cost effective. With 9 and 11-ft towers, the wind can exert a significant amount of torque. Therefore, 9 and 12-ft bases were designed with support arms connecting the bases to the poles on which the turbines are mounted. The CAD drawings in Figures 4 and 5 illustrate the designs.

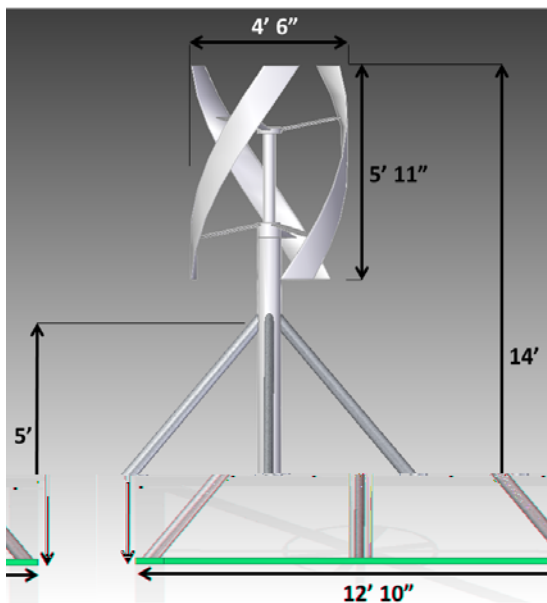


Figure 4: VAWT Tower Design

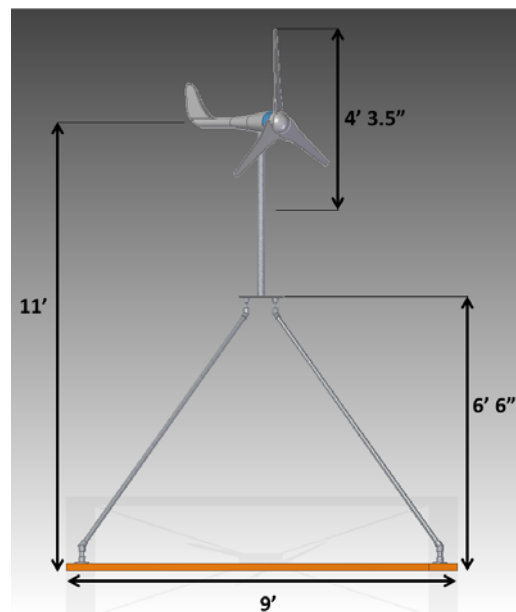


Figure 5: HAWT Tower Design

2.3.2 - Data acquisition and processing

A data acquisition device from National Instruments is used to collect data from the sensors. Two data loggers can accept both analog and digital inputs and connect to the computer via a standard USB interface. LabVIEW software is used on the computer to collect and process the data. LabVIEW allows many different types of interfaces and data outputs. Figure 6 shows the LabVIEW output data.

