Cal Poly Wind Turbine Speed Controller

by

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I would also like to thank Dr. Shaban, Dr. Nafisi, Dr. Ahlgren, Dr. Derickson, and Dr. Slivovsky for enlightening me with important skills I needed for this project.
Abstract
This project addresses the speed control for a small fixed pitch variable speed non-grid connected permanent magnet wind turbine by regulating the electrical load with a DC chopper. A Programmable Logic Controller operates in one mode to track the optimum tip speed ratio, and the second mode limits the turbine to a safe operating speed. This project focuses on the design and implementation of a PLC speed controller.
I. Introduction
The Cal Poly Wind Power Research Center is currently developing and building a non-grid connected fixed pitch variable speed 3.5KW permanent magnet generator wind turbine. The goal of the project is to provide research and hands on learning for students interested in utility grade wind energy capture systems. Significant progress has been made towards a successful design, but various sub systems must be further developed before the wind turbine can be deployed in the field.

Wind data has been recorded and a site on the Cal Poly Escuela Ranch has been chosen for deployment. Construction of a 70ft tower is set to begin in the near future. In addition, the nacelle and turbine blades have been constructed, and a 3.5kW permanent magnet generator has been acquired. Last spring a team of Cal Poly mechanical engineering students developed an off-grid load bank and emergency speed controller, but this system must be improved for field deployment. An electrical engineering student also made a contribution to the project by developing a power electronics circuit to switch on and off a resistive load.

The goal of this project is to implement a PLC based speed controller to meet the needs of the Cal Poly wind turbine. The speed controller will provide the proper signals to actively regulate the output power so the turbine can operate at desired speed.
II. Background

Improvements in wind energy capture systems and a growing interest in renewable energy has sparked a new surge of wind turbine development. Installed wind generation in the United States is increasing each year, and in 2008 new wind projects accounted for 42% of newly installed power producing capacity in the U.S. (American Wind Energy Association Annual Wind Industry Report, 2009) One of the many challenges for a wind turbine design is the uncontrollable nature of the wind. There are many wind turbine designs but they all require some type of speed control. Speed control limits the turbine to rated operating conditions, and it also provides a way to adjust the power captured from the wind. A challenge for any wind turbine is to remain operational over a large range of wind speeds. The extractable power for a wind turbine is described by equation 1. $C_p$ is the power coefficient which incorporates the net losses, $\rho$ is the density of air, $A$ is area, and $V$ is the upstream air velocity. (W. Shepherd, 2008)

$$P = \frac{1}{2} C_p \rho AV^2 \quad (1)$$

The power coefficient is usually in the range of $0 \leq C_p \leq 0.4$ and depends on wind velocity $V$, turbine rotational velocity $\omega_r$, and blade design. The maximum power coefficient occurs at a specific tip speed ratio $\lambda$ described by equation 2. Where $r$ is the radius of the blades and $v_r$ is the velocity of the blade tip. Figure 1 shows a typical $C_p$ vs. $\lambda$ curve for a fixed pitch wind turbine.

$$\lambda = \frac{r \omega_r}{V} = \frac{v_r}{V} \quad (2)$$
For maximum energy capture the tip speed must correspond to the max power coefficient. Figure 2 is an example graph showing the power vs. rotational speed characteristics for various wind speeds intersecting the optimum tip speed ratio.

In addition to understanding the steady state characteristics of the wind turbine, it is also important to understand the basic dynamic characteristics of the synchronous generator. Equation 3 describes the accelerating torque experienced by the generator. \( J \) is the inertia of the generator and rotor, \( T_m \) is the mechanical torque supplied by the rotor, and \( T_e \) is the electrical torque. (A. E. Fitzgerald, 2003)

\[
J \frac{d\omega}{dt} = T_m - T_e \tag{3}
\]
During steady state operation at a given wind speed, the mechanical torque will equal the electrical torque and the turbine will rotate with constant speed. When the electrical torque is adjusted up or down, the speed will change, which causes mechanical torque to change.
III. Requirements

Mechanical System

The controller is designed with the following primary considerations:

- Wind turbine is variable speed, with fixed blade pitch
- Blade design produces passive stall at high wind speed (see appendix for actual $C_p$ vs. $\lambda$ curve)
- Turbine yaw is produced naturally from the tail fin
- Generator type is PMG, 3-phase, with full bridge rectifier
- The electrical system is isolated from utility connection and there is no useful load

There are two modes of operation to regulate the speed. The first operation mode controls the turbine when the wind is not sufficient to achieve rated power. This control mode regulates the speed to a desired tip speed ratio by adjusting the electrical power. When rated output power is achieved, the controller will operate in the second mode which regulates the turbine to rated speed. Figure 3 shows the modes of operation for this control scheme.

![Steady State Modes of Operation](image)

Figure 3 Steady State Modes of Operation
Electrical System
The electrical system requires the following basic requirements for the controller:

- Ability to perform PID
- Powered from DC power supply (24V)
- 2 analog inputs (wind speed, rotational speed)
- 1 analog or PWM output (for DC chopper, 0V – 5V, $f_{\text{MIN}} = 18\text{kHz}$)
- 2 digital inputs (E-stop, normal stop)
- 4 digital outputs (mechanical brake, battery charging switch, optional load relays)
IV. Design

Control System Layout

Figure 4 Basic Block Diagram Layout for speed control

Figure 4 shows the basic layout of the control system. The wind speed is measured from an anemometer, and the generator voltage is measured to determine the rotational speed of the rotor. The controller outputs a duty cycle to the DC chopper and the electrical power is adjusted by opening and closing a switch to a resistor bank. The average output power is described by equation 4.

\[
P_{\text{OUT}} = \frac{D \cdot V_{WIND}^2}{R_{\text{LOAD}}} \quad (4)
\]

This method of controlling the output power uses the available uncontrolled voltage from the generator. The generator voltage is a function of the rotational speed. Figure 5 shows how the rotational speed reference is established and figure 6 shows how the rotational speed is held to the reference signal.
The first function of the controller is to determine the speed reference signal as seen in figure 5. The speed reference is determined by the available wind speed, and the optimum tip speed ratio. The optimum tip speed ratio is a constant value that is predetermined by the mechanical characteristics of the wind turbine. If the rotational speed is measured below the maximum point, then the controller will operate in mode 1 to track the tip speed ratio. If the measured rotational speed reaches the nominal speed, then the controller operates in mode 2 with fixed rotational speed.

