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CAI 335 : SOLAR AND WIND ENERGY SYSTEMS

UNIT 4

WINDMILL DES AND APPLICATIONS

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Wind energy systems rely on wind turbines and windmills to convert wind energy into mechanical or electrical energy. These systems are fundamental to the production of renewable energy and are widely used for both small-scale and large-scale energy generation. Below is a detailed explanation of turbines, windmills, and their classifications in the context of wind energy systems.

1. Wind Turbines:

Wind turbines are devices that convert the kinetic energy of the wind into mechanical energy, which can then be used to generate electricity. A wind turbine consists of several key components:

Key Components:

- **Blades**: These are the most visible part of a wind turbine. The number, shape, and size of the blades affect the efficiency and power output of the turbine. Most turbines have three blades, though variations exist.
- **Hub**: The hub connects the blades to the shaft, allowing them to rotate together when wind passes over them.
- **Shaft**: The rotating blades turn the shaft, which is connected to a generator.
- **Generator**: The generator is responsible for converting the mechanical energy from the rotating shaft into electrical energy.
- **Nacelle**: The nacelle is the housing that contains the generator, gearbox, and other essential mechanical components.
- **Yaw Mechanism**: This mechanism turns the turbine to face the wind as it shifts direction.
- **Tower**: The tower supports the turbine and raises it to a height where wind speeds are more constant and stronger.

2. Windmills:

Historically, windmills were used to convert wind energy into mechanical power for grinding grain, pumping water, and other mechanical tasks. In modern contexts, "windmills" often refer to older technology, whereas "wind turbines" are used for generating electricity. However, windmills can still be used in rural areas for various purposes, such as water pumping, where electricity is not required.

Key Difference:

- **Windmills**: Primarily used for mechanical tasks like grinding grain or pumping water.
- **Wind Turbines**: Used for generating electricity through the conversion of wind energy into mechanical energy and subsequently into electrical energy.

3. Types and Classifications of Wind Turbines:

Wind turbines are classified based on various factors such as the axis of rotation, size, location, and the mechanism for power generation.

a. Classification Based on Axis of Rotation:

- **Horizontal Axis Wind Turbines (HAWT)**:
    - These are the most commonly used wind turbines.
    - In HAWTs, the main rotor shaft is horizontal and faces the wind directly. The blades rotate around a horizontal axis.
    - Example: The typical three-blade wind turbines you see in wind farms.
    - **Advantages**: High efficiency, well-suited for large-scale commercial energy production.
    - **Disadvantages**: Require yaw control systems to adjust the position of the blades to face the wind.
- **Vertical Axis Wind Turbines (VAWT)**:
    - In these turbines, the main rotor shaft is vertical, and the blades rotate around a vertical axis.
    - Example: Darrieus or Savonius turbines.
    - **Advantages**: Do not require yaw control; they can capture wind from any direction.
    - **Disadvantages**: Lower efficiency compared to HAWTs, mechanical complexity due to the placement of generator and gearbox at the base.

b. Classification Based on Size:

- **Small-Scale Wind Turbines**:
    - These turbines are designed for use in residential homes, small businesses, or rural applications.
    - Power output generally ranges from 100W to 10kW.
    - Example: Residential wind turbines used for off-grid energy systems.
- **Large-Scale Wind Turbines**:
    - Used in wind farms for utility-scale energy generation.
    - Power output can range from 1.5MW to over 10MW per turbine.
    - Example: Offshore wind farms or large onshore wind farms used to supply electricity to the grid.

c. Classification Based on Location:

- **Onshore Wind Turbines**:
    - These turbines are located on land and are typically found in areas where wind conditions are favorable.
    - These turbines benefit from easier access for maintenance and lower installation costs.

- **Offshore Wind Turbines**:
    - Located in bodies of water (typically oceans), these turbines harness wind energy from stronger, more consistent winds at sea.
    - Offshore turbines are more expensive to install and maintain but are capable of generating more power due to the stronger winds.

