Embedded System for Wind Resource Evaluation

Damien C. Sommer, John J. Virga, and Dr. Darrin M. Hanna
Oakland University, dcsommer@oakland.edu, jjvirga@oakland.edu, dmhanna@oakland.edu

Abstract - **An embedded system for wind resource evaluation was designed to be inexpensive, reliable, accurate and easily usable for a land owner to evaluate their own property and present that information to a wind farm developer. Three anemometers and a thermistor circuit were used as input sensors. A prototyped printed circuit board for voltage regulation and analog-to-digital conversion directed signals into a field programmable gate array for processing. The wind data was sent every 2.25 seconds with a date and time stamp via a radio frequency transmission to a home computer. Power was provided by a rechargeable battery and a solar panel rated at 40 Watts. A home computer would then save the collected data in a tab-delimited file. The data was then condensed into 10-minute averages using a Visual Basic application in Excel. The 10-minute data files were then used by a second Visual Basic application to generate reports that clearly present the site's potential for wind energy development. The system was mounted on a 33 foot tower with anemometers at three different heights and implemented over a period of four weeks in Michigan fall conditions.**

Index Terms – wind resource evaluation, embedded system, anemometers, field programmable gate array.

INTRODUCTION

The wind energy industry added 8,500 megawatt of new generating capacity in the US for 2008, a 50 % increase in over 2007 [1]. With costs of $1.267 million per megawatt, wind farm developers require consistent wind resource data from a tract of land in order to make a business decision [2]. Increasingly, farmers or communities lease their land to a developer for the creation of a wind farm. With hopes of potential profits many land owners are interested in understanding their wind resource. However, current wind data logging equipment can cost several thousands of dollars and require advanced technical knowledge representing significant impediments to data collection. With this market in mind the authors set out to design and implement an embedded system that could be used by land owners for self evaluation of wind energy potential.

THEORY

I. Wind Power, Direction and Shear Exponent

The most optimal site for a wind farm requires an understanding of the power potential generated from the wind velocity, defined as:

$$P = 0.5\rho A v^3 \quad \text{(Watts)} \qquad (1)$$

Where ρ is the air density, ***A*** is the area swept by the turbine rotors and ***v*** is the velocity of the wind.

The air density of a site is affected by temperature and height above sea level. The elevation of a tract of land remains constant but the temperature values change daily and seasonally. Temperature data is also needed to understand the extent of cold weather conditions. Ice can change aerodynamic properties and jeopardize the balance of the spinning rotor, which could result in the control system not functioning properly [2]. Air density is calculated as:

$$\rho = (353.05/T)e\text{^}(-0.034(z/T)) \quad (\text{kg/m}^3) \qquad (2)$$

Where ***z*** is the height above sea level and ***T*** is the absolute temperature.

With power proportional to the cube of wind velocity it is the most important parameter to verify. Industry standards dictate wind speed measurements should be taken at 10 minute intervals [3]. Data entries should include average wind speed, standard deviation, minimum and maximum speeds.

Average direction is also recorded every 10 minutes. The face of the wind farm will be placed on the edge of the site where the wind blows most and all other turbines will be placed in relation to the leading edge [2].

Wind data is collected at 10, 25 and 40 meters for the evaluation of site potential [3]. The wind turbine may be placed higher than 40 meters so it is necessary to know the wind data at the height of the hub of the rotor. To do so, the vertical wind shear exponent, α, must be calculated from collected data at two different heights.

$$\alpha = [\log_{10}(v_2/v_1)] / [\log_{10}(z_2/z_1)] \quad \text{(no units)} \qquad (3)$$

Where $\mathbf{v_2}$ is the wind velocity at a higher elevation and $\mathbf{v_1}$ is the wind velocity at a lower elevation. The higher elevation is $\mathbf{z_2}$ and the lower elevation is $\mathbf{z_1}$. Table 1 provides a reference for typical wind shear exponents [4].