Figure 6 shows how the controller adjusts the duty cycle to keep the rotational speed fixed to the reference signal. \( n_r \) and \( n \) are compared at the summing junction and the error is sent to the PI equation. If the error is positive then the rotational speed is too fast and the duty cycle is increased. If the error is negative then the duty cycle is decreased so the speed can increase. The feed forward loop is used so the duty cycle can remain constant when the error signal is equal to 0.
Choosing a Controller
A commercially available PLC was chosen for the controller because it eliminates the need for bread board connections, and provides reliable operation in the field. A commercial PLC can be easily adapted to perform additional functions without having to modify hardware components. A commercial PLC will reduce hardware malfunction and provide reliable operation because commercial PLC’s are tested and certified to perform under harsh conditions.

The following list summarizes PLC advantages:

- Proven reliability under harsh conditions
- Screw type terminal block for secure wire connection
- Easy Programming which leads to more reliable operation
- Built in network compatibility
- Easily adaptable for data acquisition
- Commonly used in industry

Figure 7 Picture of Micrologix 1100 PLC
Based the technical requirements and the considerations in the previous sections, an Allen Bradley Micrologix 1100 1763-L16BBB controller was chosen. This controller meets the requirements for the electrical system control. This model is the most economical controller from Allen Bradley that has high speed analog inputs and in addition performs PWM, and PID control all within a self contained module.

<table>
<thead>
<tr>
<th>Cat. No.</th>
<th>Line Voltage</th>
<th>Number of Inputs</th>
<th>Number of Outputs</th>
<th>High Speed I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>1763-L1GAWA</td>
<td>120/240V AC</td>
<td>(10) 120V AC, (2) Analog Voltage</td>
<td>(6) Individually isolated Relay</td>
<td>None</td>
</tr>
<tr>
<td>1763-L16BWA</td>
<td>120/240V AC</td>
<td>(8) 24V DC, (4) Fast 24V DC, (2) Analog Voltage</td>
<td>(6) Individually isolated Relay</td>
<td>40 kHz input</td>
</tr>
<tr>
<td>1763-L16BBB</td>
<td>24V DC</td>
<td>(8) 24V DC, (1) Fast 24V DC, (2) Analog Voltage</td>
<td>(2) Individually isolated Relay</td>
<td>40 kHz output</td>
</tr>
<tr>
<td>1763-L16DWD</td>
<td>12…24V DC</td>
<td>(6) 12V DC/24V DC, (4) Fast 12V DC/24V DC, (2) Analog voltage</td>
<td>(6) Individually isolated Relay</td>
<td>40 kHz input</td>
</tr>
</tbody>
</table>

*Figure 8 Micrologix 1100 I/O configuration from AB.com*

The Allen Bradley Micrologix 1100 1763-L16BBB provides the following advantages:

- Fast analog input measurement (up to 40khz sampling)
- Built in PWM output (up to 20khz)
- PID Control
- Online editing allows programming changes while the system is operating
- LCD display provides a user friendly interface
- Embedded Web server for network compatibility

Programming any PLC in the Allen Bradley family can be accomplished with the free programming software from Rockwell Automation. RSLogix Micro provides a user friendly environment to create control logic while RSLinx Classic establishes the communication bridge between a PC and PLC. It is
relatively easy to perform programming adjustments with RSlogix because it is based on Visual Basic. The main programming instruction consists of logic rungs that execute sequentially. In addition to performing the requirements for this project, the Allen Bradley PLC can be easily adapted for data acquisition. More information on the Micrologix 1100 controller can be found on the Allen Bradley website: http://www.ab.com/programmablecontrol/plc/micrologix1100/
V. Development
During the development of this project a MATLAB Simulink simulation was performed to demonstrate the fundamental operation of the wind speed controller. A generic wind turbine and PMG model were used to show how load resistance is related to rotational speed for a given steady wind speed. The details of the test can be found in the appendix of this report. As seen in figure 22, each curve has a point when the rotational speed suddenly drops. This sudden drop occurs when the electrical power is greater than the mechanical power produced by the generator.

After the fundamental operation of the speed controller was verified, work began to program the controller. The first step was to establish communications with the PLC. The MicroLogix controller requires an Allen Bradley 1761-CBL-PM02 cable connected to a serial to USB converter for PC compatibility. Next, the AB_DF1-1 driver settings were configured with RSLinx as listed in table 1. If the PC is running on Windows 7 or Vista, Allen Bradley software must run in windows XP compatibility mode for proper operation.

<table>
<thead>
<tr>
<th>Table 1 AB_DF1-1 Driver Configuration in RSLinx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
</tr>
<tr>
<td>SLC-CHO/Micro/Panel/View</td>
</tr>
<tr>
<td>Baud Rate</td>
</tr>
<tr>
<td>19200</td>
</tr>
<tr>
<td>Station Number</td>
</tr>
<tr>
<td>00</td>
</tr>
<tr>
<td>Parity</td>
</tr>
<tr>
<td>None</td>
</tr>
<tr>
<td>Error Checking</td>
</tr>
<tr>
<td>CRC</td>
</tr>
<tr>
<td>Stop Bits</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>Protocol</td>
</tr>
<tr>
<td>Full Duplex</td>
</tr>
</tbody>
</table>
The structure of the program was designed with the block diagram of figure 6 in mind. The main program runs continually for 100ms until an interrupt occurs and the program jumps to the PID routine. Program details are listed in the appendix. The first 3 rungs of the main program define constants used later in the program (optimum tip speed ratio, PWM frequency, nominal rotational speed). The next instructions on rung 3 and 4 read analog input voltages representing wind speed (Vw) and rotational speed (n). Rung 5 starts the PWM signal. Rungs 6 and 7 determine the operation mode of the controller (mode 1, or 2) depending on the rotational speed input. If in mode 1, the rotational speed reference (n_R) is established by multiplying the optimum tip speed ratio with the wind speed input. If in mode 2, the speed reference is limited to the nominal speed (n_N).