4. Classification Based on Function:

- **Grid-connected Wind Turbines**:
    - These turbines are connected to the electricity grid and provide power to the utility grid.
    - Most commercial wind turbines fall into this category.
- **Off-grid Wind Turbines**:
    - These turbines are used in locations where grid connection is not feasible or economical.
    - Typically, they provide power to isolated areas or supplement other renewable energy sources like solar.

5. Operation and Power Generation Process:

The basic working principle of wind turbines involves the following steps:

1. **Wind blows over the blades**, causing them to rotate.
2. The rotating blades turn the **hub** and **shaft**, which is connected to the **generator**.
3. The mechanical energy from the rotating shaft is converted into **electrical energy** by the generator.
4. The electrical energy is sent through electrical cables to be either used directly, stored in batteries, or fed into the power grid.

6. Advantages of Wind Energy Systems:

- **Renewable**: Wind energy is a renewable resource that doesn't deplete over time.
- **Environmentally Friendly**: Wind energy is clean, producing no emissions or pollution during operation.
- **Sustainable**: Wind is abundant in many parts of the world, and wind energy systems can generate power without using fossil fuels.

7. Challenges in Wind Energy:

- **Intermittency**: Wind energy is not always available since the wind may not blow consistently.
- **Location Dependency**: Wind turbines require specific wind conditions and are typically located in areas with high average wind speeds.
- **Cost of Installation**: While the operational costs are low, the initial setup cost for large wind farms can be high, especially offshore wind farms.

Conclusion:

Wind energy systems, whether utilizing wind turbines for electricity generation or windmills for mechanical tasks, are an integral part of the renewable energy landscape. Understanding their classifications, mechanisms, and challenges is essential for optimizing wind energy production and transitioning toward a more sustainable energy future.

Power Curve in Wind Energy System

A **power curve** in a wind energy system is a graphical representation that shows the relationship between the wind speed and the electrical power output of a wind turbine. It is one of the most important characteristics of a wind turbine, as it helps predict the energy generation capability of the turbine under different wind conditions.

Understanding the power curve is crucial for wind turbine manufacturers, wind farm operators, and energy planners to assess how much electricity a turbine will produce over time and how it behaves under varying wind conditions.

1. Key Components of the Power Curve:

The power curve typically consists of several distinct phases, each corresponding to different wind speeds. The wind turbine's ability to generate power changes based on the wind speed, and the power curve illustrates this. Below are the key components:

a. Cut-in Wind Speed:

- The cut-in wind speed is the minimum wind speed at which the turbine begins to generate power.
- Typically, this value is between **3 m/s and 4 m/s** (meters per second), but it can vary depending on the design of the turbine.
- Below this wind speed, the turbine’s blades do not rotate fast enough to generate significant power.

b. Rated Wind Speed (Nominal Power Output):

- This is the wind speed at which the wind turbine reaches its **maximum rated power** (its nominal output).
- The turbine operates at full capacity or rated power from this wind speed onward until the **cut-out wind speed** is reached.
- The rated wind speed is typically around **12 m/s to 15 m/s**, depending on the turbine.

c. Rated Power (Maximum Output):

- The turbine's rated power is the maximum amount of power it can generate. This is the point where the turbine operates at its peak efficiency.
- From the rated wind speed onward, the turbine generates this maximum power despite further increases in wind speed.

d. Cut-out Wind Speed:

- The cut-out wind speed is the wind speed at which the turbine automatically shuts down to prevent damage to the mechanical parts.
- This is typically between **25 m/s and 30 m/s**.
- If wind speeds exceed this threshold, the turbine will stop operating to avoid stress on the blades, gearbox, and generator.

e. Wind Speed (x-axis) and Power Output (y-axis):

- The **x-axis** of the power curve represents the **wind speed** (measured in meters per second, m/s), and the **y-axis** represents the **power output** of the turbine (measured in kilowatts (kW) or megawatts (MW)).
- The shape of the curve shows how power output increases with wind speed up to the rated speed, after which it levels off at the rated power.

