Wind Turbine — Design of Turbine Blade

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Abstract

As renewable energy sources become increasingly popular, wind power provides a safe and dependable alternative to fossil fuels. Wind turbines are currently constructed in a variety of sizes; some are several hundred feet tall and weigh thousands of pounds while others are small enough to mount on top of a residential home. The aim of this study is to design and build a small wind turbine that utilized a microcontroller board to automatically adjust the blade angle of attack and also rotate the turbine toward the windward direction. The turbine will display weather information, such as the current wind speed and direction, on an LCD module.

1. Introduction

In its simplest form, a wind turbine is nothing but an electrical generator. The shaft of this generator is rotated by the torque exerted on the turbine blades by the wind, and this produces power which may be used or stored depending on the demand for electricity at any time. The most desirable feature of wind power is the fact that is completely renewable; there are no annual costs after initially purchasing the turbine. In fact, turbine owners may even sell any excess energy back to the power company (we-energies.com). The successful design of a small and affordable wind turbine provides a much needed alternative to solar panels for energy-conscious homeowners. Wind turbines may be used during every season of the year, and they have the ability to directly produce A/C power. Electrical output from solar panels is inherently DC and requires an inverter to power common household appliances. Currently, wind energy is almost exclusively produced by turbine fields involving tens or hundreds of extremely large turbines. There has not been much work done concerning the extension of wind power to the residential home, and this has resulted in a very limited selection of turbines available to individual consumers. This project will provide a cost-effective, efficient turbine which will allow more and more people to take advantage of renewable wind energy.

There are several online sources of information concerning wind turbine design, and the Danish Wind Industry Association web site is highly recommended by the author. This site has information on several aspects of wind turbine design, covering everything from blade design to wind energy economics. The purpose of this research is to design an autonomous wind turbine of appropriate size for residential consumers. There were several key objectives:

- Provide automatic control of blade pitch angle to reduce or increase blade speed depending on ambient wind conditions.
- Sense wind directions and implement a control system which will orient the turbine in the windward direction.
- Provide weather information, such as wind velocity and direction.
- Keep cost low to maximize residential consumer appeal

An LCD module has been acquired and has been programmed to display the wind speed and its direction. An H-Bridge circuit was used to drive a gear motor that rotated the nacelle toward the windward direction. Finally, the blade pitch angle was controlled by a swash plate mechanism and servo motors installed on the generator itself. A microcontroller has been programmed to optimally control the servo motors and gear motor based on input from the wind vane and anemometer sensors.

2. Blade Flow Computations

The Weibull Distribution, shown in Figure 1, is a histogram of average wind speeds experienced over the course of a year.

Based on the FEA analysis of the preliminary blade design, the cross-section was determined to be unnecessarily thick. The blade was modified by reducing its overall thickness from 4 cm to 1 inch near its base, and from 1 cm to ½ cm near its tip. The updated FEA results from the final blade shape are shown in

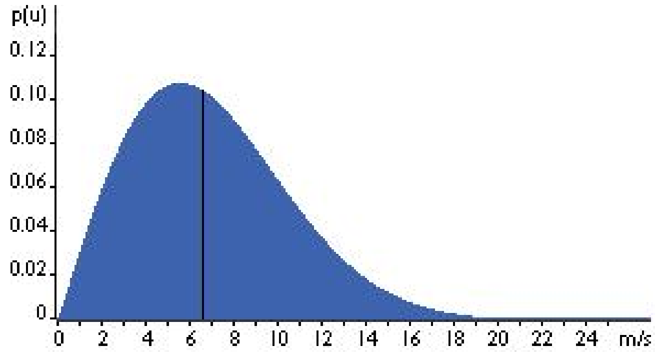


Figure 1. Weibull Distribution of average wind velocity [www.windpower.org].