This program required the use of timed interrupts for the PI instruction to execute at regular intervals. The Selectable Timed Interrupt function file was used to create automatic interrupts. After a specified time (100ms) the STI generates an interrupt which causes the main program to jump to the interrupt routine. PI computation is executed inside the interrupt routine to determine the new duty cycle. The PI instruction controls a closed loop to effectively hold a process variable at a desired set point. The set point is the rotational speed reference n_R. The process variable is the actual rotational speed n, and the control variable is the output duty cycle.
VI. Test Plans

This test demonstrates the speed controller’s ability to limit the wind turbine to a rated speed (mode 2), but does not test the controller’s ability to operate in tip speed tracking (mode 1) because the Power vs. Rotational speed characteristics of a typical wind turbine cannot be modeled with available equipment. A small scale PMG wind turbine with a non-regulated voltage output is required to perform the most accurate testing of the speed controller.

Background

This method uses a dc motor coupled to a synchronous generator to test how the speed controller stalls the turbine to limit rotational speed. The input power to the DC motor will be limited by fixing the input voltage and current. The DC generator is described by the following fundamental equation.

\[ e_a i_a = T_m w_m = K_d \Phi_d w_m \]

\[ T_m = \frac{e_a i_a}{w_m} \quad (6) \]

Eventually the field current to the DC motor will be reduced until the maximum speed threshold is detected by the controller. When this happens, the duty cycle will increase which causes the output power to increase for a short time while the motor transfers some of its kinetic energy to the load. This process causes the motor and generator to slow down.

A synchronous generator with a fixed DC field is used to model the PMG generator, and another synchronous generator with a fixed field is used as a tachometer to measure the rotational speed. The tachometer is connected to the shaft of the synchronous generator. A fixed high resistance load is
connected to the tachometer to produce a voltage proportional to the speed. The equation below shows how the terminal voltage is proportional to rotational speed of a synchronous generator.

\[ E_a = 4.44f k_w N \Phi \quad (7) \]

**Equipment**

DC Motor (EE #4216, 125V, 3.5A, 1/3 Hp 250W)

Three-Phase Synchronous Generator (EE #3403, 208V, 0.3A, 100W)

Three-Phase Synchronous Generator (EE #4221, 208V, 0.3A, 100W)

35 Ohm, 3.5A Bench resistors

Yokogawa Power Meter – EE#6232

3 Hampden Resistive Load Box

120VDC 3A Power Supply (able to limit max current)

Tri-Power Supply EE #0046

Fluke Multimeter

Fluke Instrument Calibration source meter

2 Full bridge rectifiers

Magtrol Dynamometer #4618
Circuit Diagrams

Figure 10 Power Circuit Test Configurations

Figure 11 AB MicroLogix 1763-L16BBB IO configurations
Procedure

**Part 1 Determine Speed vs Tachometer Voltage**

1. Construct the circuit of figure 15 and connect the controller as shown in figure 16 with the rotational speed sensor disconnected from the controller. Note the PWM signal is scaled down from 24V to 5V with the use of a voltage divider circuit.

2. For details about the connection of the DC chopper Refer to “DC Chopper for Electronic Speed Control of a Small Off Grid Wind Turbine” (pg. 29) senior project by Theda Silver-Pell.

3. Connect a dc power supply to the wind speed input Vw (0-10VDC max).

4. Operate the speed controller in manual by downloading the manual program to the PLC.

5. Record data by maintaining constant SG field, and constant duty cycle, while adjusting the field current to the DC generator.

6. Repeat step 6 with different duty cycle by changing the voltage to the wind speed input.

7. Analyze the data from part 1 to determine if a linear relationship can be used to represent the rotational speed.

**Part 2 Closed loop non-limited input power**

8. Connect the rotational speed input to the PLC as shown in figure 15.

9. Download the automatic program to the controller. Set the nominal rotational speed by adjusting the voltage to the wind speed input.

   Note: With the tip speed ratio set to 1, the magnitude of the wind speed input is equivalent to the rotational speed set point.

10. Verify duty cycle increases to $D_{\text{MAX}}$ when rotational speed is too fast.

11. Verify duty cycle decreases to $D_{\text{MIN}}$ when rotational speed is too slow.
Part 3 Closed loop test with DC motor input power limited

12. Set a current limit of 2A on the DC power supply connected to the DC motor.

13. Adjust the reference speed by adjusting the wind speed input voltage.

14. Decrease the field current to the DC generator to increase the rotational speed.
VII. Test Results

**Speed Vs. Tachometer Voltage**

![Graph of Speed Vs. Tachometer Voltage](image)

**Figure 12 Part 1 Experimental Speed vs. Tachometer Voltage**

**Table 2 Experimental Data Part 1**

<table>
<thead>
<tr>
<th>Measured Speed (rpm)</th>
<th>Measured Tachometer (V)</th>
<th>Linear Trend Line (V)</th>
<th>Voltage Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1483</td>
<td>7.40</td>
<td>7.47</td>
<td>0.97%</td>
</tr>
<tr>
<td>1496</td>
<td>7.50</td>
<td>7.54</td>
<td>0.48%</td>
</tr>
<tr>
<td>1508</td>
<td>7.60</td>
<td>7.60</td>
<td>0.06%</td>
</tr>
<tr>
<td>1550</td>
<td>7.80</td>
<td>7.80</td>
<td>0.01%</td>
</tr>
<tr>
<td>1599</td>
<td>8.00</td>
<td>8.04</td>
<td>0.51%</td>
</tr>
<tr>
<td>1601</td>
<td>8.00</td>
<td>8.05</td>
<td>0.63%</td>
</tr>
<tr>
<td>1612</td>
<td>8.10</td>
<td>8.10</td>
<td>0.06%</td>
</tr>
<tr>
<td>1652</td>
<td>8.30</td>
<td>8.30</td>
<td>0.01%</td>
</tr>
<tr>
<td>1692</td>
<td>8.40</td>
<td>8.50</td>
<td>1.14%</td>
</tr>
<tr>
<td>1700</td>
<td>8.50</td>
<td>8.54</td>
<td>0.42%</td>
</tr>
<tr>
<td>1709</td>
<td>8.60</td>
<td>8.58</td>
<td>0.23%</td>
</tr>
<tr>
<td>1765</td>
<td>8.90</td>
<td>8.85</td>
<td>0.51%</td>
</tr>
<tr>
<td>1791</td>
<td>8.90</td>
<td>8.98</td>
<td>0.91%</td>
</tr>
<tr>
<td>1806</td>
<td>9.00</td>
<td>9.06</td>
<td>0.61%</td>
</tr>
<tr>
<td>1810</td>
<td>9.20</td>
<td>9.07</td>
<td>1.38%</td>
</tr>
<tr>
<td>1850</td>
<td>9.30</td>
<td>9.27</td>
<td>0.31%</td>
</tr>
<tr>
<td>1881</td>
<td>9.30</td>
<td>9.42</td>
<td>1.30%</td>
</tr>
<tr>
<td>1890</td>
<td>9.40</td>
<td>9.47</td>
<td>0.71%</td>
</tr>
<tr>
<td>1909</td>
<td>9.50</td>
<td>9.56</td>
<td>0.63%</td>
</tr>
</tbody>
</table>
After recording the speed and voltage from the tachometer, a linear trend line was fit to the data. The linear trend line voltage in table 2 was determined with the linear trend line voltage equation. The tachometer produces an average voltage that is roughly proportional to the rotational speed. The voltage error is calculated in the last column of table 2.

