Study Guide: How Wind Turbines Really Work- The Hidden Secrets

Here is a study guide on how wind turbines work, drawing on the provided sources:

Wind Turbine Fundamentals: A Study Guide

This guide covers the core principles, components, and operation of wind turbines, explaining how they convert wind energy into electricity.

I. Introduction to Wind Energy

- A wind turbine's primary function is to **convert the kinetic energy of the wind into mechanical energy**, which is then **converted into electrical energy**.
- The energy of the wind can be felt on a hand and can turn a windmill.
- Attaching a generator to a spinning mechanism can produce electricity. A simple DC motor, when its shaft is spun, produces a voltage.
- Different sizes of wind turbines exist: small ones can power an LED, larger ones a small home, and **mega turbines can power entire towns**.

II. Site Selection and Physical Characteristics

- **Height and Wind Speed:** The speed of the wind **increases the higher we go** and is also **less turbulent** at greater heights. Large blades need to be higher off the ground. Towers reduce in diameter as they reach the top, rising high to reach the strongest wind.
- **Blade Size:** The **larger the blades, the more wind energy** can be captured. The speed of the wind is the largest influencer in power generation.
- **Location Challenges:**
  - **Transport:** Large turbines are difficult to transport.
  - **Offshore vs. Onshore:** Largest turbines are often found out at sea where space isn't a problem, although it's cheaper and easier to install them on land.
  - **Visual and Noise Impact (Onshore):** On-land turbines can mark the landscape, cast flickering shadows, and create noise.
- **Foundations:** Wind turbines require a **deep, strong foundation**. This can extend into the seabed, or for very deep waters, turbines can float on a platform.

III. Turbine Orientation and Efficiency

- **Facing the Wind:** The wind turbine needs to **face the wind**, as wind direction changes.
- **Yaw System (Large Turbines):** Large turbines do not have a tower fin. Instead, they use a **wind vane** to determine wind direction and an **anemometer** to measure wind speed. A computer controls **yaw motors** that turn the nacelle to align it with the wind. Once

aligned, brakes are applied to hold it in position. An encoder counts how far the turbine has rotated to prevent twisting of power cables running down the tower.

- **Tower Fin (Smaller Turbines):** Smaller wind turbines typically have a **large tail fin** that allows them to align their blades into the wind. Without it, they turn away from the wind, making it less efficient as wind hits the nacelle and tower first.
- **Upwind vs. Downwind:**
  - **Upwind** is more efficient because the wind hits the blades before the tower and nacelle. However, blades need to be stronger to prevent bending and hitting the tower.
- **Vertical Wind Turbines:** These work in any wind direction and do not need a yaw system. However, they are usually **less efficient** and **don't scale up very well** compared to horizontal designs.

IV. Key Components of a Wind Turbine

- **Steel Tubular Tower:** Rises high, reduces in diameter towards the top. Contains an access ladder for engineers, power cables, and often a transformer at the base.
- **Nacelle:** A **fiberglass housing** that covers the bed plate and all main components, protecting them from weather. Located on top of the tower.
- **Bed Plate:** The main support structure on top of the tower, attached to a large bearing and ring gear.
- **Yaw Motors:** Bolted onto the bed plate, their gears interlock with the large bearing gear to control turbine direction.
- **Electrical Generator:** Located at the back of the bed plate. Converts mechanical energy into electricity. Common types include:
  - **Doubly Fed Induction Generator (DFIG):** Most common for large wind turbines. Consists of a rotor (with three sets of coils and slip rings) and a stator (with three sets of coils).
  - **Permanent Magnet Generators:** Often used in small direct-drive turbines.
  - **Three-phase Brushless Motor:** Used in smaller domestic turbines.
  - **Brushed DC Generator or Basic DC Motor:** Used in tiny DIY wind turbines.
- **Gearbox:** Connects the main low-speed shaft from the hub to the high-speed shaft of the generator. It **increases the rotational speed** from the blades (e.g., 18 rpm) to the speed required by the generator (e.g., 1800 rpm). Typically a **three-stage gearbox** consisting of a planetary gear set and two spur stages.
- **Shafts:**
  - **Main Low-Speed Shaft:** Connects the hub to the gearbox. Supported by the main bearing. Rotates slowly but with high torque.
  - **High-Speed Shaft:** Connects the gearbox to the electrical generator. Rotates quickly with low torque.
- **Bearings:** Large bearing and ring gear support the bed plate. The main bearing supports the low-friction rotation of the low-speed shaft. Geared bearings allow blades to be tilted.
- **Hub:** The metal structure at the front where blades bolt on. Covered with a nose cone for protection and aerodynamics.
- **Blades:** Bolt onto the hub. Typically made from **reinforced glass fiber** for strength and lightness, allowing them to be longer to capture more wind.

- **Blade Pitch Motors:** Typically three motors inside the hub that interlock with geared bearings, allowing the **blades to be tilted**.
- **Brakes:**
  - **Hydraulic Brakes and Large Disc Brake:** Hold the turbine in position (yaw system).
  - **Hydraulically Controlled Disc Brake:** Attached to the high-speed shaft.
  - **Hydraulic Disc Brake:** At the back of the gearbox (on the low-torque shaft, easier to stop). Brakes hold the turbine in place (e.g., during maintenance). Blades are first used to stop rotation.
- **Electrical and Controls Panel:** Usually found at the back of the bed plate near the generator.
- **Power Cables:** Run from the generator down the tower to the transformer.
- **Transformer:** Located at the base of the tower, it prepares the electricity to be sent to the electrical grid.

