Wind Turbines

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Outline

• Wind profiles and their effects
• Turbine capacity factor
• Turbine power controls
• Effect of rated power per unit rotor area
• Tip speed ratio
• Turbine power calculator
• Environmental effects

Wind Change with Elevation

• Wind speed is zero at ground level
• Simple equation for wind speed at height, \( z \), relative to reference elevation, \( z_r \), is \( v(z) = v(z_r)(z/z_r)^a \)
  – Value for \( a \) varies with area (urban vs. rural) and day vs. night
  – Can be determined in terms of atmospheric stability conditions
  – Default value is \( a = 1/7 \)

Wind Change with Elevation II

• Roughness length, \( r = z_0 \), accounts for rough terrain effects
  – \( z_0 \) is effective elevation where wind speed is zero (instead of ground at \( z = 0 \))
• Equation for wind speed at height, \( z \), relative to reference elevation, \( z_r \), is \( v(z) = v(z_r) \ln(z/z_0) / \ln(z_r/z_0) \)
  – Assumes neutral stability (ground neither heated or cooled)

Roughness Parameters

• Open water (\( r = 0.0002 \) m)
• Completely open terrain with smooth surface (\( r = 0.0024 \) m)
• Agricultural area varying amounts of fences, hedgerows, buildings (\( r = 0.03 \) m, 0.055 m, 0.1 m, 0.2 m)
• Small villages (\( r = 0.4 \) m)
• Larger cities with tall buildings (\( r = 0.8 \) m)
• Very large cities/skyscrapers (\( r = 1.6 \) m)
More on Roughness

- Can get same power at lower tower heights with smoother surfaces
- Typical onshore tower heights are about the same as the rotor diameter
- Typical offshore tower heights are about 0.75 times the rotor diameter
- Offshore winds also have less impact from obstacles (“wind shade”)

Wind Capacity Factor

- Normally want a high capacity factor to make best use of capital investment
- For wind, fuel is free and speeds above rated power speed are useless
  - Can pick a small turbine that will run a large fraction of the time giving a high capacity factor but a low energy output
  - A larger turbine will have a smaller capacity factor but could have a larger energy output

Wind Turbine Standards

- Developed by International Electrotechnical Commission (IEC)
  - IEC 6400-nn standards for wind turbines
  &progdb=db1&committee=TC&number=88
- American Wind Energy Association (AWEA) is represents US on IEC

Turbine Power Controls

- Pitch controls – adjusts the angle of the blades (pitch)
  - Reduces fraction of power extracted from wind, keeping generator power constant
- Stall controls adjust design the angle of the rotor blades to reduce lift force at higher wind speeds
  - Maintains constant force on rotor shaft as wind speed increases above maximum

Turbine Power Controls II

- Passive stall control
  - uses basic rotor design to ensure proper control
  - no changes in rotor blades’ position during operation
- Active stall control
  - Changes blade pitch to increase stall force in a manner similar to pitch control
Power/Area Ratio

- Use larger rotor area to develop same power in lower winds
- Chart on next two slides taken from report prepared for California Energy Commission by California Wind Energy Collaborative at UC Davis
  - CEC-500-2005-181, December 2005
  - Shows data for several wind turbines ranked by ratio of rated power divided by rotor area (W/m²)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Rated Power (MW)</th>
<th>Rotor Diameter (m)</th>
<th>Power/Area (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEG Micon</td>
<td>1.5</td>
<td>82</td>
<td>284</td>
</tr>
<tr>
<td>GE Wind</td>
<td>1.5</td>
<td>77</td>
<td>322</td>
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<td>Vestas</td>
<td>1.8</td>
<td>80</td>
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<tr>
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<td>GE Eind</td>
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<tr>
<td>Bonus</td>
<td>1.3</td>
<td>63</td>
<td>417</td>
</tr>
</tbody>
</table>

Tip Speed Ratio

- Measure of this factor is called the tip speed ratio, \( \lambda = r \omega / V \)
  - \( r \) is rotor radius
  - \( \omega \) is rotational speed of rotor
  - \( V \) is wind speed
- Measure of resistance to air flow due to rotor rotation to the air
  - No blade rotation, little resistance
  - High speed blade rotation would make the rotor look more like a solid

Equation for Maximum \( C_p \)

\[
C_{p,\text{max}} = \frac{16\lambda}{27} + \frac{1.32 + \left(\frac{\lambda - 8}{20}\right)^2}{B^3} - \frac{0.57\lambda^2}{C_L/C_D \left(\lambda + \frac{1}{2B}\right)}
\]

- \( \lambda \) = tip speed ratio (4 ≤ \( \lambda \) ≤ 20)
- \( B \) = number of rotor blades (1 ≤ \( B \) ≤ 3)
- \( C_L/C_D \) = lift-to-drag ratio (\( C_L/C_D \) > 25)
- Actual \( C_p \) values may be less if blades do not have optimum design because of manufacturing requirements (also hub friction losses)
Maximizing $C_p$

