Wind contains huge amount of kinetic energy.
Windmills have been used for at least 3000 years.
The use of wind turbines to generate electricity started from late 19th century, e.g. 12 kW DC wind turbine generator constructed by Bush, USA.
Because of the wide spread of inexpensive grid power supply, there was little interest in using wind energy for much of the 20th century.
The re-emergence of wind energy occurred in late 20th century because of the shortage of fossil fuels.
On 14 July 2003, the UK government announced a project to build the world’s biggest wind farms in three sites off the English coast, providing enough power for one in six British homes, which will boost the renewable energy sector so that Britain can reach its target of 10% of electricity from renewables by 2010.
Introduction

- Worldwide growth of wind energy capacity

- Incentives make small wind systems more economic

Introduction

- Cost of wind energy

1979: 40 cents/kWh

2000: 4 - 6 cents/kWh

- Increased Turbine Size
- R&D Advances
- Manufacturing Improvements

2004: 3 – 4.5 cents/kWh

Introduction

- Trend of wind energy cost

12 mph is Class 3 wind power
14 mph is Class 5 wind power

- Net metering only
- 50% buy-down and net metering

NSP 107-MW Lake Benton wind farm
4 cents/kWh (unsubsidized)
Global winds are caused by pressure differences across the earth’s surface due to the uneven heating of the earth by solar radiation. In a simple flow model, air rises at the equator and sinks at the poles.

The atmospheric winds are affected by many factors, such as the pressure gradient, gravitational forces, inertia of air, the earth’s rotation, friction with the earth’s surface (resulting in turbulence).

As shown in the diagram above, the worldwide wind circulation involves large-scale wind patterns, affecting prevailing near surface winds, that cover the entire planet.

It should be noted that this model is an oversimplification because it does not reflect the effect that land masses have on the wind distribution.

Variation of wind speed can be divided into inter-annual, annual, diurnal, and short term (gusts and turbulence).

The kinetic energy per unit time or power of a mass flow of air through a rotor disk is

\[ P = \frac{1}{2} \frac{dm}{dt} U^2 = \frac{1}{2} \rho A U^3 \]

where \( \frac{dm}{dt} = \rho A U \)

The wind power per unit area or wind power density is

\[ \frac{P}{A} = \frac{1}{2} \rho U^3 \]

Note: Under standard condition (sea-level, 15°C), the density of air is 1.225 kg/m³

Qualitatively, a wind resource is poor if the hourly average wind power density \( \frac{P}{A} \) is less than 100 W/m², good if \( \frac{P}{A} \approx 400 \) W/m², and great if \( \frac{P}{A} > 700 \) W/m².
Wind Resources
-- Statistical analysis of wind data

- Rayleigh distribution
  \[ p(U) = \frac{\pi}{2} \left( \frac{U}{\bar{U}} \right)^2 \exp \left[ -\frac{\pi}{4} \left( \frac{U}{\bar{U}} \right)^2 \right] \]

- Weibull distribution
  \[ p(U) = \left( \frac{k}{c} \right) \left( \frac{U}{c} \right)^{k-1} \exp \left[ -\left( \frac{U}{c} \right)^k \right] \]
  \[ k = \left( \frac{\sigma_U}{\bar{U}} \right)^{-1.86} \]
  \[ c = \frac{\bar{U}}{\Gamma(1+1/k)} \]
  \[ f(x) = \left( \frac{2\pi \sigma_U}{U} \right)^{1/2} \left( e^{-\left( \frac{x-\bar{U}}{\sigma_U} \right)^2} - \frac{1}{12 \pi \sigma_U^2} \left( \frac{x-\bar{U}}{\sigma_U} \right)^2 \right) \]

Wind Resources
-- Wind map

Wind Power Generating System

- Rotor – Wind turbines (HAWT or VAWT)
- Hub – Pitch control
- Drive train – Gear box
- Generator – Synchronous or induction
- Main frame / Yaw system – Direction control
- Control system – Variable speed control
- Balance of electrical system – Transformer
- Tower and foundation