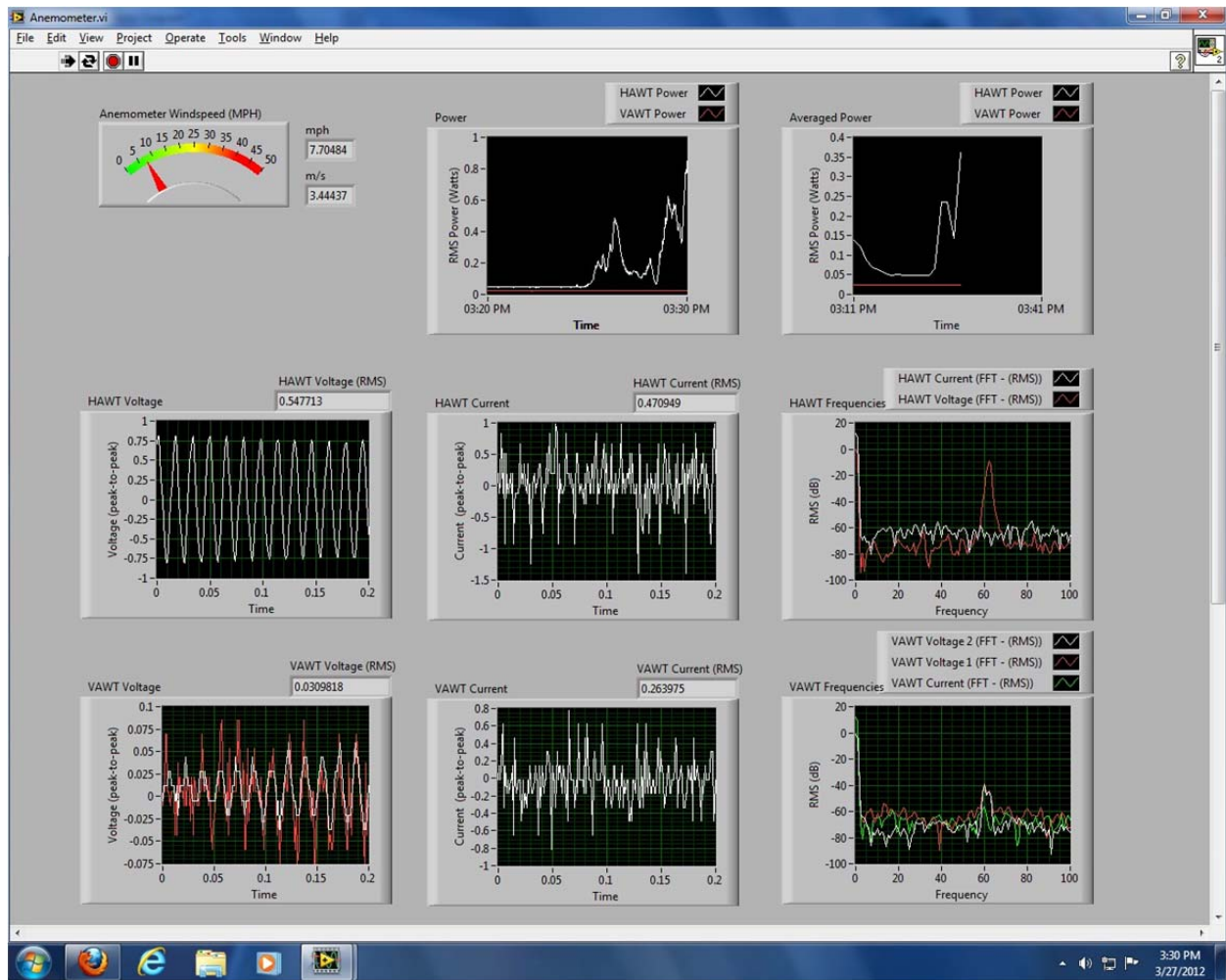


Figure 6: LabVIEW Virtual Instrument Panel

This interface is available locally on the computer, and is continually running and updating information in real-time.

2.3.2.1 - Wind speed

An anemometer is used to measure the wind speed in the approximate location of the turbines. The anemometer output is a variable-frequency signal which is sent to LabVIEW. The frequency of the signal is directly proportionate to the wind speed. The processed data are displayed locally on the computer as a visual gauge (Figure 7).

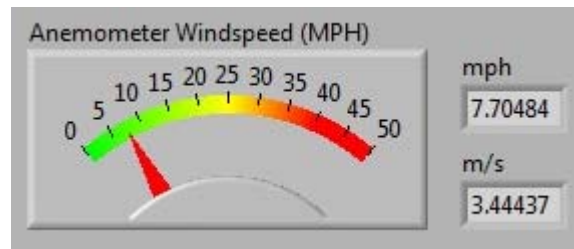


Figure 7: Wind Speed Dial

2.3.2.2 - Wind direction

A wind vane is used in a similar manner as the anemometer and information is displayed locally on the computer as shown in Figure 8. The wind vane uses a potentiometer like device that sends a signal to LabVIEW to be processed as a direction based on a 360 degree compass.