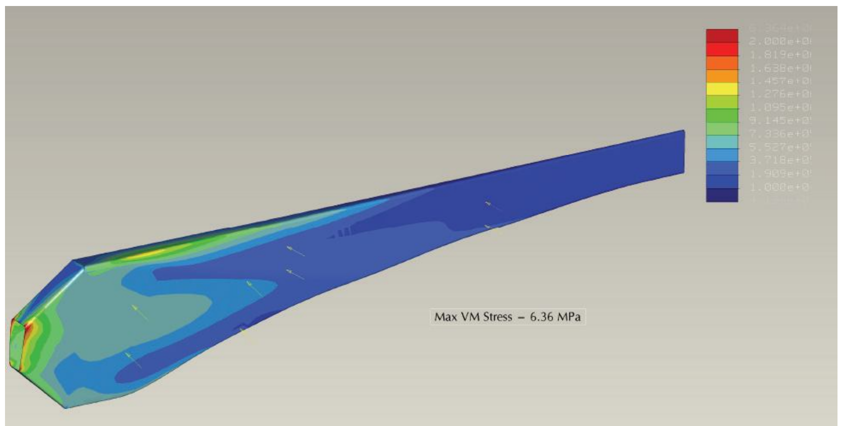


Figure 2. FEA computed results.

Figure 3; these analyses demonstrate how the reduction in material did not elevate stresses above acceptable levels.

One major design challenge involved the implementation of a mechanism to control the angle of each rotor blade during turbine operation. Caster bearing plates allowed rotation between each blade and an aluminum hub. Dual servo motors were used to adjust the blade angle through translational motion of a swash plate on the generator shaft. The blade design has been optimized using both online calculators and a Matlab program written specifically for this project. The thickness and profile of the blades have been adjusted to achieve a balance between weight and strength. These blades were cast in fiberglass for low weight and sufficient resistance to weather conditions, and they were cut from Styrofoam blanks to achieve the desired shape. A gear motor was used to rotate the mast because it generated more torque than a servo of similar size. Finally, this turbine cost less than three-hundred dollars and should provide approximately 100W of power, depending on wind conditions.

The efficiency of a wind turbine depends on several parameters, the most important of which are the yaw angle and the angle of attack employed by the blades. When a turbine is not facing the windward direction, the effective area swept out by the rotor blades is decreased and this results in a reduction in power transfer from the air to the wind turbine. Also, it is necessary to precisely control the angle of attack because rotational speed and power output depend heavily on the torque that is generated by the blades. A change in blade angle will correspondingly affect the torque that is generated, and this will influence turbine performance by altering the angular speed of the rotor.

Control of these turbine parameters is most easily accomplished by using a microcontroller which has the ability to sense changes in blade rotational speed or yaw angle and promptly make any necessary adjustments. A program may be written which imposes tolerances on the aforementioned parameters and utilizes corrective algorithms to change the mast angle or the angle of attack to optimize power output. These adjustments may be made at intervals of one millisecond or less, but such high speed sampling is unnecessary for many mechanical devices. A delay of several seconds is usually inserted between adjustments to avoid excessive power consumption and motor fatigue in wind turbine applications.

There are many wind turbine rotor configurations in use today. Turbines may have as few as 1 or as many as 12 blades, depending on the relative size and function of the turbine. Large turbines typically utilize a three-blade design which maximizes power output while providing increased stability over turbines with a larger number of rotors. In order to avoid resonance from periodic wind gusts, an odd number of turbine rotors are preferred; this is the primary reason a three-rotor turbine design has become the industry standard. Rigidity and resonant frequency are also important considerations when designing the cross section and profile of a turbine blade (windpower.org).

