Teachers' Guide: FloDesign Wind Turbine Challenge

Extracting Energy from a Wind Turbine

SPOILER ALERT!! THIS RESOURCE IS FOR INSTRUCTORS ONLY! IT DEFEATS THE PURPOSE OF PROBLEM BASED LEARNING IF THIS INFORMATION IS SHARED WITH STUDENTS BEFORE THEY COMPLETE THE PBL CHALLENGE!

The Challenge: A team of engineering students is tasked with developing a strategy for extracting energy from a new compact wind turbine design.

What you need to know to solve the challenge (key concepts):

- How wind turbines work
- Faraday’s Law of Induction
- How an electrical generator creates electricity

How a wind turbine works

A wind turbine converts wind energy into mechanical motion through the use of a propeller, or “prop.” When wind passes over the propeller, the force against the propeller blades causes it to spin. The stronger the wind, the faster the propeller spins. In general, modern wind turbines begin rotating at wind speeds of about 9 miles per hour and can handle wind speeds of up to 55 miles per hour. Typical wind turbines have very large propellers, some as big as 150 feet in length, to capture as much wind as possible. Because of the large size of the propellers, wind turbines are limited in how fast they can rotate. This requires that the propeller shaft be connected to a gearbox to increase the rotational speed, enough to turn an electrical generator thus creating electricity. In short, a wind turbine can be thought of as an electric fan in reverse. Instead of an electric motor turning the fan blades to create wind, the wind turns the fan blades, which in turn rotates an electrical generator.

Most commercially available wind turbines contain a number of special features designed to optimize their ability to convert wind into electrical energy. For example, the pitch, or angle of the propeller blade can controlled to maintain a constant rotational velocity. A device known as an “anemometer” measures the wind speed and transmits wind speed data to a controller that adjusts the pitch of the prop blade accordingly. A “wind vane” is used to measures wind direction and communicates that information to a “yaw drive,” which controls a motor to orient the turbine properly with respect to the wind. Figure 1, adapted from the US Department of Energy website, illustrates the inner workings of a typical wind turbine. The website (http://www1.eere.energy.gov/windandhydro/wind_how.html#inside) provides a wealth of information about wind power and other alternative sources of clean energy.
Anemometer: Measures the wind speed and transmits wind speed data to the controller.

Blades: Most turbines have either two or three blades. Wind blowing over the blades causes the blades to "lift" and rotate.

Brake: A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

Controller: The controller starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they might be damaged by the high winds.

Gear box: Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring "direct-drive" generators that operate at lower rotational speeds and don't need gear boxes.

Generator: Usually an off-the-shelf induction generator that produces 60-cycle AC electricity.

High-speed shaft: Drives the generator.

Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.

Nacelle: The nacelle sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake. Some nacelles are large enough for a helicopter to land on.

Pitch: Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low to produce electricity.

Rotor: The blades and the hub together are called the rotor.
**Tower:** Towers are made from tubular steel (shown here), concrete, or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

**Wind direction:** This is an "upwind" turbine, so-called because it operates facing into the wind. Other turbines are designed to run "downwind," facing away from the wind.

**Wind vane:** Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

**Yaw drive:** Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive, the wind blows the rotor downwind.

**Yaw motor:** Powers the yaw drive.

![Figure 1 – Inner workings of a typical wind turbine](http://www1.eere.energy.gov/windandhydro/wind_how.html#inside)

Some additional websites include:

- **How a wind turbine works:** [http://www.bp.com/iframe.do?categoryId=9025015&contentId=7047453](http://www.bp.com/iframe.do?categoryId=9025015&contentId=7047453)
- **Making a model wind generator:** [http://www.re-energy.ca/pdf/wind-turbine.pdf](http://www.re-energy.ca/pdf/wind-turbine.pdf)

### Faraday’s Law of Induction

In order to understand the FloDesign Wind Turbine solution, it is important to have a basic understanding of Faraday’s Law of Induction. Faraday’s Law of Induction describes how an electromotive force, or EMF, is created in a conductor in the presence of a changing magnetic field. For example, when an alternation current is allowed to flow through a stationary coil of wire, a magnetic field will be induced in the coil. This case is called a **motational EMF** and is essentially how an electromagnet or solenoid works. Conversely, if an alternating magnetic field from a permanent magnet is placed on a stationary coil of wire, an electric current will be induced in the wire. This case is called an **induced EMF** and is how an electrical generator creates electricity. This principle is illustrated in figure 2.