- Generators need to operate at a constant speed to maintain a fixed voltage for the grid
- Want rotor speed variation for rotor-tip speed that maximizes $C_p$
- Current solution is use of variable speed drives and inverter or rectifier to provide constant voltage for grid

Turbine Power Calculator

- Provides calculations of annual energy output for various turbine models
- Allows specification of user-input power curve (kW output vs wind speed)
- Uses Weibull parameters for wind distribution
  - Some location wind data or user input

Environmental Impacts

- Visual impact
- Noise
- Effect on birds (avian impacts)
- Electromagnetic interference
- Not discussed
  - Environmental benefits in reduction of fossil-fuel generated pollutants, including greenhouse gas CO$_2$

Mitigating Visual Impacts

- Use local land forms to minimize visibility of roads and avoid erosion
- Use buildings that minimize urban or industrial appearance of rural projects
- Use non-obtrusive colors and designs
  - May conflict with flight regulations and with methods to reduce avian impact
- Design electrical lines to reduce their visual impact

Mitigating Visual Impacts II

- Minimize signs
- Use minimal lighting required for safety and aircraft warnings
  - May help to reduce effects on birds who feed on insects attracted to lights
- Control layout of turbines, especially different types, to minimize visual impact

Turbine Noise

- Mechanical noise from gears, cooling fans, generator, yaw drives, etc
  - Can be minimized by low noise designs and is not significant in new turbines
- Aerodynamic noise
  - From flow of air around turbine blades
  - Generally increases with tip speed
  - Broadband character
  - Main noise component
Sound Basics

• Sound power level, $L_W$, in decibels (dB) = $10 \log_{10}(W/W_R)$
  – $W$ = source sound power
  – $W_R$ = reference sound power (10$^{-12}$ W)
• Sound pressure level, $L_p$, in decibels = $10 \log_{10}(p/p_R)$
  – $p$ = instantaneous sound pressure
  – $p_R$ = reference sound pressure = 200 $\mu$Pa

Sound Basics II

• A change of 1dB cannot be perceived
• A 3 dB change is barely perceptible
• A 5 dB change will generate some community response
• A 10 dB increase in sound is perceived as a doubling of sound
  – This will almost always result in an adverse community response
• Frequency weighting on A, B, C scales

Sound Basics III

• dB(A) scale weighted towards frequencies to represent human hearing
  – Threshold 0 dB(A)
  – Wisper 30 dB(A)
  – Talking 60 dB(A)
  – City traffic 90 dB(A)
  – Rock concert 120 dB(A)
  – Pain threshold 140 dB(A)
  – Jet engine 10 m away 150 dB(A)

Decibel Weighting Scales

Wind Turbine Noise

• Energy in sound waves (and sound intensity decreases with square of distance from source)
• The sound level emitted by a wind turbine is about 100 dB(A)
• One rotor diameter (43 m) away the sound is about 55 – 60 dB(A)
  – Applies to white noise; humans perceive pure tones more easily

Wind Turbine Noise II

• Since noise level is on a log scale, doubling the sound pressure level increases the total sound by 3 dB(A)
  – $SPL_1 = 10 \log_{10}(p/p_R)$
  – $SPL_2 = 10 \log_{10}(2p/p_R) = 10 \log_{10}(p/p_R) + 10 \log_{10}2 = SPL_1 + 3$
• Sound map calculator available at http://www.windpower.org/en/tour/env/db/dbcalc.htm
Reducing Noise

- New blade designs reduce noise
- Avoid slits, holes, blunt regions, and other obstructions that generate noise
- Three main contributions
  - Trailing edge noise
  - Tip noise
  - Inflow turbulence noise
- Various regulations limit noise from turbines in US and Europe

Avian Impacts

- Wind energy advocates usually say that problems are only associated with migration routes as in Altamont Pass
- Look at impact relative to other sources
- Audubon society supports wind energy
  - "When you look at a wind turbine, you can find the bird carcasses and count them. With a coal-fired power plant, you can't count the carcasses, but it's going to kill a lot more birds." — John Flicker, National Audubon Society, president

Reducing Avian Impacts

- Avoid migration corridors
- Fewer, larger turbines
- Avoid micro habitats or fly zones
- Tower designs with few or no perch sites
- Remove nests and birds from site
- Bury electrical lines
- Site specific studies

Bat Deaths

- Unexpectedly high bat fatalities at wind energy sites, especially those on ridge tops in the eastern United States
- The Bats and Wind Energy Cooperative (BWEC) formed in 2003
  - Bat Conservation International (BCI), US Fish and Wildlife Service, American Wind Energy Association (AWEA), and NREL
  - http://www.batsandwind.org/
Electromagnetic Interference

- Based on scattering off rotating blades
  - Same signal may be received (with distortion) simultaneously by two receivers
  - Effect lessened by modern turbines that do not use metal in rotor blades
  - Not a problem if electromagnetic signals are not present
  - Not well understood in a quantitative sense for improved designs