Wind Power Fundamentals and Applications

EECE 492 – Distributed Energy Systems Management

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1.0 Introduction

An increase in the demand of energy has risen dramatically in the past few decades since the industrial revolution, and also due to the earth's growing population. Currently the most dominant source of energy usage is fossil fuels. This non-renewable resource will be depleted if we continue our energy usage trends over the next century. Furthermore burning of these fuels emits greenhouse gases into the environment, thus contributes to global warming. New sources of renewable energy must be developed in order to meet our world’s demands in energy. Renewable energy sources are readily available such as wind, hydro, solar, biomass, and more. The technology for harvesting these sources have been in development for many years and the awareness for it has gradually increased. Within the past two decades has nations been investing heavily into these sources.

Wind energy been harvested and used for many decades. An example of a machine that converts this energy into mechanical energy is the windmill. They have been developed for milling grain, pumping water, and other uses. Wind turbines have been used to generate electricity over a century ago, but today the technology has advanced to a level where they can be installed offshore and operate on a massive scale to feed a nation's electricity demand. We can see leading nations striving for renewable energy systems as a way to sustain our planet. This report will focus on wind energy and how the energy is converted into electricity, as well as different types of wind turbine configurations, the economics and future growth as well as the environmental concerns related to it.
2.0 Wind Power Fundamentals

Wind energy originates from the conversion of radiation from the sun into kinetic energy. It is caused by the uneven heating of the atmosphere. About two percent of the solar energy absorbed by the earth is converted into wind. Wind energy is defined as the kinetic energy of moving air, and by harnessing this energy we can convert it into mechanical or electrical power. There are limitations in the location which a wind turbine can be placed. Some of these factors are depend on the geographical location because land heats up faster than water. Below is an image of a wind energy map of Canada which shows the average power \( (W/m^2) \) that can be potentially extracted from the wind. As we can see from the figure, areas that are near the coast theoretically generate more power because of a high-low atmosphere system.

![Figure 1 - Wind Energy Map of Canada](http://c21.phas.ubc.ca/sites/default/files/SU-Wind_Turbines_Lecture_Notes.pdf)

The subsequent sections will discuss different types of wind turbines and provide a brief overview of the technical details supporting wind turbines.
2.2 Wind Turbine Conditions

Theoretically turbines are 100% efficient, but in reality it cannot reach this efficiency. Some limitations which contribute to losing efficiency is that wind conditions change all the time and are never constant. Other factors include turbulence caused by land formations, trees, and buildings. A practical location to build a wind turbine is on high ground by a coastal plain where water exists. The local wind speed is also another important factor because the power is directly proportional to the cube of the wind speed, \( P \propto v_{wind}^3 \) (Refer to the figure below).

![Figure 2 - Relationship between Wind speed and Wind Power](http://www.omafra.gov.on.ca/english/engineer/facts/03-047.htm)

The minimum requirements that is feasible for a wind turbine is that the local wind speed should be at least 7\( m/s \) and located a minimum of 25\( m \) above the ground. As we can see from the figure below, the amount of wind power increases significantly as the tower height increases because the amount of highly turbulent flow is reduced. Turbulence will cause increased wear and tear on the turbine thus increased maintenance costs and decreased life expectancy.
2.3 Wind Turbine Types

The horizontal-axis wind turbine (HAWT) rotates around a horizontal axis and they are the most commonly used and are more efficient than the vertical-axis wind turbine. In order to harness wind energy, it must be pointed into the wind. Large wind turbines which are used in wind farms have a computer controlled motor which turns them to the direction of the wind., also the anemometer detects the wind speed.

The blades which are connected to the rotor, converts the wind energy into energy into a rotational shaft. Since most large HAWTs have a low rotating speed, the gearbox converts the low speed rotating shaft speed into a higher speed which is more suitable for the generator. The speeds are typically from 30-60 rpm to 1000-1800 rpm which is required for the induction generator. Also, the blades of the HAWT are placed a distance away from the tower and is tilted up slightly to avoid turbulence made by the tower. Below is an image of a horizontal-axis wind turbine which consists of many different components.
A second type of wind turbine is the vertical-axis wind turbine (VAWT) which is less commonly used due to various reasons but it also has its own advantages. One of the advantages of a VAWT is that the turbine doesn't need to face the wind for efficiency, thus they can use wind coming from all directions. This is advantageous on areas with varying wind directions. Also another advantage is that a tower isn't needed due to the generator and gearbox being placed near the surface of the ground, thus lowering the construction costs. Although having these advantages, VAWTs are less commonly deployed than HAWTs. Some major reasons are that the VAWT designs produce drag and pulsating torque. They are also about 50% of the efficiency of an HAWT due to the drag that the blades produce from rotating into the wind.
2.4 Wind Power Calculations