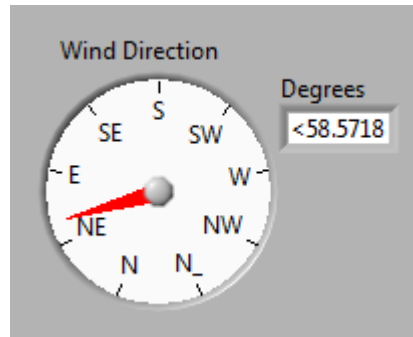


Figure 8: Wind Direction Dial

2.3.2.3 - Power

Measurements of the output electrical powers from the turbines as functions of wind speeds are the salient goals of this project. The Root-Mean-Square (RMS) current and voltage are measured from each turbine individually as AC signals with time-varying amplitude and frequency. To calculate actual average electrical power the RMS values of voltage and current need to be measured. LabVIEW has a processing block which uses the RMS value of the current and voltage and applies the appropriate algorithm to produce a measurement of the power. These results are shown on two charts shown in Figure 9.

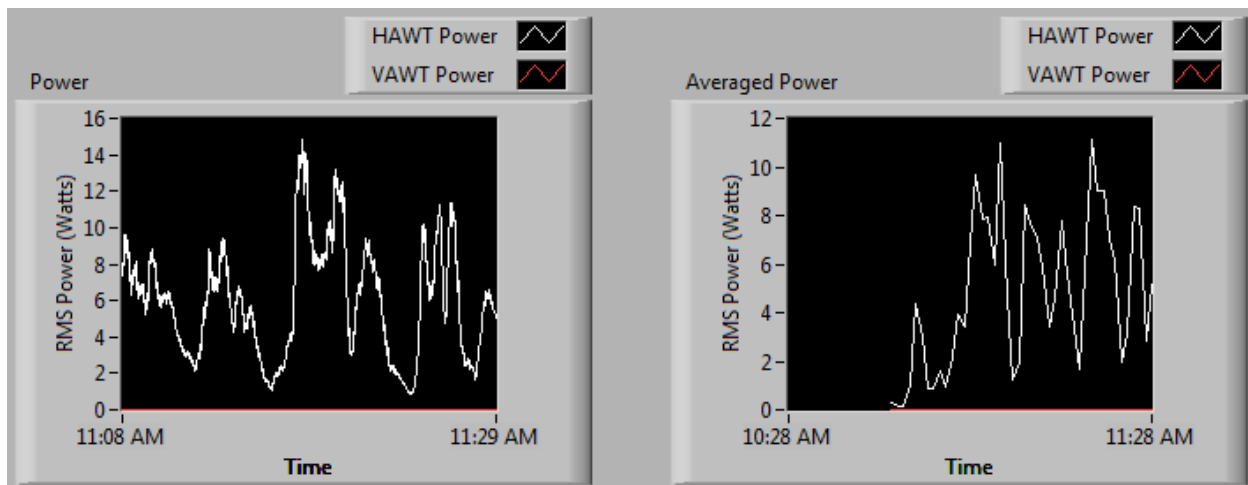


Figure 9: Power Output in Real-Time and Averaged results

The chart on the left shows outputs each second while the right-hand chart shows one-minute averaged outputs.

Total power from a three-phase AC generator is the sum of the power of each internal phase. Assuming a balanced system, the phases should all be equal in magnitude and contribute an equal amount of power to the overall system output. Each turbine generator is rated at 600 W. Therefore each internal phase winding would generate up to 200 W. The output power of the balanced three-phase generator is calculated using the following equation:

$$P = \sqrt{3} * V_{ll} * I_l$$

where V_{ll} is the output line-to-line voltage and I_l is the output line current.

2.3.2.4 - Current measurement

The current is measured for each turbine using a non-intrusive Hall Effect current sensor. The sensors are coupled to one of the three-phase lines coming from each turbine. The current sensor outputs a differential voltage. When the current is AC, the differential voltage reading is also AC. A simple linear equation is used to modify the differential voltage reading into a current measurement. The RMS current is calculated from the peak current measurements and is shown locally on the computer. Figure 10 shows the instrument which displays both the AC current and its corresponding RMS value of the VAWT.