Wind Turbines
-- Various concepts of horizontal & Vertical axis turbines

Horizontal axis turbines
- Single-bladed
- Double-bladed
- U.S. farm windmill
- Multi-bladed
- Reciprocating blades

Vertical axis turbines
- Darrieus
- Sirocco
- Others

Various concepts for horizontal axis turbines (Eldridge, 1985)
Various concepts for vertical axis turbines (Eldridge, 1985)
Wind Turbines

- **HAWT vs VAWT**

**HAWT** – suitable for both small and large systems, and most commercial wind turbines are HAWT.
- Advantages: High wind speed at a greater height, High efficiency
- Disadvantages: Complex system, High installation cost for large systems (Generator and gearbox installed on top of tower)

**VAWT** – suitable for small systems
- Advantages: Gearbox and generator can be placed on the ground, Do not need a yaw system to turn the rotor against wind
- Disadvantages: Wind speed is low near the ground, Low efficiency, May need guy wires to hold the turbine, and difficult maintenance

Wind Turbines - Number of blades of horizontal axis turbines

- For the reason of mechanical stability of the turbine, even number of blades are avoided in large systems. At the very moment when the uppermost blade bends backwards, because it gets the maximum power from the wind, the lowermost blade passes into the wind shade in front of the tower.
- Most modern wind turbines are three-bladed designs with the rotor position maintained upwind (on the windy side of the tower) using electrical motors in their yaw mechanism. This design is usually called the classical Danish concept, and tends to be a standard against which other concepts are evaluated. The vast majority of the turbines sold in world markets have this design.
- Two-bladed wind turbine designs have the advantage of saving the cost of one rotor blade and its weight. However, they tend to have difficulty in penetrating the market, partly because they require higher rotational speed to yield the same energy output. This is a disadvantage both in regard to noise and visual intrusion. Two- and one-bladed machines require a more complex design with a hinged (teetering hub) rotor as shown in the picture, i.e. the rotor has to be able to tilt in order to avoid too heavy shocks to the turbine when a rotor blades passes the tower. The rotor is therefore fitted onto a shaft which is perpendicular to the main shaft, and which rotates along with the main shaft. This arrangement may require additional shock absorbers to prevent the rotor blade from hitting the tower.
- One-bladed wind turbines can save the cost of another rotor blade. One-bladed wind turbines are not very widespread commercially, however, because the same problems that are mentioned under the two-bladed design apply to an even larger extent to one-bladed machines. In addition to higher rotational speed, and the noise and visual intrusion problems, they require a counterweight to be placed on the other side of the hub from the rotor blade in order to balance the rotor. This obviously negates the savings on weight compared to a two-bladed design.

**Betz’s law**

Betz’ law states that only less than 16/27 (or 59%) of the wind power can be converted into mechanical power using a wind turbine.

Consider a disk of air of mass \( \rho A dx \). After it passes the turbine, its speed varies from \( U_1 \) to \( U_2 \). The kinetic energy extracted by the turbine is

\[
de = \frac{1}{2} \rho A (U_1^2 - U_2^2) dx
\]

and the power

\[
P = \frac{dE}{dt} = \frac{1}{4} \rho A (U_1^2 - U_2^2) (U_1 + U_2)
\]

Therefore

\[
P = \frac{1}{2} \left( 1 - \frac{U_2}{U_1} \right)^2 \left( \frac{U_1}{U_1 - U_2} \right) P_0
\]

where

\[
\frac{dx}{dt} = \frac{U_1 + U_2}{2} \quad \text{and} \quad P_0 = \frac{1}{2} \rho AU_1^3
\]

**Turbine capacity vs rotor diameter and tower height**

- Rated capacity: 50 kW to 5000 kW
- Rotor diameter: 15 m to 113 m
- Tower height: 25 m to 170 m
- Washington Monument: 160 m
Wind Power Generators

\textbf{- Fixed speed operation}

- The stator frequency of an induction generator is independent of its rotor speed.
- In modern systems, e.g. Opti Slip ® (Vestas, Denmark), the slip of the generator is allowed to vary slightly if the torque varies. This means that there will be less wear and tear on the gearbox. The slight variation of slip is achieved by varying the rotor circuit resistance.
- In Opti Slip ®, the external resistors and switches are mounted on the rotor while the control signal is transmitted to the rotor via an optical fibre mounted on the stator and the control signal is sent to the rotor every time it passes the optical fibre.