![Speed vs. DC Motor Field](image)

The Speed vs. DC Motor Field graphs shows how the speed controller operates in mode 2 to limit maximum rotational speed. This test was performed by first setting a current limit on the DC power supply to limit the maximum available power to the DC generator. The separately excited field current to the DC motor was initially set at a high value so the motor was fixed at a slow operating speed. Next, the speed reference voltage was sent to the controller corresponding to the rotational speed set point. The set points were arbitrarily selected as 1590rpm, 1692rpm, and 1795rpm for three separate tests. As seen in table 4, when the DC motor is held to a low speed, the speed controller responds properly by decreasing the duty cycle and reducing the load in an attempt to allow the DC motor to speed up. The
DC motor is not capable of speeding up because the high DC field current and the inherent losses of the system create a maximum controllable speed that is impossible to regulate for the given DC motor field and power losses. To better explain how losses limit the controller’s range of speed regulation, it is useful to look at the speed voltage of a DC motor.

\[ e_a = V_T - i_a R_a \]
\[ P_{DC} = V_T i_a \]
\[ e_a = K_a \Phi_d \omega_m \]

\( \omega_m \) is proportional to \( n \), and the \( \Phi_d \) is proportional to the field current \( i_f \). Increasing power causes \( i_a \) to increase, which causes \( e_a \) to decrease, and as \( e_a \) decreases, the speed must decrease as well. If the machines were ideal and lossless, the input power to the DC motor would equal \( P_{OUT} \) from the synchronous generator. However, the system is not lossless so there is always power being supplied to the losses. The maximum controllable speed is determined by combining the three equations above.

\[ \omega_{MAX} = \left( \frac{V_T - \frac{P_{LOSS}}{V_T} R_a}{K_a \Phi_d} \right) \]

\( \omega_{MAX} \) occurs when all machines are operating at the lightest loads. At this speed the controller has reduced the output power to the minimum value and it can do nothing more to increase the rotational speed. Referring to figure 13, when the field current is decreased, the rotational speed increases, and \( \omega_{MAX} \) slowly decreases. When \( \omega_{MAX} = \omega_m \) the speed controller can finally do its job and regulate the speed. The linear non-speed regulated trend line shows how the speed would increase if the controller was not used.
### Table 3 Data Part 3

<table>
<thead>
<tr>
<th>IFDC (A)</th>
<th>Speed</th>
<th>nr (V) Setpoint = 1795rpm</th>
<th>n (V)</th>
<th>P SG (w)</th>
<th>Idc (A)</th>
<th>Duty (%)</th>
<th>Speed Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.54</td>
<td>1525</td>
<td>9</td>
<td>7.5</td>
<td>2.3</td>
<td>1.54</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>0.47</td>
<td>1612</td>
<td>9</td>
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<td>1.46</td>
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</tr>
<tr>
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<td>1650</td>
<td>9</td>
<td>8.1</td>
<td>2.6</td>
<td>1.44</td>
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<tr>
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<td>1711</td>
<td>9</td>
<td>8.4</td>
<td>2.8</td>
<td>1.42</td>
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<tr>
<td>0.37</td>
<td>1763</td>
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<td>8.6</td>
<td>3</td>
<td>1.41</td>
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<tr>
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<td>1793</td>
<td>9</td>
<td>8.9</td>
<td>3.1</td>
<td>1.42</td>
<td>2</td>
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</tr>
<tr>
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<td>1806</td>
<td>9</td>
<td>8.9</td>
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<td>2.04</td>
<td>na</td>
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</tr>
</tbody>
</table>

<table>
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<th>IFDC (A)</th>
<th>Speed</th>
<th>nr (V) Setpoint = 1590rpm</th>
<th>n (V)</th>
<th>P SG (w)</th>
<th>Idc (A)</th>
<th>Duty (%)</th>
<th>Speed Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55</td>
<td>1535</td>
<td>8</td>
<td>7.6</td>
<td>2.3</td>
<td>1.52</td>
<td>2</td>
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<td>1601</td>
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<td>7.9</td>
<td>2.4</td>
<td>1.46</td>
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<td>0.65%</td>
</tr>
<tr>
<td>0.46</td>
<td>1601</td>
<td>8</td>
<td>8</td>
<td>na</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>1622</td>
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<td>2.06</td>
<td>na</td>
<td>2.41%</td>
</tr>
<tr>
<td>0.31</td>
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<td>8.1</td>
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<td>na</td>
<td>2.41%</td>
</tr>
<tr>
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</tr>
</tbody>
</table>

<table>
<thead>
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<th>n (V)</th>
<th>P SG (w)</th>
<th>Idc (A)</th>
<th>Duty (%)</th>
<th>Speed Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.57</td>
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<tr>
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<td>1571</td>
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<td>2.3</td>
<td>1.48</td>
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<tr>
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<tr>
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<td>1.41</td>
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</tr>
<tr>
<td>0.43</td>
<td>1713</td>
<td>8.5</td>
<td>8.5</td>
<td>2.8</td>
<td>1.41</td>
<td>2</td>
<td>1.20%</td>
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<tr>
<td>0.4</td>
<td>1738</td>
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<td>1.89</td>
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<tr>
<td>0.36</td>
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<td>2.21%</td>
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<tr>
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<td>1.96</td>
<td>na</td>
<td>2.50%</td>
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<tr>
<td>0.29</td>
<td>1735</td>
<td>8.5</td>
<td>8.5</td>
<td>na</td>
<td>1.96</td>
<td>na</td>
<td>2.50%</td>
</tr>
</tbody>
</table>