TABLE 1
TYPICAL WIND SHEAR EXPONENTS

Condition	Wind Shear Exponent
Water or Ice	0.1
Low Grass or Steppe	0.14
Rural with Obstacles	0.2
Woodlands	0.25

When the wind shear exponent of a site is known the wind velocity at any hub height can be calculated from observed data.

$$v_{hub} = v_{observed}(z_{hub} / z_{observed})^{\alpha} \quad \text{(m/s)} \qquad (4)$$

Where $\mathbf{v_{hub}}$ is the wind velocity at the elevation of the hub height of the turbine and $\mathbf{v_{observed}}$ is the wind velocity at the height $\mathbf{z_{observed}}$ and respectively the elevation $\mathbf{z_{hub}}$ is the height of the turbine.

II. Wind Power Density, Frequency Distribution and Power Curves

Wind power density, WPD, is a calculation of the average power generated from the wind blowing over an area without taking into account the area swept out by the rotor blades or the inefficiencies of the turbine system.

$$WPD = \frac{1}{2n}\sum_{i=1}^{n}(\rho_i)(V_i^3) \quad \text{(Watts/area)} \qquad (5)$$

WPD may help to give a rough idea of a site's potential but a more accurate calculation of energy production is necessary for development plans. Therefore, a frequency distribution of the wind speed data is needed to calculate energy production. The 10 minute averages should be used to create hourly averages and the hourly averages should then be input into a histogram to create the frequency distribution.

A wind energy system power curve represents the power output of the system at different wind speeds. Wind turbine systems extract little power at low speeds and ramp up to maximum conversion between 10-30 mph. They continue to operate at their maximum efficiency up to about 60 mph, at which point, the control system will stop the rotor to avoid structural damage. The power curve of a Vestas V66-1650 system is shown in Figure 1 [5].

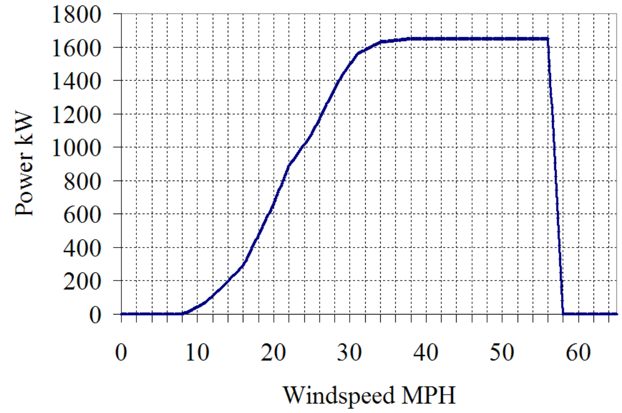

FIGURE 1
VESTAS V66-1650 POWER CURVE

III. Calculating Wind Power Production

With the power curve of the proposed wind turbine and the frequency distribution of the site known, power production can be calculated. The total number of hours that the wind blew at each particular wind speed is multiplied by the corresponding power output at that speed from the power curve. This method is then carried out for every observed wind speed and all the products are summed to give the total energy produced over a given time, Q.

$$Q_{calculated} = \sum_{i=1}^{n} Hours_{wind,i} Power_{wind,i} \quad \text{(Watts)} \qquad (6)$$

DESIGN

As shown in Figure 2, input sensors fed wind data to an input PCB that also regulated power. Sensor signals were serially transmitted to an FPGA for processing and wireless transmission to a home PC. Data was saved to file and later converted to summary reports by 2 VBA programs.