A German physicist named Albert Betz discovered that no wind turbine can convert more than 59.3% of wind energy into mechanical energy when turning a rotor. This concept is called the Betz Limit, which is the theoretical power efficiency of any wind turbine. This coefficient is explained as

\[ C_p = \frac{\text{electricity provided by wind turbine}}{\text{total energy available in the wind}} \]

The coefficient has a theoretical limit of 59.3%. To achieve an efficiency of 100% it would be impossible. Wind turbines operate by slowing down the wind to extract energy, and thus it would have to stop all of the wind completely, and therefore no kinetic energy would have been converted. The Betz limit assumes a frictionless, incompressible and steady flow of wind.

An example taken from the Royal Academy of Engineering shows a theoretical calculation for a typical commercial sized turbine. Given the blade length \( l = 52m \), wind speed \( v = \frac{12m}{s} \), air density \( \rho = \frac{1.23kg}{m^3} \), power coefficient \( C_p = 0.4 \) we can calculate using the given formula

\[ P_{\text{available}} = \frac{1}{2} \rho A v^3 C_p = 3.6MW \]
The figure below shows the relationship between the blade length and the sweep area which is used in the calculation above.

Figure 5 - Wind turbine sweep area

To design a wind turbine it is important to know the relationship between all these factors affecting the available output power. The design will be effect the amount of income generated by these turbines.
2.3 Wind Turbine Safety

Inside a wind turbine there are many safety features which will help protect it from dangerous conditions. The rotor blades are tested to withstand fatigue from bending due to high wind speeds. Also the turbine has overspeed protection, which is essential to stop the turbine in case of overheating. The various methods of braking are discussed below.

When a wind turbine spins too fast, the braking system slows down the turbine to a safer speed. The turbine can only absorb a certain amount of power and often the wind is unreliable and therefore it has to handle the occasional high wind speeds. This can be done with electrical and/or mechanical braking.

Electrical braking is used in small wind turbines where the excess energy can be dumped into a resistor bank therefore converting the kinetic energy into heat. The effect of this braking system is that it causes the blades to slow down which reduces the efficiency of the blades, but will keep the turbine at a safe speed.

A second method of braking is mechanical braking where it uses a drum or disk brake which is used to slow down the turbine for maintenance purposes. This braking system is used after electromagnetic braking has reduced the turbine speed, or else this would cause too much wear on the mechanical brakes.
3.0 Wind Energy Applications

Wind turbines come in a variety of different sizes, from small residential turbines to large commercial ones which are used in wind farms. The large wind turbines may produce hundreds of megawatts of electricity, while small wind turbines may only about 100 kilowatts. This section will discuss wind farms and also residential wind turbines.

3.1 Wind Farms

A wind farm consists of a group of wind turbines in the same area used to produce power. They could consist of hundreds of turbines which can cover many square kilometres in area. The land that the turbines occupy can still be used for agricultural needs. Wind farms can be located onshore or offshore depending on the project. For a wind farm to be built, a suitable site has to have appropriate wind speeds. The sites are chosen based upon wind energy maps, which show specific data critical for the wind farm. Data of wind speeds and direction are taken over a course of many years to create an accurate and reliable map. To have optimal energy production, wind turbines are spread out 5-9 rotor diameters apart in the each direction because the wind slows down as it passes through a turbine, thus there is no use placing turbines too close to each other. In offshore wind farms, the estimated capital costs of installing a wind turbine are 30-50% higher than onshore. Although offshore wind farms cost more at the start, they encounter higher wind speeds which mean increased energy production. This increased energy will generate more income thus, offsetting the capital costs by a little. The high capital costs associated with offshore wind installations are largely due to making the turbine foundations, installations and maintenance. We will examine an example of installing offshore wind turbines in the U.S.
The above figure shows the wind speeds at a tower height of 90m. Offshore winds blow more consistently and operate at a higher capacity than onshore turbines. Also the wind speed profiles match well with the periods of high demand by the cities surrounding it, which make offshore wind development worthy. This allows for better competition with fossil fuels because of a much lower carbon footprint. Also the coastal states have higher electricity rates compared to the inland states.