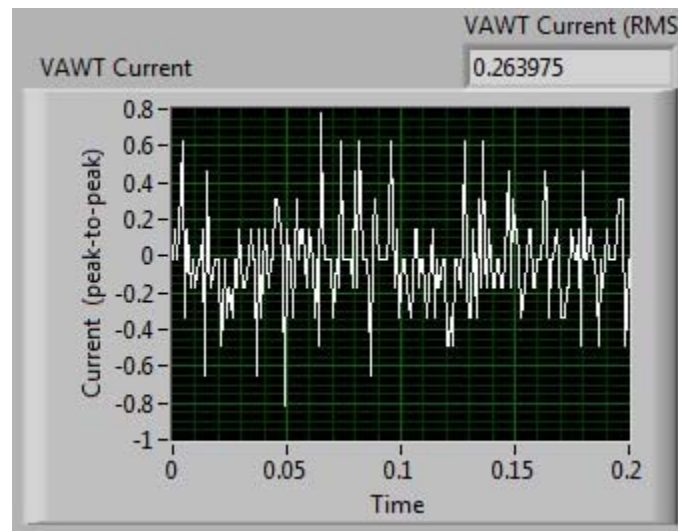


Figure 10: Peak-to-Peak and RMS Current of VAWT

2.3.2.5 - Voltage measurement

At maximum power output on the VAWT (600 W), a peak voltage of 25.5 V would be seen. Since the data logger can only accept a 10-V analog input, a voltage divider is used to step the voltage down to a maximum of just under 10 V when the turbine is running at full power capacity. Unlike the current measurement, the voltage is measured on all three phases. This is more than is needed to calculate the power in a single line. However, it provides a good indication of how well-balanced the lines are with respect to each other. Also, like the current measurement, a RMS voltage is calculated and used in the power calculation. Figure 11 shows the voltage output of the VAWT.

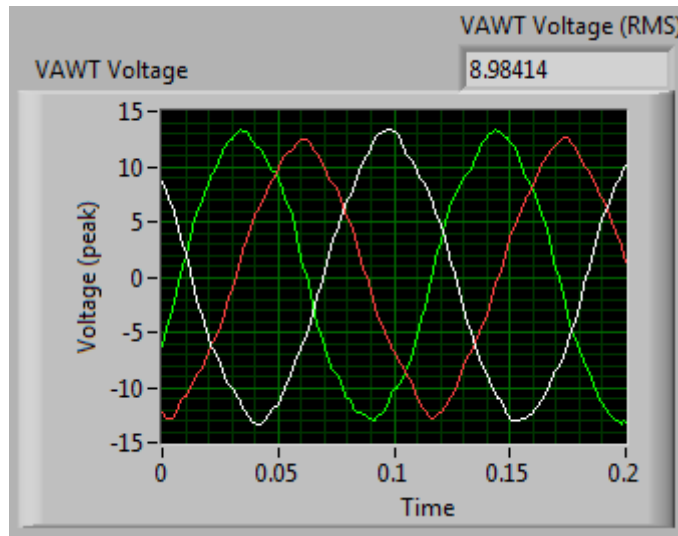


Figure 11: Peak-to-Peak Three-phase Voltages of VAWT

2.3.3 - Data transfer and display methods

The web server is setup using the Xampp web server system. This system can be installed on nearly any Windows computer, and provides Apache, PHP, MySQL, and FileZilla servers. The Apache server accepts website hits from the web, and delivers the web content. PHP is used to dynamically update content from the web database onto the website. MySQL is used as a free, fast, and efficient database program that is compatible with LabVIEW and PHP. The FileZilla server is useful for uploading pictures from the webcam to the web server.