The experimental data for part 3 shows how speed is held to a desired set point after $w_{MAX} \leq w_R$. When the controller regulates the speed the power begins to oscillate faster than the metering devices can record. The duty cycle on the oscilloscope was changing rapidly between $D_{MAX}$ and $D_{MIN}$. This was an indication that the gain of the PI controller was set too high and causing oscillations.
The speed error is calculated as follows:

\[ \text{Speed Error} \% = \frac{n_r - n}{n_r} \times 100 \]

The data of part 2 in table 4 shows how the controller operates in open loop mode. When the speed is too slow the duty cycle decreases to reduce the load. When the rotational speed is too fast, the duty cycle increases to the maximum value. It is important to note that max and min duty cycles are 98% and 2% respectively. These values were programmed as the limits based on the requirements for the DC chopper. The set points in table 4 are outside the controllable range because the duty cycle is adjusted to the maximum and minimum values.

<table>
<thead>
<tr>
<th>set point nr (V)</th>
<th>n (V)</th>
<th>Duty Cycle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>7.8</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>8.7</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>8.5</td>
<td>98</td>
</tr>
<tr>
<td>8</td>
<td>8.2</td>
<td>98</td>
</tr>
</tbody>
</table>

The results of this test show how the speed controller can regulate the speed when the machines have the proper field current applied. This test could be improved by increasing the field current which would cause the torque to change by a larger amount when the current changes.

\[ T_m = K_a \Phi_d i_a \]
VIII. Conclusion

After completing the test, the gain of the PI was determined to be too large because it caused oscillations in the motor and generator. In the future it would be useful to tune the proportional integral gain using the Ziegler Nichols method described in the appendix. PI gain can also be determined with the use of computer simulation after the mechanical system has been fully characterized. A dynamic study of the wind turbine system would be highly useful for future development.

Another improvement to this project is developing a more straightforward method to test the speed controller. If a DC motor and synchronous generator are used in a future test, it would be very important to determine the range of possible speed control before the test began. For a given field current, the full load and no load speeds could be determined and then the controller could be adjusted to operate within that range. The test I performed did not initially account for the limited range of possible speed control and the results are somewhat misleading without a thorough explanation. An improved test setup would also include measuring the transient response of the controller by triggering off the input speed reference signal. Analyzing the transient response could verify the proper PI gain settings.

For field deployment, it is recommended that a pulse counter be used for the rotational speed measurement. Although this project did not interface with an anemometer, it should be noted that various anemometer configurations are used to produce the most desirable wind speed measurement. Some utility grade wind turbines use arrays of anemometers to predict changes in wind speed before the change occurs at the blades.

In the future the PLC can be adapted to meet additional safety and operation needs. Some of the safeties include high wind speed shut down, manual shut down, and mechanical brake control. It will
also be important to monitor and benchmark the wind turbine. The PLC can be adapted for data acquisition with the use of the embedded web server.

The electrical system of the wind turbine should be upgraded to extract useful power from the wind turbine. Possible power electronics devices to obtain this goal include phase controlled rectifiers, DC-DC voltage regulators and inverters. When designing these devices it would be beneficial to use a common control voltage in order to simplify the power system. The DC chopper used with this project requires 15V and 5V, and the PLC requires 24V. If the wind turbine is deployed in the field as an isolated power source, a small battery circuit must be developed to provide control voltage when the turbine is not producing electricity.
IX. Works Cited


Appendices

A. Speed Controller Steady State MATLAB Simulink Simulation

**Objective:**

The objective of this simulation is to demonstrate the fundamental operation of the wind turbine speed controller.

**List of Equipment:**

- MATLAB 7.6.0.324 (R2008a) with Simulink
- SimPowerSystems Library

**Circuit Diagrams:**

![Figure 14 Steady state Simulink Model](image)

Figure 14 Steady state Simulink Model
Procedure:

1. Construct the circuit of figure 19 using the following blocks from SimPowerSystems Library:
   a. Wind Turbine
   b. Permanent Magnet Generator
   c. Three phase series RLC branch

2. Configure the Wind Turbine as seen in the figure below.
3. The next step is to configure the Permanent Magnet generator. This model was chosen from the configuration list. It is a generic PMG generator designed to operate at 2300RPM.
When connecting the PMG to the wind turbine it is important to properly adjust the magnitude of the generator speed so to be in pu for the wind turbine block. The generator speed signal going into the wind turbine is scaled by $1/w$. In order to do this, the synchronous speed of the generator was found from the $n_s = 2300\text{rpm}$ and $P=4$ as follows:

$$n_s = \frac{120}{p} f_e \quad (\text{eq1})$$

$$f_e = \frac{w}{2\pi} \quad (\text{eq2})$$

$$w = 478\,\text{rad/s}$$

4. The PMG also requires a torque gain to operate properly. From the model information it was determined that a gain of $10\text{Nm}$ was desired for the proper operation of the PMG. The gain block is connected between $T_m_{\text{wind turbine}}$ and $T_m_{\text{PMG}}$ as seen in figure 19. It is important to note for generator mode $T_m$ must be negative.