3.2 Small Wind Turbines

Small wind turbine installations can be used off-grid where all the energy used is generated at the site. They can also be connected to the grid and can be sold back to the utility for extra income. Small wind turbines are designed to be installed in residential areas often used as a backup electricity supply. As with a wind farm, producing energy with a small wind system also needs same considerations such as a reasonable wind speed, tower height, and location.
4.0 Economics

The increase in more renewable energy solutions are caused by the debate of climate change due to increased greenhouse gases. With the depletion of fossil fuels and the increasing oil prices, there has been a huge shift in favour of these free energy solutions. There has been increased awareness of the dangers and risks associated with using nuclear energy due to the recent nuclear disaster in Fukushima. Moreover, government incentives are made available for more renewable energy supplies to be created. The prospects for wind energy capacity are increasing every year and this section will show the increased capacity for the recent years.

In 2010 all the wind turbines installed represented 2.5% of the global electricity demand. This amount of energy far exceeds the demand of the entire population of the United Kingdom. China has a growing wind market and it dominates with having wind powered capacity of more than half the world market for new wind turbines. Although China has the greatest capacity ranked by country, Denmark has the highest capacity per capita at 0.675kW per person, compared to China which has only 0.033kW per person. Referring to the figure below, in the recent 10 years, the world total installed capacity has dramatically increased almost five times as much since 2001.

![World Total Installed Capacity](http://www.wwindea.org/home/images/stories/pdfs/worldwindenergyreport2010_s.pdf)
From the figure below we can see China is dominating the world market for new turbines which has more than half the world market.

Offshore wind capacity continued to grow significantly, which shows a growth rate as high as 59% from 2009 to 2010.
5.0 Concerns

Wind energy is a free renewable resource and it will always be abundant and readily available. Wind power generation consumes no fuel and water for its operation and is highly environmentally friendly. Wind power generation is not reliable in terms of available resources. It can only generate whenever wind is available. This causes the concern that it might not generate electricity when needed and generate it when it is needed. Although energy storage devices can be used, it may not meet the electricity demands in time. Usually the most efficient wind producing sites are often in remote locations which are far away from the demand location, and that those sites may be better off for other uses such as agriculture instead. In every renewable energy technology, there are always some concerns with the environment and costs.

5.1 Environmental Concerns

Even though the environmental impact compared to other traditional energy sources are minimal, the energy used to manufacture and transport the materials used to build wind turbines are substantial. According to Vestas, they state that the initial carbon emissions for producing the turbines are compensated within 9 months of operation for their offshore turbines. Wind farms can cover a large area of land which would have been used for agriculture. Also wind farms are strategically placed to ensure the highest efficiency. In this case, often wind turbines are placed on top of hills which lead to complaints about visibility of the landscape. In addition, the noise produced by a turbine causes complaints from the people living around them. The noise of a typical wind turbine at 250m away is 45dB which is as low as the background noise in an office. Furthermore the concern for avian deaths has been analyzed. A study showed that the amount of bird deaths due to wind turbines is very low.
5.2 Costs

The cost to maintain a wind farm is very low, but the capital costs are moderate. The high construction costs can make the total cost to build wind turbines higher than regular fossil fuel burning plants. Also the total cost to produce a commercial wind turbine varies significantly depending on contracts, type of turbine, location and many other factors. In 2007 a commercial scale wind turbine cost between $1.2 million to $2.6 million per megawatt. However, in the recent years the cost to produce wind power has dropped. There are subsidies provided by many countries in order to encourage the development of renewable energy sources. In Canada, U.S. and Germany, they provide incentives for the construction of wind turbines.
6.0 Conclusion

This report examined the fundamentals of extracting wind energy into usable electrical energy. The concept of harvesting renewable energy sources has been around for many years and only have we recently began to shift towards these sources. Many countries have energy targets that will need to be met and to achieve these goals, they will have to invest in many of these technologies. The environmental benefits of wind energy outweigh any other non-renewable energy source. Many countries already have large wind farms in place and many other countries are soon to follow their steps. Wind farms are the main generator of wind power, but there are also small residential wind turbines which can be used off-grid. The different types of wind turbine configurations are chosen to suit the land capable of its use. Many factors are considered before a wind turbine can be installed. Wind speed and direction play a dominating factor in choosing a suitable site. Eventually our planet will meet our energy targets and we will be able to sustain our planet much longer than before.
Works Cited