WordPress was used for a quick graphical design layout. The WordPress Mantra theme suited the project requirement. The Exec-php plugin (by Soren Weber) can be used for executing PHP code scripts in the Wordpress pages. The data in the MySQL server can be displayed graphically using the JGGraph PHP graphing libraries. Figure 12 below illustrates the basic layout used for the website.

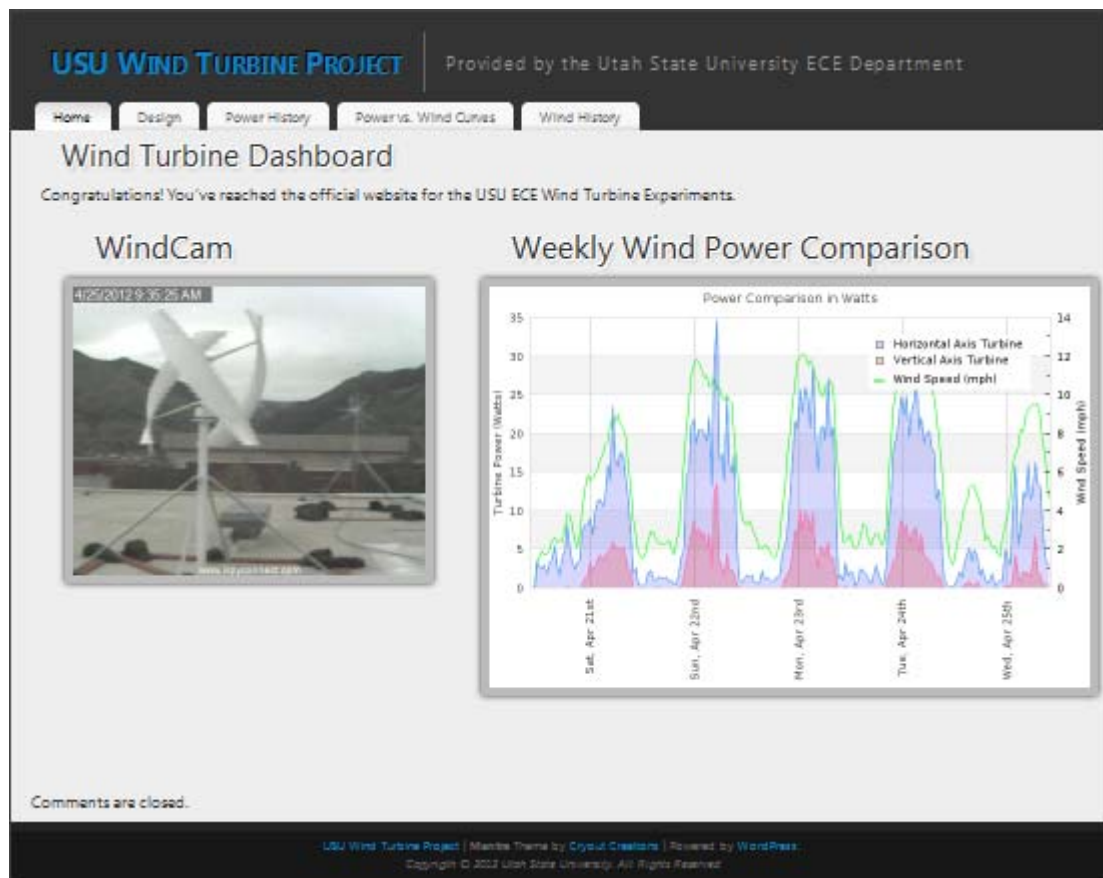


Figure 12: Webpage screenshot

Data in LabVIEW can be inserted into MySQL in the following manner. First, the data need to be down-sampled from the one-second sampling period to a five-minute sampling period. This helps avoid excessive network, storage, and computational overhead. Then, the data need to be converted to strings and concatenated into a MySQL insert statement, as shown in the left side of Figure 13. Finally, the insert statement can be sent to MySQL using the open source LabSQL modules, as shown in the right side of Figure 13. Care must be taken to ensure the data in the insert string are properly matched to appropriate table entries in the MySQL database. Also, a Microsoft ODBC connection needs to be setup one time to connect LabSQL to the database server.