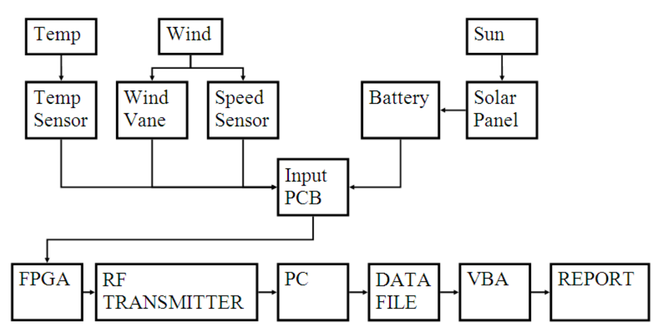

FIGURE 2
TOP LEVEL DESIGN

I. Input Sensors and PCB

Three Davis instruments anemometers 7911 were used for wind speed and direction sensors. The wind speed sensors contain a Hall Effect sensor on a stator and a small magnet on a three half cup rotor. Once per rotation when the magnet crosses over the Hall Effect sensor the output signal falls low. The instrument is calibrated so that the number of pulses observed over 2.25 seconds is equal to the wind speed in mph. Figure 2 illustrates an output signal over 13.5 seconds and a range of wind speeds.

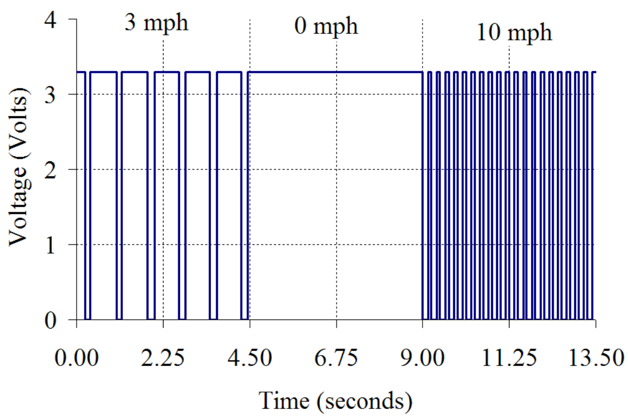

FIGURE 2
WIND SPEED SENSOR OUTPUT

The direction sensors consisted of a plastic wind vane attached to a 20 kΩ potentiometer. The potentiometer was set to 0 V and then the wind vane was attached facing north. Increased voltage readings signaled directional changes. For example, a 1.5 V reading out of 3.3 V applied showed 164 degrees from north.

$$(1.5 / 3.3) * 360 \text{ degrees} = 164 \text{ degrees}$$

A thermistor circuit was used for the collection of temperature data. A thermistor with a linearly changing resistance value from -40° C to 60° C was placed in series with a resistor that maintained a 10 kΩ value over the same temperature range. The two resistors created a voltage divider. The changing voltage of the resistor was fed into an amplifier for a gain and used to determine the ambient temperature.

With analog signals as outputs from the direction and temperature sensors it was necessary to create a circuit for conversion to digital signals and then serial transmission to the FPGA. The TLC0838I 8-bit analog-to-digital converter chip with serial control was used in the circuit design.

II. FPGA and VHDL Programming

A Digilent NEXYS 2 FPGA was programmed with VHDL for processing the sensor signals. Functions for setting time, setting date and viewing data were implemented as shown in Table 2

TABLE 2
FPGA BUTTON AND SWITCH FUNCTIONS

Description	Number	Function
Single Throw Switches	0	Set Hour / Minutes (0 - 24 Hr / 0 - 59 Min)
	1	Set Month / Day
	2	Set Year
	3	Display Direction 1 (0° - 360°)
	4	Display Direction 2 (0° - 360°)
	5	Display Direction 3 (0° - 360°)
	6, 7	3 Options for Switches 6 & 7
		Sw6 on, Sw7 off: Display Velocity 1 (mph)
		Sw6 off, Sw7 on: Display Velocity 2 (mph)
		Sw6 on, Sw7 on: Display Velocity 3 (mph)
Push Buttons	0	Increment Minutes / Days / Years
	1	Increment Hours / Months or Decrement Years
	2	N/A
	3	Reset Programming to default

As depicted in Figure 4 the velocity signals entered the FPGA through ports ja7, ja8 and ja9. These signals were concatenated into vector inVel(2:0). InVel and clk190 from module Clk1 were fed into module DbV3. DbV3 is a debounce module which ensures that falling edges from the signals are only counted once.