5. To perform the experiment the internal resistance of the three phase series branch was adjusted manually. The blade pitch angle was set to 0 degrees and the wind speed was manually adjusted. The generator speed, resistance of the load, and the voltage on the output terminal of the PMG were measured for each step. The simulation time was set for 5s. Signal information from the simulation can be measured by clicking on the scopes.
**Simulation Results:**

Table 5 Simulink Simulation results

<table>
<thead>
<tr>
<th>wind speed = 10</th>
<th>R (ohm)</th>
<th>Vp (V)</th>
<th>Pload (w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>18</td>
<td>20</td>
<td>33.33333</td>
</tr>
<tr>
<td>35</td>
<td>21</td>
<td>21</td>
<td>31.5</td>
</tr>
<tr>
<td>407</td>
<td>25</td>
<td>260</td>
<td>4056</td>
</tr>
<tr>
<td>478</td>
<td>33</td>
<td>310</td>
<td>4368.1818</td>
</tr>
<tr>
<td>521</td>
<td>40</td>
<td>345</td>
<td>4463.4375</td>
</tr>
<tr>
<td>560</td>
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<td>373</td>
<td>4173.87</td>
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</tbody>
</table>

<table>
<thead>
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<th>R (ohm)</th>
<th>Vp (V)</th>
<th>Pload (w)</th>
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</thead>
<tbody>
<tr>
<td>28</td>
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<td>31</td>
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<tr>
<td>308</td>
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<td>543</td>
<td>75</td>
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<td>2450</td>
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<table>
<thead>
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<th>Vp (V)</th>
<th>Pload (w)</th>
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<td>200</td>
<td>1500</td>
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<td>55</td>
<td>240</td>
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<td>1306.6667</td>
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<table>
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<th>Pload (w)</th>
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<tr>
<td>255</td>
<td>80</td>
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<td>561.16875</td>
</tr>
</tbody>
</table>
Figure 22 shows how resistance is related to the speed of the generator and turbine for a given steady wind speed. As we expect, each curve has a point when the rotational speed suddenly drops. This sudden drop occurs when the electrical power is greater than the mechanical power produced by the generator. The only way to supply the sudden electrical power demanded by the resistance is to transfer some of the stored rotational energy to the load, which results in a sudden drop in speed.

**Problems:**

It was very difficult to simulate this circuit because it was the first time using the Simulink software. I encountered numerous problems. Initially the simulation results did not seem correct because Simulink would converge on different numerical solutions depending on the initial conditions of the system. I eventually realized this after many hours of trouble shooting. To solve this problem I estimated the initial value for the speed of the PMG and I inserted it into the model characteristics.
Suggestions:
In the future a more accurate model could be developed with additional information about the actual PMG generator. A more accurate model could also be developed for the wind turbine once its mechanical characteristics are known. This would allow a designer to accurately model the system and test system adjustments before implementing changes on the actual machine.

In addition, the DC chopper circuit could also be simulated to determine its effects on the system because there is some concern about how it will perform. The control logic should also be simulated to verify the proper signal flow. In addition to simulating the control signal flow, it could also be useful to simulate the dynamic characteristics of the system. This could be achieved by testing the system with a wind gust model.

Conclusion:
After additional thought about the convergence of two numerical solutions, I realized this is actually the expected result for the system. The reason is related to the wind turbine power characteristics of figure 21. For a given wind speed, there are two mechanical speeds that could satisfy a given power output. One point is on the rising side of the power curve and the other point is on the falling side of the curve. From a controls standpoint it important to understand where the operating point is. This consideration becomes especially important when the operating point is at the top of the power curve, because an increase in resistance can cause the turbine to speed up or slow down. When the turbine is operating at the top of the curve, decreasing resistance will always decrease the speed, because the turbine will not be able to supply additional power.
B. Program Details

Function File Selected Details

PWM
OUT - Output = 2
OF - Output Frequency (Hz) = 2000
DC - Duty Cycle (e.g., 456 = 45.6%) = 20 [PWM Duty Cycle]

STI
PFN - Program File Number = 3
UIX - User Interrupt Executing = 0
UIE - User Interrupt Enable = 1
UIL - User Interrupt Lost = 0
UIP - User Interrupt Pending = 0
TIE - Timed Interrupt Enabled = 0
AS - Auto Start = 1
ED - Error Detected = 0
SPM - Set Point Msec (between interrupts) = 100

PID Configuration

PID - Rung #3:2 - PD9:0
Controller Gain, Kc: 500.0
Reset Term, Ti: 0.60
Rate Term, Td: 0.00
Loop Update Time: 0.10
Control Mode: E = PV - SP
PID Control: Auto
Time Mode: STI

List of Integers

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<th>wind speed input</th>
</tr>
</thead>
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<td>N7:1</td>
<td>rotational speed input (n)</td>
</tr>
<tr>
<td>N7:2</td>
<td>rotational speed reference (nr)</td>
</tr>
<tr>
<td>N7:3</td>
<td>optimum tip speed ratio</td>
</tr>
<tr>
<td>N7:4</td>
<td>Not used</td>
</tr>
<tr>
<td>N7:5</td>
<td>rotational speed error (ne)</td>
</tr>
<tr>
<td>N7:6</td>
<td>Duty Cycle</td>
</tr>
<tr>
<td>N7:7</td>
<td>nominal rotational speed</td>
</tr>
<tr>
<td>N7:8</td>
<td>New Duty Cycle Control Variable</td>
</tr>
<tr>
<td>N7:9</td>
<td>Not used</td>
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<tr>
<td>N7:10</td>
<td>Inverse Duty Cycle</td>
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</table>
Control Variable from PID is sent to New Duty Cycle signal

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<th>Dest</th>
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</thead>
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</tr>
<tr>
<td></td>
<td>N7.8</td>
<td>20-</td>
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</table>

<table>
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<th>Source B</th>
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<td>N7.6</td>
<td>20-</td>
</tr>
<tr>
<td></td>
<td>1000-</td>
<td>980-</td>
<td>20-</td>
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<table>
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<th>Source</th>
<th>Dest</th>
</tr>
</thead>
<tbody>
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<td>N7.10</td>
<td>PWM:0:DC</td>
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<tr>
<td></td>
<td>980-</td>
<td>20-</td>
</tr>
</tbody>
</table>

Test Output

- O.0
- 6
- Run 1763

(END)
C. Speed Signal Input (When using 3.5kW PMG generator):
As seen in figure 4, the rotational speed of the generator is measured from the rectified output voltage of the generator. During the initial development stages, the generator voltage was considered to be proportional to turbine rotational speed only, but there are additional variables that affect the output voltage. The generated voltage changes depending on speed, current and internal generator temperature. For control purposes it is important to have an accurate measurement of the turbine speed so an intelligent algorithm was developed to improve the accuracy of the speed measurement.
To better understand this problem it is useful to look at a simple equivalent model for a permanent magnet generator.

\[ V_a = R_a I_a - jX_s I_a - E_{af} \]  