According to Faraday’s Law:

$$\text{EMF (Volts)} = -N \frac{[\Delta \phi]}{[\Delta t]}$$

where EMF is the electromotive force measured in volts, N is the number of turns of wire in the coil, and $[\Delta \phi]/[\Delta t]$ is the rate of change of the magnetic flux through a single loop of wire. Magnetic flux (\(\phi\)) is a term that describes the strength of the magnetic field multiplied by the area of the coil (B x A), where B is the magnetic field strength measured in units of Tesla (T), and A is the area of the coil. As a result, Faraday’s Law of induction can also be written as:
EMF (Volts) = -N [\Delta B \cdot A / \Delta t]

In general, Faraday’s Law shows that any change in the magnetic field in a coil of wire will cause a voltage to be generated in the coil. The change in magnetic field can be produced in several different ways; moving a magnet in and out of the coil, moving the coil into or out of the magnetic field, rotating the coil around a stationary magnet, or passing a magnet over a coil. No matter how the change in magnetic field is produced, it will generate a voltage across the coil.

![Figure 2 – Faraday’s Law Illustration](image)

**Example:**
Assume the coil of wire in figure 1 has 10 turns of wire and an area of 1 cm². Find the induced voltage in the coil if a magnet is passes through the coil generating a change in magnetic field strength of 0.5T in 1 second.

\[
\text{EMF (Volts)} = -N \left[ \Delta B \cdot A / \Delta t \right]
\]
\[
= - (10)[(0.5T)(1 \text{ cm}^2)/1 \text{ sec}]
\]
\[
= - 5 \text{ volts}
\]

In this example, it is clear that the faster the magnet moves in and out of the coil, the greater the rate of change in the magnetic field, and hence the greater the voltage generated.

A number of very good websites that provide additional information include:

**Faraday’s Law for Kids**
Faraday’s Law Java simulations
http://phet.colorado.edu/en/simulation/faraday

How an Electrical Generators Creates Electricity
An electrical generator converts mechanical motion into electrical energy. There are several ways in which the generator can be turned including wind, steam, human power, water, gasoline or diesel engine, etc. An AC electrical generator creates electricity by either rotating a permanent magnet over a stationary coil of wire (Figure 3a), or by rotating a coil of wire through the magnetic field of a stationary permanent magnet (Figure 3b).

Figure 3a – Rotating magnet generator
In either case, when the magnetic field of the magnet is aligned with the coil the maximum voltage will be induced. As the generator rotates, the alignment of the coils with the magnetic field of the magnets increase, peak, and then decrease, as does the induced EMF and hence the voltage generated. Depending on the polarity of the magnet with respect to the coil, the voltage will be either positive or negative. The faster the rotation, the greater the voltage. In a DC generator, the positive and negative cycles of the voltage are separated by a device called a commutator, which results in a positive oscillating sinusoidal waveform as shown in figure 4.
In either case, increasing the number of magnets and coils will increase the voltage generated. The magnets and coils may also be interlaced to create two and three phase voltages. Figure 5 illustrates a two and three phase generator with multiple coils and magnets.

**Figure 5**

(a) Two- and Three Phase Generator configurations

(b) Two-phase multi-coil connection diagram with blue coils and orange coils connected in series on separate circuits. Blue coils will have north facing magnets pass simultaneously as all south magnets pass the orange coils. The two waveforms can then be superimposed. *(Source: FloDesign Student Project Final Report, “Designing and prototyping drive trains for the next generation of wind turbines.”)*
In figure 5a, the configuration for the three-phase generator shows 4 magnets and 6 coils with the coils arranged 30° apart from each other. The reason for this offset is to counter the drag effects caused by a phenomenon called “back EMF,” which is greatest when the magnets and coils are perfectly aligned.

There are a number of excellent websites with great simulations that illustrate how electrical generators work. Below are just a few:

Motor and Generator Simulations
http://www.animations.physics.unsw.edu.au/jw/electricmotors.html#mandg

Student Exercise: Making a Simple Electrical Generator
http://www.creative-science.org.uk/gen1.html

The FloDesign Solution
The FloDesign solution developed by a team of engineering students was called “The Integrated Permanent Magnet Configuration” or IMP. Based on specification provided by FloDesign Corporation, a scale model was built using the rapid prototyping capabilities of the engineering school’s laboratory.

The IMP prototype was designed to produce maximum output power at a rotational speed of rotational speed of 66 rpm. The basic concept involved attaching 60 permanent neodymium magnets with alternating polarity (North & South) to each of 60 turbine rotor blades and 60 equally spaced stationary coils of wire to the stator of the turbine. Each of the 60 coils was wrapped around an iron core to strengthen the field through the coil. A number of possible core configurations were examined before deciding on a simple “I” core. While the other core configurations were considered to have better magnetic properties, these designs would be significantly harder (if not impossible) to machine and wind at the scale of the prototype.