\textbf{- Variable speed operation}

- By allowing the variation of speed, the generator is able to capture the maximum energy contained in gusty winds.
- The system above requires the converter to be rated full capacity as the generator, which increases the system cost.
- Typically used with PM synchronous generators
- Vector control techniques are employed in modern systems.

\textbf{- Doubly fed induction generator}

- Doubly fed induction generators need a converter of only $\frac{1}{4}$ to $\frac{1}{3}$ of its capacity depending on the variable speed range.
- It needs a wound rotor induction generator, which uses slip rings and brushes and the maintenance can be difficult and expensive.
- Wound rotor is not as robust and economic as the squirrel cage rotor.
- A special form of vector control is employed in modern systems.
For a given turbine of diameter $D$ meters, the wind power it can harvest at a wind speed $U$ m/s can be expressed as

$$P_{wind\,power} = \frac{1}{2} \rho \pi D^2 U^3 C_P$$

where $C_P$ is the power coefficient, which is determined by the aerodynamic design of the turbine and varies with the tip speed ratio $\lambda$ (the ratio of rotor tip speed to free wind speed), $\eta$ the drive train efficiency, and $\rho$ the mass density of air, which is 1.225 kg/m³ under standard condition (sea level, 15°C).

The diagram above illustrates the $C_P - \lambda$ curve of a 225 kW wind turbine of a rotor diameter of 20 m.

Direct drive was developed on the basis of variable speed drive techniques. Using direct drive, the gear box can be eliminated and the following benefits can be achieved:
- lower maintenance
- lower acoustic noise
- lower mass
- lower losses
- lower cost

Direct drive requires the generator to operate at low speeds and high torque. This may result in large generator volume, which would increase the cost of tower, nacelle and installation.

Most direct drive generators are PM synchronous generators. With special design, it is also possible to have direct drive induction generators.
Wind Power Generators
- Westwind/UTS 20kW PM synchronous generator

Turbine
PM Generator
PWM Converter
DC Bus
PM Generator
PWM Converter
To Power Grid

Wind

Efficiency at constant DC voltage = 282 V

DC CURRENT (A) (Note: DC voltage was constant at 282V)

EFFICIENCY (%)

Output power (kW)

Torque per unit total mass

Nordex asynchronous geared
Durham/UMIST concept design direct drive
Nordex 20 kW direct drive
Durham UMIST direct drive PM synchronous generator

Enercon direct drive PM synchronous generator

Wind Power Generators
- Efficiency at constant DC voltage = 282 V

DC CURRENT (A) (Note: DC voltage was constant at 282V)

EFFICIENCY (%)

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Durham/UMIST concept design direct drive
Nordex 20 kW direct drive
Durham UMIST direct drive PM synchronous generator

Enercon direct drive PM synchronous generator

Wind Power Generators
- Enercon direct drive PM synchronous generator

Technology of the E-36-33
Power transmission via a gearless drive to a low-speed high-torque generator

Technology of the E-48
The rotor of the multi-pole generator is directly connected to the rotor blades via the hub.

IN COMPARISON - E-36-33
Wind Power Generators
- Enercon direct drive PM synchronous generator

Wind Power Generators
- ABB windformer

The first installation of ABBs Windformer is a 3 MW mill at Näsudden on southern Gotland, Sweden.
Rated capacity: 3 MW, achieved at a wind speed of 13 m/s
Wind speed range: 5 – 29 m/s
Estimated annual production: 8.2 GWh, based on an average

Wind Power Generators
- UTS twin stator doubly fed induction generator

Research team:
- J.G. Zhu
- V. Ramaswamy
- D. Basic
- G. Boardman
- S. Jayatileke
Wind Energy

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