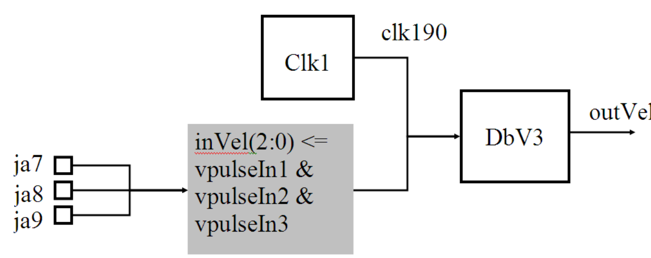

FIGURE 4
VHDL CODE FOR ANEMOMETER INPUT SIGNALS

Each of the components of the signal outVel(2:0) was sent to a counter module VEL1, VEL2 or VEL3 as depicted in Figure 5. Every falling edge from the output of the anemometer sensors incremented the counter by 1. The velocity counter added for 2.25 seconds until tout was sent high from CNT225. On the next clock pulse the velocity counters were cleared and velocity1(10:0), velocity2(10:0) and velocity3(10:0) were sent to registers VPREG1, VPREG2 and VPREG3. Register outputs were sent to modules BCD1, BCD2 and BCD3 where they were converted into 16-bit binary coded decimal numbers.

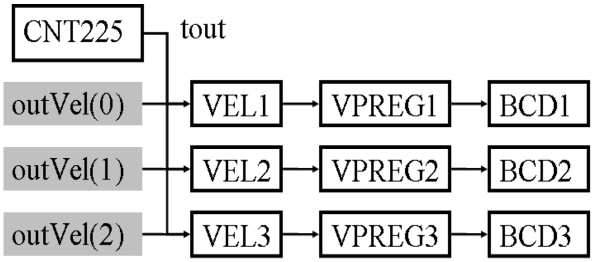

FIGURE 5
VELOCITY COUNTERS, REGISTERS AND BCD MODULES BLOCK DIAGRAM

The velocity signals were simultaneously sent to multiplexers txMX1 and sMux1 as depicted in Figure 6. Signals tVelocity1(15:0), tVelocity2(15:0) and tVelocity3(15:0) were all sent into sMUX1. The signal enSel(7:0) controlled the sMUX1 output and resulted from switch settings chosen by the user. The sMUX1 output was sent to module xSeg for conversion into a vector for showing wind speed on the 7-segment display of the FPGA. Signals vel81(7:0), vel82(7:0) and vel83(7:0) were sent to txMX1 where they were multiplexed to TX1 and TXCNT2 for transmission through the serial port. One clock pulse after all the data is available to the txMX1 the enable signal, tdreM, is set high which enables the data to be multiplexed to the serial transmission modules. Each channel of the MUX is stored in an 8 bit register in TX1, when the last bit has been sent out the MUX switches to the next value until all values have been sent.