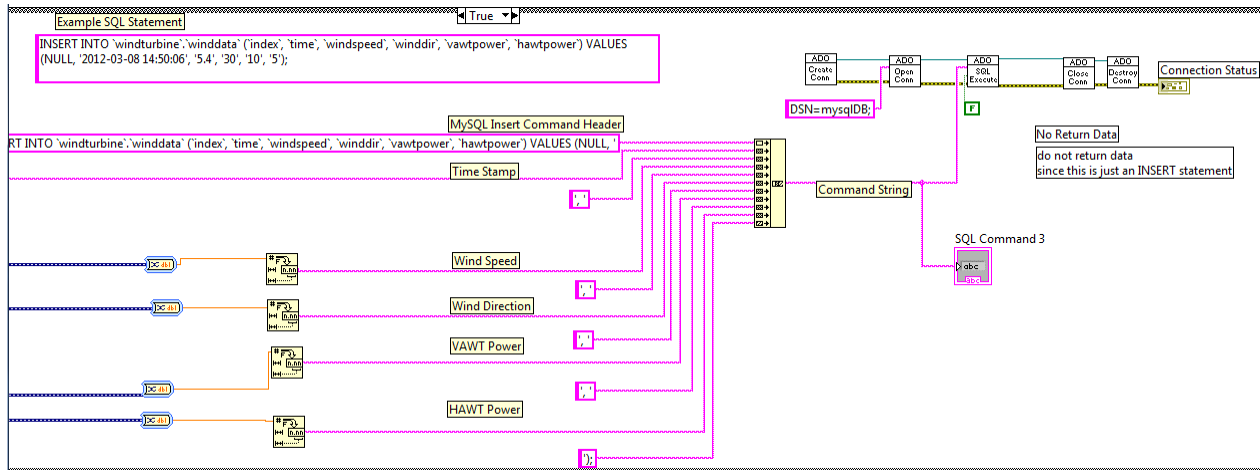


Figure 13: LabVIEW Implementation of LabSQL to Insert Data into MySQL Server

The final component of the main webpage is a webcam still image of the wind turbine. This allows users to see whether the turbine is spinning. This is accomplished by setting up an iSpy security camera system and linking the camera to an ftp server for uploading still image frames to the web server directory. Once this is accomplished, the website can refer to the image in the web directory using an image html tag.

2.4 - Component Level Specifications and Designs

The next section discusses the different devices used to monitor the outputs of the two turbines and the wind speed.

2.4.1 - Anemometer

The anemometer being using is an Inspeed Vortex three cup device. The rotor diameter of the anemometer is approximately five inches. Due to the small size, the anemometer cups do not begin to rotate until the wind reaches a velocity of about 3 mph. Below this speed the graph displays a noisy signal. The output of the anemometer is a pulse signal with the frequency being directly correlated to wind speed. To obtain the wind speed, the output frequency is multiplied by 2.5 mph. Figure 14 is the anemometer used.



Figure 14: Inspeed Vortex Anemometer

2.4.2 - Current measurement device

Electrical current through a conductor in a magnetic field causes a force that moves the electrons to one side of the conductor and also generates a transverse induced voltage. The result is a difference of charge between the two sides of the conductor. This voltage can be used as a measurement of the amplitude of the current along the conductor. This Hall Effect voltage is give by:

$$V_h = -IBned$$

where I is the current along the conductor, B is the magnetic field, d is the depth (thickness of the plate), e is the electron charge, and n is the charge carrier density of the carrier electrons. Note that with an alternating current, the output voltage from the Hall Effect sensor will be alternating as well. Figure 15 shows the Hall Effect device that is used.