Figure 18 Equivalent model for permanent magnet generator

With known values of Ra and Xs it would be possible to theoretically predict the generator speed, but exact values of Ra and Xs will not remain constant when the generator temperature, speed, and current change. Based on previous experimental data gathered from a previous senior project, a mathematical model was developed to determine the turbine speed based on an equivalent output resistance and terminal voltage. Figure 10 and 11 show the results of the test from the ME senior project.
Figure 19 Measured Voltage vs. Speed for wind turbine generator (Li, Robinson-Carter, & Kulgevich, 2009)

Figure 20 Measured Current vs. Speed for wind turbine generator (Li, Robinson-Carter, & Kulgevich, 2009)
The data above shows how the rectified terminal voltage changes depending on load resistance and rotational speed. The data from the experiment follows a general mathematical trend that can be used to more accurately determine the speed. Figure 12 shows the trend for voltage vs. resistance when the rotational speed is 200rpm. The speed of 200rpm was chosen arbitrarily because the same general trend can be found at any speed.

![Voltage vs. Resistance, nr= 200rpm](image)

**Figure 21 Voltage vs. Resistance @ 200rpm**

The voltage and resistance trend found in figure 12 defines a set of points that can be extended for all speeds given the assumption that voltage is linear with respect to speed within generator ratings. Figure 13 shows the family of curves used to determine the rotational speed of the turbine, based on voltage and resistance.
In the future it would be useful to implement a device to measure speed directly from the rotor. Measuring the speed directly from the rotor would produce a more accurate input signal while shortening the overall program length. Possible devices for improved speed measurement include a tachometer or pulse counter.
D. Cp vs. Lambda for Cal Poly Wind Turbine

The steep Cp vs. Lambda curve reinforces the need for accurate speed regulation of the Cal Poly Wind Turbine. If the wind turbine operates at a tip speed outside the nominal value the power coefficient drops quickly. The nominal wind speed for this turbine is 10m/s.
E. Ziegler Nichols Method Tuning for PID
The Ziegler Nichols method is a classic tuning method to determine the gain constants of the PID equation. First, the integral and derivative gains are set to zero. Next, the ultimate gain is determined by increasing the proportional gain until the system becomes marginally stable and begins to oscillate. The gain at marginal stability is the ultimate gain $K_u$ and the period of oscillation is $P_u$. The Ziegler Nichols criteria can be applied as follows with the derivative term excluded. The derivative term of the PID equation is sensitive to noise therefore it is not used with this controller.

\[
P_{\text{Output}} = K_C \left[ (e) + \frac{1}{T_i} \int (e) dt \right] + D_{\text{OLD}} = D_{\text{NEW}}
\]

(PID gain) \quad K_C = \frac{K_u}{2.2} \quad [\text{unitless}]

(Reset Term) \quad T_i = \frac{P_u}{1.2} \quad [\text{minutes}]
F. Pictures of Test Setup

Figure 24 Test setup showing PLC and DC Chopper

Figure 25 Test setup showing DC motor, SG, and tachometer
Figure 26 DC Power Supply and Dynamometer
Summary of Functional Requirements

Describe the overall capabilities or functions of your project or design. Describe what your project does. (Do not describe how you designed it).

A Programmable Logic Controller operates in one mode to track the optimum tip speed ratio, and the second mode limits the turbine to a safe operating speed. In mode 1 the controller measures the wind speed, and multiplies this value with the optimum tip speed ratio to determine the rotational speed reference. Then the rotational speed reference is compared to the actual rotational speed, and the duty cycle controlling the output power is adjusted to compensate for the rotational speed error. In mode 2 the controller limits the speed of the turbine to rated rotational speed which is a predetermined constant based on mechanical considerations.

Primary Constraints

Describe significant challenges or difficulties associated with your project or implementation. For example, what were limiting factors, or other issues that impacted your approach? What made your project difficult? What parameters or specifications limited your options or directed your approach?

The primary constraint on this project was the limited resources available for testing the speed controller. Ideally a small scale PMG wind turbine with a non-regulated voltage output is required to perform the most accurate testing of the speed controller. Unfortunately, the Hampden wind turbine in the sustainable energy lab is not suitable for testing because it is limited by input wind speed, and it uses a max power point tracker connected to a battery. In the future it could be possible to test the speed controller with a permanent magnet generator connected to a programmable dynamometer that is capable of modeling the power vs. rotational speed characteristics of a particular wind turbine. The ME department has a large programmable dynamometer that could produce a successful test if the dynamometer can operate in power limiting mode instead of the typical torque limiting mode that most dynamometers use.

Economic

• Original estimated cost of component parts (as of the start of your project).

The original estimated cost depended primarily on the PLC controller. Multiple quotes were obtained from $500-$600. Additional miscellaneous parts were estimated to cost no more than $50.

• Actual final cost of component parts (at the end of your project)

The final cost of the project was $525. This was the cost of the PLC controller.

*Attach a final bill of materials for all components.*
Table 7 Bill of Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allen Bradley Micro Logix 1100 1763-L168BB PLC</td>
<td>Direct</td>
<td>$525</td>
</tr>
<tr>
<td>Allen Bradley 1761-CBL-PM02 Cable</td>
<td>donation</td>
<td>na</td>
</tr>
<tr>
<td>USB to Serial Converter</td>
<td>donation</td>
<td>na</td>
</tr>
<tr>
<td>Off line Linear 24V Pwr. Supply</td>
<td>donation</td>
<td>na</td>
</tr>
<tr>
<td>600VAC Fused disconnect</td>
<td>donation</td>
<td>na</td>
</tr>
<tr>
<td>2A fuse</td>
<td>donation</td>
<td>na</td>
</tr>
</tbody>
</table>

TOTAL $525

• Additional equipment costs (any equipment needed for development?)

The development equipment is included in the bill of materials. A special cable to connect to the PLC was required, in addition to a USB to serial converter, and an offline power supply to provide 24V to power the PLC. Free programming software was required, but it is available from the Allen Bradley website.

• Original estimated development time (as of the start of your project)

The original estimated time for project development was approximately 150hrs. This was a rough estimate based on the time it would take to develop a list of project requirements, choose a controller, develop a controls scheme, and program the controller.