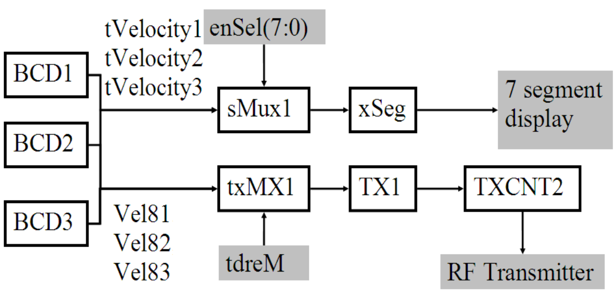

FIGURE 6
MULTIPLEXERS TO 7-SEGEMNT DISPLAY AND RF TRANSMITTER

The input signals from the A-D circuit were fed into the FPGA on port jb3 as shown in Figure 7. The signal was shifted one bit at a time into module ADC1 as SDATA1, then output as a 12 bit vector DATA1(11:0) to AdcCntrl1. AdcCntrl1 output that value to the correct register within the txMX1. After the value had been stored, ADC1 started converting the next analog value, until all temperature and directions were digitalized. ADCDI & nCS were outputs to the A-D chip which enabled the chip and selected the channel to be converted. When the input to the FPGA SARS (the status register of the A-D) went high then the current conversion was ready to be input serially to the FPGA. The output sCLK was a 250 kHz external clock for the A-D chip. The ADC modules began the conversion process when tout pulsed high.

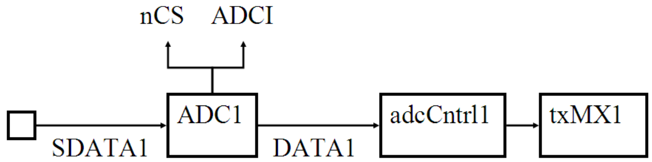

FIGURE 7
A-D CIRCUIT INPUT BLOCK DIAGRAM

The 12-bit values for the temperature sensor and 3 direction sensors were sent to modules for conversion into 16-bit BCD, stored in registers and multiplexed in the same method outlined in Figure 5.

The timing information set up by the user was continually updated by the module CLOCK1. The module kept track of minutes, hours, days, months and the year. The outputs were concatenated with the appropriate number of leading zeros for input into the multiplexers shown in Figure 5. This time stamp was sent out with every entry of data at 2.25 second intervals.

III. Power Source

While operating, the system consumed 148 mA from a VRLA rechargeable battery model HR9-12FR. The system would draw 3.55 Ah per day at that rate. Assuming a 15% safety factor, a solar panel producing 4.08 Ah per day was necessary. The system was placed in solar region E from Figure 10 [6]. Using the factors given in Table 4 it was calculated that a 40 Watt solar panel would provide sufficient power [6].

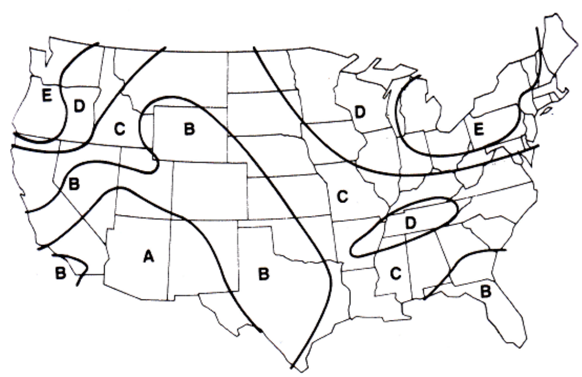

FIGURE 8
GEOGRAPHIC SOLAR REGIONS OF THE UNITED STATES

TABLE 3
SOLAR FACTORS FOR DIFFERENT REGIONS

Area A	Ah/day x 3.08 = Array Watts
Area B	Ah/day x 3.77 = Array Watts
Area C	Ah/day x 5.20 = Array Watts
Area D	Ah/day x 6.90 = Array Watts
Area E	Ah/day x 9.77 = Array Watts

IV. RF Transmission

The K173 serial transmitter operated at 433.92 MHz amplitude modulation. The transmission method was On-Off Keying (OOK) with a BAUD rate of 9600.

V. Tower Installation

Ideally, the anemometers would have been placed on a 40 meter tower far from obstacles. However, due to cost constraints a smaller 33 foot tower was constructed from 1 inch PVC pipe. Wind sensors were placed on 3 foot boom arms placed at 33, 23 and 8 foot heights. Due to limited options for site placement the tower was placed relatively close to a 30 foot tall house and trees. The house acted as a wind shield to the lower anemometers when the wind blew from most directions but left wind blowing into the top anemometer unobstructed. Therefore, the wind speed difference between the top and lower anemometers was exacerbated by local conditions resulting in abnormally large wind shear exponents. To compensate, a more realistic shear exponent of 0.2 was used in later calculations of hub wind speed and power production.