© <http://measure-current.com>

Figure 15: Current Measurement Device

For this device, the current in a wire passed through the hole can be calculated from the measured voltage with the following formula:

$$I_{measured} = \frac{V_{measured} - 4}{0.032}$$

2.4.3 – Battery protection circuit

Lead acid batteries are used for electrical energy storage. They have certain levels past which they should not be charged or discharged. The controllers used with the wind turbines provide overcharge protection. The HAWT controller does not have undercharge protection. Consequently, a circuit was designed to prevent the battery connected to the HAWT from discharging too much. This was accomplished by comparing the battery voltage to a reference voltage. A simple approach is to compare the voltages by using a comparator circuit that controls a relay switch that turns the load on and off. Figure 16 shows the schematic diagram for the circuit.

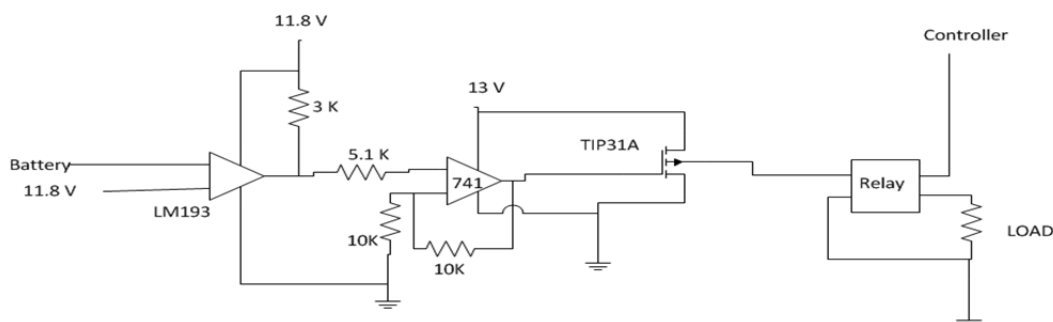


Figure 16: Battery Protection Circuit Diagram

The LM 193 is a silicon device similar to an op-amp that compares two voltages. If the voltage at the non-inverting input is greater than the voltage at the inverting input, the comparator will output a high voltage approximately equal to the reference voltage. If the inverting input is larger, the comparator will output zero voltage. The reference voltage is connected to the non-inverting input of the comparator, while the battery is connected to the inverting input. In this way, when the voltage across the batteries is too low, the comparator outputs a high voltage. This output is connected to an amplifying circuit that switches off a relay when the voltage is high.

2.4.4 Voltage measuring circuit for turbine output

The data logger can only handle inputs of about 10.5 V. The turbine voltages have been measured to have peak output voltages of up to 26 V. A voltage divider circuit is used to lower the measured voltages to no more than 10 V. Figure 17 shows the voltage divider circuits.

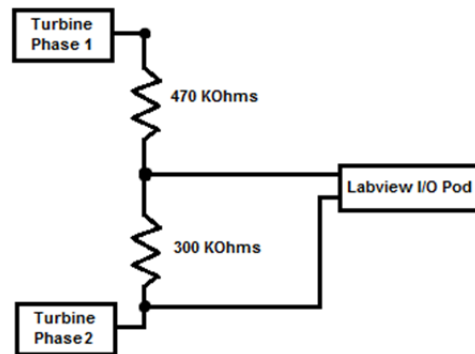


Figure 17: AC Voltage Divider

2.5 – VAWT and HAWT wiring diagrams

A block diagram of the complete electrical energy turbine system is given in Figure 18. The components mentioned above are used in the overall system.