2. Phases of the Power Curve:

A typical wind turbine power curve can be divided into the following phases:

a. Low Wind Speed (0 to Cut-in Wind Speed):

- At wind speeds of **0 m/s to cut-in speed**, the turbine does not generate any power.
- In this range, the wind is not strong enough to turn the blades at a speed sufficient to generate electricity.

b. Increasing Wind Speed (Cut-in to Rated Wind Speed):

- Once the wind reaches the **cut-in speed**, the turbine begins to spin, and power output starts to increase.
- As wind speed rises, the turbine generates more power, typically in a non-linear fashion, as the blades begin to catch more wind and rotate faster.

c. Rated Power (Rated Wind Speed):

- When the wind speed reaches the **rated wind speed**, the turbine reaches its maximum power output, typically between **12 m/s to 15 m/s**.

- The power output stabilizes here, meaning that the turbine is operating at its full capacity.

d. High Wind Speed (Rated Wind Speed to Cut-out Wind Speed):

- Between the **rated wind speed** and the **cut-out wind speed**, the turbine continues to operate at its rated power. Even if the wind speed increases, the power output remains constant at the rated power level.
- This is a safety feature to prevent damage from excessively high wind speeds.

e. Cut-out Wind Speed and Shutdown:

- If the wind speed exceeds the **cut-out wind speed**, typically between **25 m/s to 30 m/s**, the turbine is designed to stop generating power.
- The turbine shuts down to avoid mechanical stress and damage to the blades and other components of the turbine.

3. Factors Influencing the Power Curve:

While the basic shape of the power curve is common to most wind turbines, several factors can influence its characteristics:

a. Turbine Design:

- The size and aerodynamic design of the blades, the generator, and the entire system significantly affect the power curve. Larger turbines generally have higher rated capacities and different power curve characteristics.
- The pitch control system (which adjusts the angle of the blades) also influences the power curve, particularly in managing the rated power phase.

b. Wind Resource (Location and Turbulence):

- The wind conditions at the location where the turbine is installed affect the power curve. Locations with consistent, high-speed winds will allow turbines to operate closer to their rated power more often.
- **Wind turbulence** (irregular wind flow caused by terrain, obstacles, or atmospheric conditions) can reduce the turbine's efficiency and alter the shape of the power curve.

c. Air Density:

- Air density varies with altitude, temperature, and humidity. Lower air density (e.g., at higher altitudes) results in less power generation for a given wind speed. Conversely, higher air density (cooler temperatures and lower altitudes) results in greater power output for the same wind speed.

4. Interpreting the Power Curve:

The power curve is crucial for understanding a turbine's performance and estimating energy production. Wind farm operators use this information to estimate the **capacity factor**, which is the ratio of the actual output of a turbine or wind farm to its maximum possible output if it were operating at full capacity all the time.

a. Capacity Factor:

- **Capacity factor** is an important performance indicator. It is calculated using the power curve and actual wind data over a specific period.
- For instance, if a turbine is rated at 1 MW and operates at an average output of 0.5 MW over a year, its capacity factor would be **50%**.

5. Example:

Let’s consider a wind turbine with the following specifications:

- **Cut-in wind speed**: 3 m/s
- **Rated wind speed**: 12 m/s
- **Cut-out wind speed**: 25 m/s
- **Rated power output**: 2 MW

If the wind speed is **5 m/s**, the turbine might generate **500 kW** (as the output increases with wind speed). At **12 m/s**, the turbine reaches **2 MW** and maintains that power output up until **25 m/s**, at which point it will shut down.

6. Conclusion:

The power curve is essential for understanding the operational behavior and energy output of a wind turbine. By knowing the wind conditions and how they correlate with the turbine’s power output, engineers and operators can optimize wind farm performance, plan maintenance schedules, and predict energy generation. It helps in understanding the **efficiency** of a turbine under varying conditions, and assists in making informed decisions about turbine selection, siting, and system operation.