• Actual development time (at the end of your project)

The actual development time for the items listed above actually took about 175hrs. It is estimated that meetings, simulations, debugging, testing, proposals, weekly progress reports, and final report writing took an additional 225hrs.

If manufactured on a commercial basis:

• Estimated number of devices to be sold per year

This project was not designed for the commercial market because it was a specific design for the Cal Poly Wind Turbine. This project was treated like a consulting job for a company that needed a specific design. Normal customers of this device include universities, and wind turbine manufacturers.

If the design could be modified for widespread commercial use, in which case the estimated devices to be sold each year would depend on the market for small wind turbines. In 2009 the American Wind Energy Association reports that 9,800 small wind turbines were sold in the US. If 1% of this market purchased my controller that would account for 98 units sold per year.
• Estimated manufacturing cost for each device

The PLC is manufactured by Allen Bradley and no additional hardware components are added to the device.

• Estimated purchase price for each device

It is estimated that a high quantity order for the PLC’s would reduce the cost per item to $500 per unit.

• Estimated profit per year

The profit per year is calculated as follows:

It would take an engineer approximately 20 minutes per device to download and modify the program for a specific wind turbine if the characteristics of the wind turbine are known. If the engineer earns $40 per hour the total profit is estimated as follows.

<table>
<thead>
<tr>
<th>Table 8 Profit Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineer Per Unit Cost</td>
</tr>
<tr>
<td>Estimated wholesale bulk price</td>
</tr>
<tr>
<td>Total Cost</td>
</tr>
<tr>
<td>Selling Price</td>
</tr>
<tr>
<td>Total Profit Per Unit</td>
</tr>
</tbody>
</table>

Annual profit = 98 units * $37/units = $3626

• Estimated cost for user to operate device, per unit time (specify time interval)

The cost to operate the device depends on the electricity it uses to operate. The device requires 35W to operate as listed in the general specifications section of the device data sheet. If the device is connected to a metered utility system with the cost of electricity at $0.16$/kWhr, the cost is estimated as follows:

0.035KW * 365 day/year * 24 hr/day * $0.16$/kWhr = $49.06/year

When the device is connected to the proposed wind turbine system the operating cost will be offset by the energy it produces.

Environmental

• Describe any environmental impact associated with manufacturing or use.

This product has no known disruptive environmental impacts from the manufacture of the device. Most electronic components can be constructed with RoHS compliance components to reduce environmental impact. There are no harmful environmental impacts from downloading the program to the controller.

Manufacturability

• Describe any issues or challenges associated with manufacturing.
This project design does not address the manufacture of the Speed Controller. The controller is designed and manufactured by Allen Bradley. Specific information about the manufacture of the PLC can be obtained from Allen Bradley.

**Sustainability**

- Describe any issues or challenges associated with maintaining the completed device, or system

There are no known issues or challenges with the maintenance of this system. The PLC will operate most reliably if it is mounted in an enclosed dust free location. The device should be kept away from water and extreme heat sources. Electrical surge protection should be used with this device to protect the inputs and outputs from exceeding the internal ratings of the device. Once this device is installed it will continue to operate with no additional maintenance required.

- Describe how the project impacts the sustainable use of resources.

This device is used to control power from the wind. The speed controller is an integral part of the wind turbine system which captures renewable energy from the wind. When the controller is used with the intended system it is completely sustainable. This device has potential to help increase the use of renewable energy. The device regulates the wind turbine speed to produce the most efficient energy capture for a given wind speed. Wind turbines without speed control systems will produce significantly less energy than they would with a speed control system like the one developed for this project.

- Describe any upgrades that would improve the design of the project.
- Describe any issues or challenges associated with upgrading the design.

Improvements can be made to improve the PI tuning and ensure stability of the control system. Tuning can be performed by creating a computer model for the specific wind turbines, or tuning can be performed on with the actual operating system in the field. For field deployment, it is recommended that a pulse counter be used for the rotational speed measurement. Although this project did not interface with an anemometer, it should be noted that various anemometer configurations are used to produce the most desirable wind speed measurement. Some utility grade wind turbines use arrays of anemometers to predict changes in wind speed before the change occurs at the blades.

In the future the PLC can be adapted to meet additional safety and operation needs. Some of the safeties include high wind speed shut down, manual shut down, and mechanical brake control. It will also be important to monitor and benchmark the wind turbine. The PLC can be adapted for data acquisition with the use of the embedded web server.

The electrical system of the wind turbine should be upgraded to extract useful power from the wind turbine. Possible power electronics devices to obtain this goal include phase controlled rectifiers, DC-DC voltage regulators and inverters. When designing these devices it would be beneficial to use a common control voltage in order to simplify the power system. The DC chopper used with this project requires 15V and 5V, and the PLC requires 24V. If the wind turbine is deployed in the field as an isolated power source, a small battery circuit must be developed to provide control voltage when the turbine is not producing electricity.
Ethical

• Describe ethical implications relating to the design, manufacture, use, or misuse of the project.

There are no known major ethical implications for the use or manufacture of this device. The device should be used for its intended purpose.

Health and Safety

• Describe any health and safety concerns associated with design, manufacture or use of the project.

Before this device is deployed in the field, it should be adapted to meet additional safety demands before the wind turbine is deployed in the field. Some of the safeties include high wind speed shut down, manual shut down, and mechanical brake control. This device is a commercially available PLC that is widely used in industry and known for its reliability and dependable operation. The voltage levels connected to this devise do not exceed 120VAC. Only a trained technician should be allowed to work on the device after all power sources are disconnected.

Social and Political

• Describe any social and political concerns associated with design, manufacture or use.

The increased use of wind energy resources is becoming an important social issue because of growing energy demands. The unknown long term effects of global warming and increased emissions from fossil fuels will continue to be major issue for the next decade. This device is part of a system which harnesses clean renewable energy from the wind.

Development

• Describe any new tools or techniques, used for either development or analysis that you learned independently during the course of your project.

I learned how to use MATLAB Simulink and I also learned how to program using RSLogix Micro. Simulink is a powerful tool that can be used for many engineering designs. RSLogix Micro is programming software that is specifically designed for programming Allen Bradley PLC’s. I also developed an original test procedure, and I adopted the use of a synchronous generator to function as a tachometer.