The 60 coils were wound from 24-gauge enameled magnet wire. The choice of wire gauge was a tradeoff between current-carrying capacity and size. The thinner wire allowed for more turns of wire to fit into the coil pocket to increase the output voltage, but at the expense of current carrying capacity. In the end, 24-gauge wire was used because it provided the best tradeoff between current and voltage. A simplified schematic of the prototype design is shown in Figure 6 (Note: Figure 6 was drawn with only 12 coil/magnet pairs for clarity).
Analysis

A simplified analysis of the generator is provided to approximate the total induced EMF of the generator (output voltage) and rated power based on the coil size, permanent magnet size, rotational velocity, and air gap. To simplify the analysis, we make the assumption that the magnets are pure magnetic dipoles. In other words, the magnetic field drops with a $1/r^3$ relationship on axis with the coil, but does not change in the direction perpendicular to the magnet axis.

Recall that the induced EMF of a coil in the presence of a changing magnetic field is given by Faraday’s Law of Induction

$$\text{EMF (Volts)} = -N \left[ \frac{\Delta B \cdot A}{\Delta t} \right]$$

**Example:**

For the electrical generator configuration shown in figure 6 with the following parameters, find the induced EMF for (a) a single coil, (b) 60 coils connected in series, and (c) maximum power rating.

- 60 magnets (Dimensions: $\frac{3}{4}” \times \frac{1}{2}”$)
- Nominal air gap of 1/16” (.158 cm)
- Coil dimensions = $\frac{1}{2}” \times \frac{3}{4}”$ (1.27 cm x 1.9 cm)
- 24 gauge wire (24 windings)

**Figure 6 – Simplified diagram of the FloDesign Wind Turbine**
- Rotational speed = 66 rpm
- Magnetic field strength of magnet at distance of 1/16” (.158 cm) of .05 Tesla (T).
- Turbine blade diameter = 10”

The first step is to determine the rate of change of magnetic flux $\Delta t$ for 60 magnets rotating at 66 rpm.

$$\text{Rotational velocity} = \frac{1}{[66 \text{ rev/min}] \times [1 \text{ min/60 sec}]} = \frac{1}{1.1 \text{ rev/sec}} = 0.91 \text{ sec/rev}$$

Assuming just one magnet and coil, with a rotational rate of 0.91 seconds/rev and a rotor diameter of 10”(radius = 5”), we must calculate the time it takes for the magnet to pass over the 0.5” diameter coil.

Circumference = $2\pi r$

= $2\pi(5”) = 31.4”$

This shows that each magnet travels 31.4” each revolution in .91 seconds. Calculating the magnet velocity we get:

Magnet velocity = $\frac{31.4”}{0.91 \text{ sec}} = 34.5”/\text{sec}$

Therefore, for a coil with a diameter of 0.5”, the time it takes for the magnet to pass over the coil is

$$\Delta t = \frac{(0.5”)}{(31.4”/\text{sec})} = 0.015 \text{ sec}$$

The rate of change of magnetic flux for each coil is

$$\frac{\Delta B}{\Delta t} = 0.05 \text{T/0.015 sec} = 3.33 \text{T/sec}$$

The area of each coil is

$$\text{Area} = 1.27 \text{ cm} \times 1.9 \text{ cm} = 2.41 \text{ cm}^2$$

Applying Faraday’s equation, the EMF for each coil is

$$\text{EMF (Volts)} = -N \cdot A \cdot \frac{\Delta B}{\Delta t}$$

$$\text{EMF (Volts)} = - (24 \text{ turns}) (2.41 \text{ cm}^2) (3.33 \text{ T/sec})$$

$$= -192.8 \text{ volts}$$

For 60 coils in series, the total EMF is

$$(-192.8 \text{ volts/coil})(60 \text{ coils})$$

$$= -11,568 \text{ volts}$$
For a 24-gauge wire with a current rating of 0.577 amp (AWG #24), this equates to a maximum power rating of

\[
P = \text{Volts} \times \text{Amps}
\]

\[
= -11,568 \text{ volts} \times 0.577 \text{ amps}
\]

\[
= 6674.7 \text{ watts}
\]

Student Exercise: Making a Simple Electrical Generator

http://www.creative-science.org.uk/gen1.html

Making a model wind generator:

http://www.re-energy.ca/pdf/wind-turbine.pdf