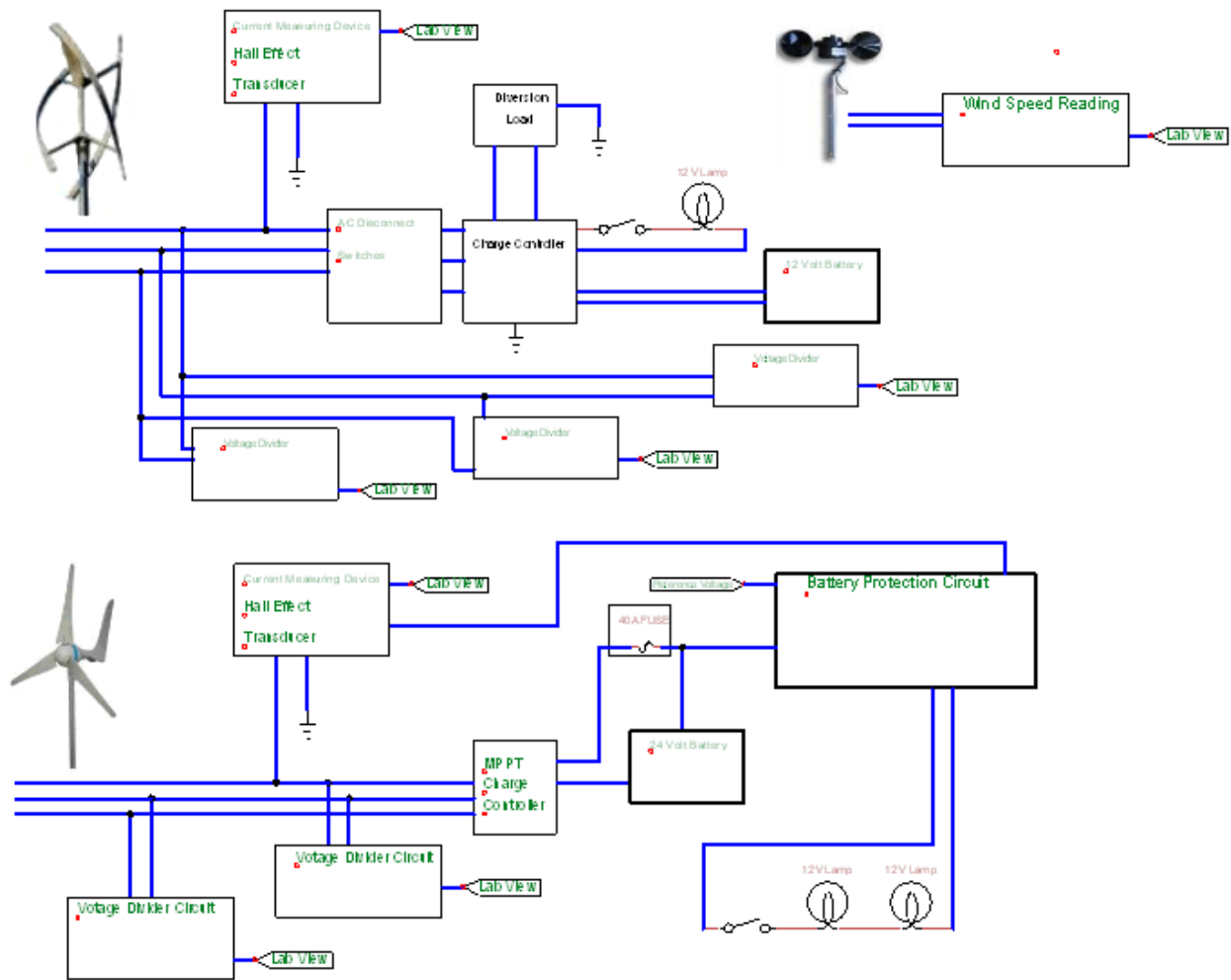


Figure 188: HAWT and VAWT Wiring Diagram

3.0 – Results and Conclusions

1. Wind speeds in Logan, Utah, are typically not conducive for wind turbine electrical energy production.
2. The HAWT performed better in the low wind conditions.
3. The cut-in wind speed of the HAWT was approximately 2 mph.
4. The cut-in wind speed of the VAWT was approximately 5 mph.
5. The rated 600-W cut-out capacity of neither turbine was achieved.
6. The daily average midnight to 10:00 a.m. wind speed was measured at about 12 mph.
7. The effectiveness of the data storage, recording, display, and dissemination of the wind power system based upon data logging hardware and software was effectively validated.
8. The roof mounting, towers, bases, and cabling was safe and robust.
9. The battery maintenance and protection circuitry performed effectively.
10. The webpage design is compact, easy to understand, and view from remote locations.

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