3. Results

The successful operation of the control programs have confirmed the ability of the microcontroller shown in Figure 3 to facilitate the autonomous wind turbine design. The microprocessor has time and date registries, so a dated display would be possible if it is deemed useful. Also, a possible extension of the general control program involves a serial output which could be routed to a central computer for data logging and remote display. The orientation of the nacelle (yaw angle) was controlled by comparing the angular position of the turbine with the angular position of a small weather vane. This comparison was conducted using potentiometers for position feedback on both the turbine and weather vane. When the yaw angle was sufficiently different from the weather vane angle, the microcontroller actuated a small gear motor, which caused the turbine to rotate toward the windward direction. When the error between the wind vane and the yaw angle was sufficiently small, the motor sequence stopped. A delay was implemented between successive adjustments to prevent continual operation of the motors on the wind turbine, and the dead band time was contoured to provide adequate control while minimizing power consumption. A one second sampling delay was implemented in the final control code. A simplified block diagram of the control code is shown in Figure 4.

Several design challenges have been addressed since the beginning of this project. Initially, a significant amount of time was spent on the development of code for the control program. The hardware interfacing capabilities of the microcontroller had to be understood and exploited, and function library files were written for LCD control and analog to digital conversion. The development of the control system also involved electronic circuit fabrication. The authors recommend subsequent wind turbine groups to design a printed circuit board to speed up this circuit building process.

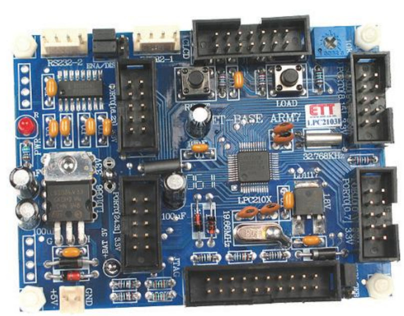


Figure 3. Microcontroller.

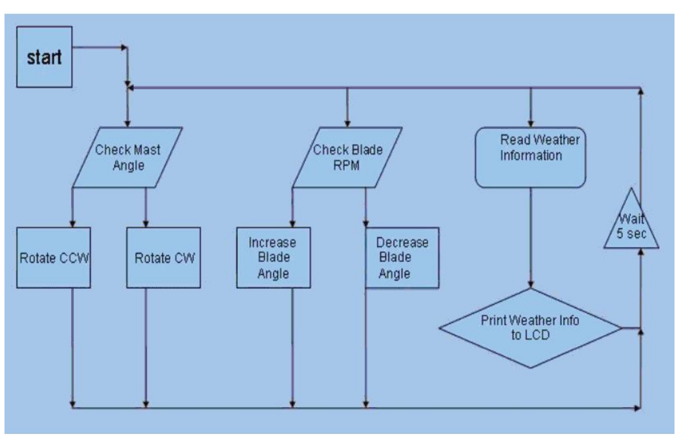


Figure 4. Block diagram.

After developing the control program, the next major challenge involved the blade design. Several online sources were studied, and a Matlab program was written to generate the final blade chord width profile. The most difficult part of blade fabrication involved cutting an angled blade face after the chord width profile had been removed.

The most time-consuming and complicated aspect of this project was the implementation of a pitch-control mechanism for the turbine blades. A homemade swash plate was constructed using a standard turntable bearing, and this swash plate was translated up and down a shaft extension emanating from the electrical generator. The blades were connected to one side of the swash plate, and the lever arms coming from the servo motors were connected to the other side.

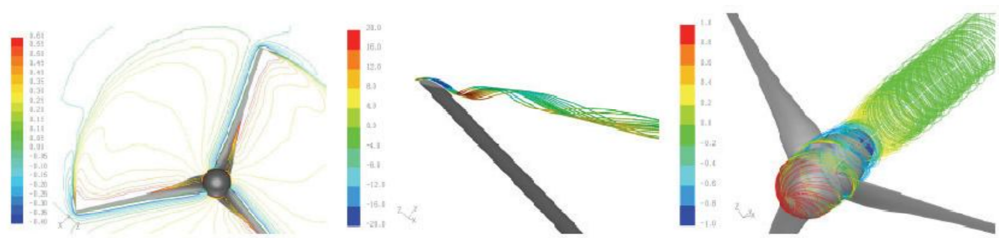
General details and specifications of the turbine design are given in Table 1.

The computed results are shown in Figure 5 for blade front, along the blade, and meridional view.