V. Blade Design and Aerodynamics

- **Aerofoil Shape:** Blades have an aerofoil shape. The shape and twist change along the length to improve aerodynamic efficiency.
- **Terminology:**
  - **Leading Edge:** The front of the aerofoil.
  - **Trailing Edge:** The rear of the aerofoil.
  - **Chord Line:** The line between the leading and trailing edges.
- **Angle of Attack:** The difference between the chord line and the relative wind direction. Tilting the blade alters the amount of lift produced.
- **Forces:**
  - **Drag:** Forces that act parallel to the wind, slowing the blade down, caused by friction and resistance from the blade's shape. Aerofoil is designed to minimize drag.
  - **Lift:** The aerofoil design forces air to travel a longer distance over the top, increasing its speed and decreasing pressure (Bernoulli's principle). This creates a lower pressure region above and a higher pressure region below, pushing the blade upwards. Air colliding with the underside and being deflected downwards also contributes to lift. Lift forces are maximized by the aerofoil design.
- **Blade Tilting (Pitch Control):**
  - Used to **control how fast the blades rotate**, which in turn controls how much power is generated, helping to stay under the generator's maximum rating.
  - As the angle of attack increases, more lift is generated.
  - If the angle of attack is too high, air streams separate and become turbulent, reducing lift and increasing drag, slowing rotation.
  - Optimal angle: Blades tilted to an optimal angle generate a large amount of lift and spin the hub very fast, generating more voltage. If blades are perpendicular to the wind, max drag occurs with no lift; if parallel, very little lift.

VI. Operational Parameters

- **Cut-in Speed:** The **minimum wind speed** at which the wind turbine will start. A generator with a load is harder to rotate, requiring a minimum wind speed to overcome this.
- **Cut-out Speed:** At a certain wind speed, the turbine will tilt its blades to stop generating power, and brakes will be applied to protect it.
- **Blade Tip Speed:** The tip of the blade travels much faster than the hub. If it travels too fast, it can break the sound barrier, creating a sonic boom and potentially ripping the blades apart.
- **Centrifugal Forces:** Even at low speeds, large centrifugal forces act on the blades.

VII. Number of Blades

- **One Blade:** Very slow, unstable, low voltage, hard to self-start.
- **Two Blades:** Self-starting, much more stable, higher voltage than one blade. Common in medium-sized turbines due to being cheap and fairly stable.
- **Three Blades:** Produces slightly higher voltage than two blades, much harder to stop, very stable, and costs the least to build. This is the **obvious choice for large turbines**.
- **Four/Five Blades:** Produce slightly higher voltage than three, but voltage starts to drop with five blades.
- **Six Blades (or many blades):** Produces even lower voltage and is very hard to stop. Micro wind turbines might have many blades because they are installed lower and experience slower, weaker wind speeds.

VIII. Electricity Generation and Grid Integration

- **Generator Operation:**
  - When the hub and shafts rotate, the generator's rotor turns, inducing a voltage and generating electricity.
  - A basic generator has a magnet at the center of the rotor and a coil on the stator. When the rotor rotates, the magnetic field interacts with electrons in the wire, creating an alternating current (AC) with a sine wave.
  - The **frequency** of the AC current depends on the rotational speed of the rotor. Household outlets require 50 or 60 Hertz.
  - To achieve this frequency, the generator's rotor needs to rotate thousands of times per second (e.g., 18,000 rpm for a 60 Hz output with a two-pole generator). The gearbox helps achieve this speed.
- **Doubly Fed Induction Generator (DFIG) in Detail:**
  - The rotor coils are connected to a three-phase electrical supply via slip rings.
  - Each rotor coil produces an alternating magnetic field that combines to create a **rotating electromagnetic field**.
  - The controller determines the frequency and direction of this rotating electromagnetic field.
  - As this field rotates, it **induces a voltage into the stator coils**, generating AC current for the grid.
  - The controller constantly adjusts the frequency of the rotor current to **maintain a consistent 60 Hz output**(or 50 Hz) for the grid, even with variable wind speeds.

    This is achieved by combining the rotor's physical rotation speed with an applied electromagnetic field that compensates for speed differences.
  - If the rotor speed matches the required synchronous speed (e.g., 18,000 RPM for 60Hz), a constant DC current is applied to the rotor.
- **Power Flow:** The generator's output flows through a cable down the tower to a transformer, then is sent to the electrical grid for distribution.
- **Grid Connection:** Solar power plants and wind power plants are generally **connected to the electrical grid system**.
- **Inverters: Power inverters are used to convert the DC current** from solar cells (or the raw output from some simpler generators) **to AC current** before it is fed to the grid.
- **Renewable Energy Combination:** Wind and solar are a great combination because it's usually either sunny or windy.

IX. Challenges and Limitations

- **Global Energy Contribution:** Despite negligible running costs, solar photovoltaic's total global energy contribution is only 1.3% [from previous source, but relevant context].
- **Capital Costs and Efficiency:** The main challenges for solar photovoltaic panels are capital costs and efficiency constraints, which do not yet match conventional energy options [from previous source, but relevant context]. This implies similar challenges for wind power.
- **Storage:** While solar panels on home roofs can store electricity using batteries, **massive storage is not possible for large power plants** [from previous source, but relevant context].