VI. Data Storage

When the data was received in the home computer it was stored as a tab-delimited file. Information was saved in the same row of the file until the sequence "11111111" was received. This was to ensure that all incoming data was input with its associated time and date stamp. A display window was also created for the home PC to view the data in real time.

VII. Data Analysis

This system generated an enormous amount of data, therefore, it was important to condense the information into manageable pieces and present it in a way that highlighted the important points as shown in Figure 9. The raw files of 2.25 second data were stored daily and input into the 10 minute calculator VBA. The 10 minute average values were to be saved together in one month intervals. When a full month of 10 minute data was collected it was processed by the monthly report generator VBA. Three shorter intervals of data were used because of system disruptions that left periods of uncollected information.

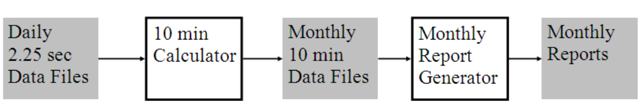

FIGURE 9
DATA ANALYSIS METHOD

The report generator created a summary page that displayed the observed shear constant, average wind speed at a theoretical 200 feet hub height, the WPD at 200 feet and the estimated power production of one turbine system at 200 feet. A power curve from a Vestas V66-1650 system was used in the energy production calculation. A wind shear exponent of 0.2 was used in the calculations rather than the observed wind shear exponent. The report also generated graphs of frequency distribution, WPD over time, wind speed at hub height over time and wind speed from the three sensors over time.

The report generator did not produce wind roses. Wind roses were created using a demo version of WaSP software.

VIII. Accuracy, Reliability, Usability and Cost

Sensor accuracy data is summarized in Table 5 along with two systems already sold in the market. The Nova Lynx is a complete system on the lower end of the price range. NRG Systems is a respected brand. Their equipment is expensive and considered highly accurate.

TABLE 4
SENSOR ACCURACY COMPARISON

System	Speed (mph)	Direction (%)	Temperature (°C)
OU Students	± 2	± 2	± 3
NovaLynx	± 1	± 3	± 0.8
NRG System	± 0.1	± 1	± 0.8

The sensor, FPGA and transmitter are manufactured to operate in a range of outdoor temperatures typical throughout the US. The wind speed sensors will safely operate in wind speeds up to 150 mph.

Usability of the system is appropriate for a resourceful individual without much background in wind resource evaluation. The user will have to find a suitable tower and can find instructions in Paul Gipe's Wind Energy Basics [4]. It was assumed that the end user was proficient in using Microsoft Excel and had a home computer. A user's manual was also created by the authors of this report to aide in implementing the system.

A cost analysis and production plan for 10 units was created. Each unit would cost $770.44 to produce with a target sale price of $1,500. A price comparison is shown in Figure 7. The system developed here would cost $2,000 less than one of the cheaper models on the market.

TABLE 5
COST COMPARISON

System	Cost
OU Students	$1,500.00
NovaLynx	$3,500.00
NRG Systems	$14,500.00

RESULTS

The system was operated from October 11, 2009 through November 11, 2009 in Southeastern Michigan, a period that included cold and stormy weather. There were two periods of lost data due to problems with the receiving laptop but there were no reliability issues with the sensors, transmitters or FPGA. On October 19 data stopped transmitting because the laptop automatically rebooted for software updates. The system was reinstated the next day with the laptop's internet card taken out. Data collection stopped on October 25 from a power outage resulting from a faulty power cord. The power outage was not noticed until October 30, 2009. The system was reinstated until November 11, 2009 when it had to be taken down because of objections from the local authorities.