The computed power as a function of the wind speed is given in Figure 6. Here the turbulence models of k-ω/SST, Spalart-Allmaras, and k-ε models were employed. The computed results were compared with the blade element momentum theory (BEM). As is expected the computations using higher turbulence models show better results.

Table 1. Preliminary design parameters.

Parameter	Description
Mast Height	5'
Mast Material	PVC
Blade length	27”
Blade Material	Fiberglass
Generator	12V
Battery	12V
Blade Control	Mechanism in Hub
Yaw Control	Gear Motor on Mast
Controller	LPC2103
LCD	16x4 character
Approximate Power	100W
Cost	Less than $300



a) Front view; b) Along a blade; c) Meridional view

Figure 5. Blade flow computed results.

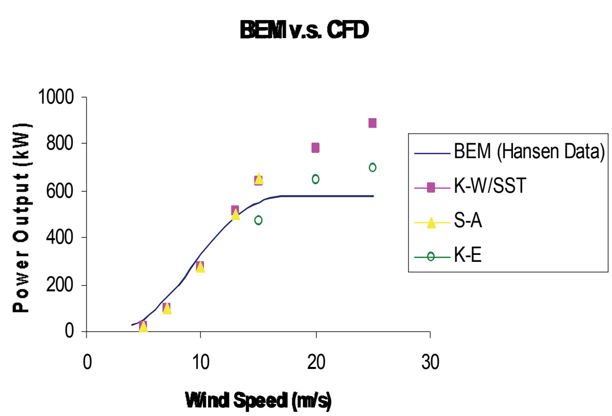


Figure 6. Computed results compared with BEM Data.

4. Conclusions and Recommendations

The following conclusions were drawn:

- It is very possible to design and fabricate a residential wind turbine.
- Quick pay-off time when compared to other alternative energy systems.
- Millions less than a home fossil/natural gas/nuclear power system with less hazards.
- Microprocessor-based control is useful for many mechanical systems. Simple programs may eliminate hours or days of analogue circuit design.
- Easy scalability for larger systems.

Recommendations for future work are as follows:

- The generator used in this project was simply a permanent magnet DC motor. It would be beneficial to employ a generator with larger power output capabilities for optimal energy extraction efficiency.
- Cast fiberglass has inherent bumps and convolutions throughout its surface profile. To facilitate the smoothest flow over the blade face, it may be useful to look into a different material for the blade shell. This material should be sufficiently strong and have relatively low density, so as to minimize the overall inertia of the rotor assembly.
- The windward yawing functionality of this wind turbine may be emulated by installing a tail on the back of a turbine nacelle. This tail would have the disadvantage of inducing some oscillatory motion, but it would minimize cost and provide similar yawing control.
- As a substitute for the variable-pitch blade system designed for this project, fixed blades may be designed with a blade angle that changes significantly from root to tip. The blades would incorporate a high (large) blade angle near the root, and a small angle near the tip. This configuration limits the maximum rotational speed of the blade by inducing stall and additional drag forces when the wind velocity becomes large. Also, the large blade angle near the root allows the rotor to begin spinning at low wind velocities, since maximum torque is generated with large blade angles at these low wind velocities.
- Wireless data transfer may be explored in more detail. A transmitter may be installed on the control box and a receiver may be installed somewhere off-site from the turbine itself. This would eliminate the need for wires going to and from the turbine if data collection and recording was to be performed.

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Author Biographies

Prof. Ryo Amano has worked on energy systems including turbomachinery and energy recovery systems of over 20 years. He has published one book on Power Systems, twenty book chapters, and over four hundred fifty technical journals and proceedings. He has received three best paper awards from ASME in the Power Division and Computer & Information Divisions. He is a recipient of the AIAA Sustained Service Award and a recipient of the Excellence of Research Award from the University of Wisconsin, U.S.A. He is currently an ASME Fellow and AIAA Associate Fellow. He is also an editorial member of WIT Press, Bentham Journal Publisher (editor for two journals).