TABLE 6
COLLECTED WIND DATA SUMMARY

Wind Data Type	10/11/09 - 10/19/09	10/20/09 - 10/25/09	10/30/09 - 11/11/09
Wind Shear Exponent (unitless)	0.94	0.39	0.38
Average Wind Speed at Hub (mph)	2.69	3.17	2.69
Wind Power Density (W/m^2)	53.72	73.12	67.1
Calculated Energy Production (kWh)	1579.79	1709.59	3728.54

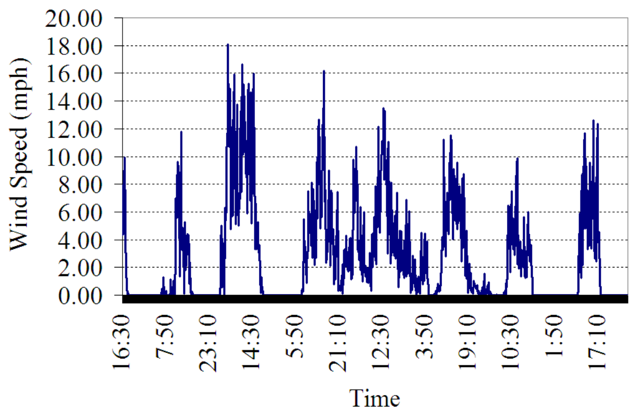

FIGURE 10
WIND SPEED AT 200 FOOT HUB HEIGHT 10/11/09 – 10/19/09

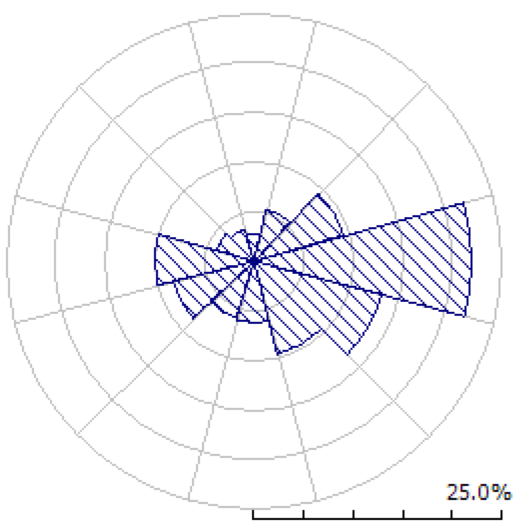

FIGURE 11
WIND ROSE 10/11/09 – 10/19/09

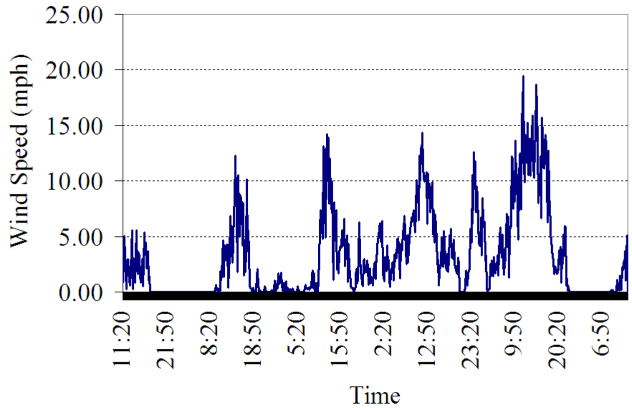

FIGURE 12
WIND SPEED AT 200 FOOT HUB HEIGHT 10/20/09 – 10/25/09

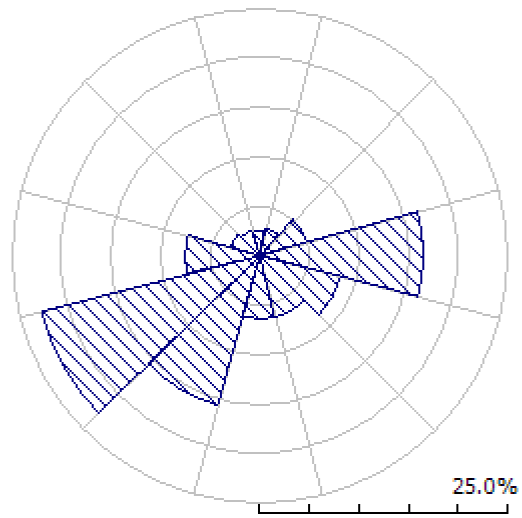

FIGURE 13
WIND ROSE 10/20/09 – 10/25/09

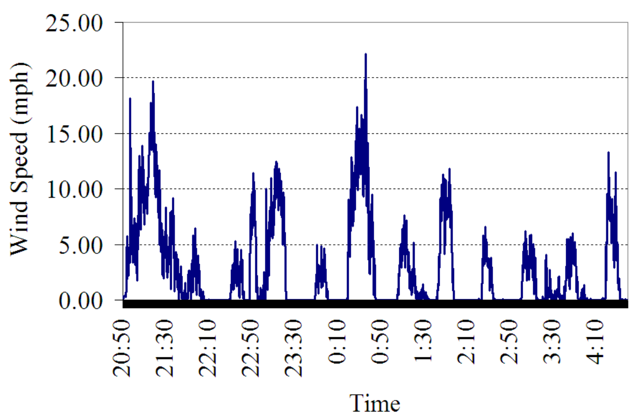

FIGURE 14
WIND SPEED AT 200 FOOT HUB HEIGHT 10/30/09 – 11/11/09

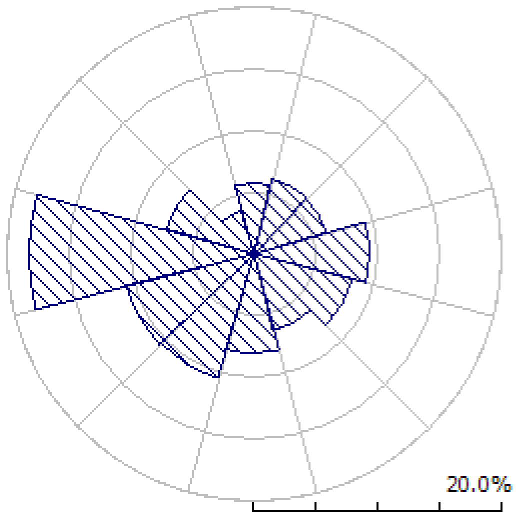

FIGURE 15
WIND ROSE 10/30/09 – 11/11/09

CONCLUSION

The system proved to meet its objectives of accuracy, reliability, usability and cost for a period of one month in Michigan fall conditions. Longer term reliability will need to be proven through more implementation. A taller tower and more desirable placement will be needed to verify that the system can identify realistic wind shear exponents.

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AUTHOR INFORMATION

Damien C. Sommer MSE Electrical and Computer Engineering, Oakland University, Rochester, MI, 48309, dcsommer@oakland.edu.

Damien Sommer received a BSE in Electrical Engineering from Oakland University in 2007 and then went on to complete a MSE in Electrical and Computer Engineering from Oakland University in 2009. Damien is currently a transmission planning engineer for the American Transmission Company in Pewaukee, Wisconsin. He has also held positions as a supplier quality engineer for Chrysler, data integrity engineer for DTE Energy and as a teaching assistant at Oakland University.

John J. Virga Computer Engineering, Oakland University, Rochester, MI, 48309, jjvirga@oakland.edu.

John J. Virga is currently enrolled in his last semester of undergraduate studies at Oakland University with intentions to immediately pursue his MSE in Computer and Electrical Engineering in the Fall of 2010. John is currently self employed with primary focus in developing hardware and software solutions. Recently he has been employed as an engineering technician for Malibu Technologies, INC. a contract engineering, design, and manufacturing company and a Network Operations Engineer for PowerStream, LLC an award winning content distribution network.