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CAI 335 : SOLAR AND WIND ENERGY SYSTEMS

UNIT 4

WINDMILL DESIGN AND APPLICATIONS

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In wind energy systems, **batteries** and **energy storage** play critical roles in ensuring reliable and consistent power supply. Wind energy, while renewable and sustainable, is intermittent, meaning it depends on the availability of wind, which is variable throughout the day and year. To address this, energy storage systems, particularly batteries, are used to store excess energy produced during periods of high wind and release it during periods of low wind or when the energy demand exceeds the wind turbine's production. This storage system improves the efficiency, reliability, and economic viability of wind energy systems, particularly in **standalone systems** or off-grid locations.

Key Concepts of Wind Energy Storage

- **Energy Storage Systems (ESS):** These systems are designed to store electricity for later use. In the context of wind energy, they store surplus power generated by the wind turbines when demand is low and release it when wind energy production is insufficient.
 - **Batteries:** These are the most common form of energy storage in wind energy systems, especially in small-scale and standalone (off-grid) applications. They store electrical energy and release it as needed to ensure continuous energy supply.
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1. Role of Batteries in Wind Energy Systems

Batteries are essential for storing the energy generated by wind turbines when the wind is blowing. This stored energy is released when wind generation is insufficient, ensuring a stable power supply.

Key Functions of Batteries:

- **Storing Excess Energy:** When the wind turbine generates more energy than the system requires, the excess electricity is stored in the battery bank. This is crucial because wind energy generation is intermittent, and the wind may not always be blowing when demand is high.
 - **Providing Power During Low Wind:** When the wind slows down or stops, the battery discharges to supply power to the load (house, facility, etc.), ensuring that the user still has electricity even without wind generation.
 - **Load Management:** Batteries can help manage load variations by providing energy when demand spikes and the wind turbine cannot meet the power demand.
 - **Grid Independence (for Off-Grid Systems):** In standalone (off-grid) systems, batteries enable the wind turbine to operate independently of the electrical grid. In cases where wind power generation is insufficient, batteries can provide the energy needed to meet the demand, ensuring reliability.
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2. Types of Batteries Used in Wind Energy Systems

The type of battery used in wind energy storage depends on factors like the required capacity, budget, and the specific needs of the system. The most common types of batteries used in wind energy systems are:

a) Lead-Acid Batteries

- **Description:** Lead-acid batteries are the oldest type of rechargeable battery and are widely used in both off-grid and grid-connected wind energy systems. They are available in both flooded and sealed (maintenance-free) types.
- **Advantages:**
 - **Low Initial Cost:** Lead-acid batteries are cheaper than most other types of rechargeable batteries.
 - **Proven Technology:** They are widely used in various applications, including renewable energy systems, and have a well-established track record.
 - **Availability:** Lead-acid batteries are easy to find and maintain.
- **Disadvantages:**
 - **Limited Cycle Life:** Lead-acid batteries have a relatively short lifespan, typically 500-1,000 charge/discharge cycles, which means they need to be replaced more frequently.
 - **Lower Efficiency:** Compared to newer technologies, lead-acid batteries have lower energy efficiency and higher self-discharge rates.
 - **Environmental Impact:** Disposal and recycling of lead-acid batteries can be environmentally harmful due to the lead and acid components.

b) Lithium-Ion Batteries

- **Description:** Lithium-ion (Li-ion) batteries are increasingly popular in modern wind energy storage systems. These batteries have a higher energy density and are used in both small-scale and large-scale applications.
- **Advantages:**
 - **High Energy Density:** Li-ion batteries store more energy in a smaller and lighter package, making them more compact and efficient than lead-acid batteries.
 - **Longer Lifespan:** Li-ion batteries typically last 2,000-5,000 charge/discharge cycles, making them more durable than lead-acid batteries.
 - **Higher Efficiency:** They have higher round-trip efficiency (90-95%) compared to lead-acid batteries, meaning less energy is lost during charging and discharging.
 - **Fewer Maintenance Needs:** Lithium-ion batteries require minimal maintenance compared to lead-acid batteries.
- **Disadvantages:**
 - **High Initial Cost:** Li-ion batteries are more expensive upfront than lead-acid batteries, which can make them less attractive for small-scale systems.
 - **Temperature Sensitivity:** They perform poorly in extreme temperatures, especially cold weather, which can reduce their effectiveness in some locations.

- **Risk of Overheating:** If not properly managed, Li-ion batteries can overheat or experience thermal runaway, which may cause safety concerns.

c) Sodium-Sulfur (NaS) Batteries

- **Description:** Sodium-sulfur batteries are high-temperature batteries that are commonly used in large-scale renewable energy storage applications.
- **Advantages:**
 - **High Energy Density:** NaS batteries offer a higher energy density compared to lead-acid batteries and can store more energy in a given volume.
 - **Long Life:** These batteries have a long lifespan of approximately 4,500 cycles, making them suitable for large-scale wind energy storage.
- **Disadvantages:**
 - **High Operating Temperature:** NaS batteries must be maintained at high temperatures (around 300°C), which requires thermal management and makes them less suitable for residential applications.
 - **High Cost:** Sodium-sulfur batteries are expensive to install and maintain.

d) Flow Batteries

- **Description:** Flow batteries use two electrolyte solutions that flow through a cell to generate electricity. They are being explored for use in large-scale energy storage applications, including wind energy.
- **Advantages:**
 - **Scalability:** Flow batteries can be scaled up easily by increasing the size of the tanks containing the electrolytes, making them suitable for large-scale systems.
 - **Long Lifespan:** Flow batteries can last 5,000-10,000 cycles or more, offering longevity compared to other types of batteries.
 - **Modular Design:** They allow for modularity and flexibility, making them suitable for both small and large installations.
- **Disadvantages:**
 - **Low Energy Density:** Flow batteries have a lower energy density than lithium-ion batteries, requiring more space for energy storage.
 - **High Initial Cost:** Flow batteries are expensive to install, particularly for small-scale systems.

3. Energy Storage Technologies in Wind Energy Systems

While batteries are the most common form of energy storage, there are several other energy storage technologies used in conjunction with wind energy systems:

a) Pumped Hydro Storage

- **Description:** This is one of the oldest and most widely used forms of large-scale energy storage. It involves pumping water from a lower reservoir to an upper reservoir during periods of excess wind energy and releasing it back down to generate electricity when needed.
- **Advantages:** It offers high storage capacity and long operational lifespans.
- **Disadvantages:** It requires large geographical areas and specific topographies, making it unsuitable for all locations.

b) Compressed Air Energy Storage (CAES)

- **Description:** Compressed air is stored in underground caverns during periods of low energy demand and is released to generate electricity when demand rises.
- **Advantages:** CAES can store large amounts of energy and can be integrated into grid-connected systems.
- **Disadvantages:** It requires suitable geological formations and infrastructure, limiting its widespread use.

c) Flywheel Energy Storage

- **Description:** Flywheel systems store energy in the form of rotational kinetic energy by spinning a rotor at high speeds. The stored energy can be converted back into electrical power when needed.
- **Advantages:** Flywheels have high power output and fast response times.
- **Disadvantages:** Flywheels typically have lower energy storage capacity compared to batteries and require a high-speed rotor, making them suitable for short-term energy storage.

4. Challenges of Wind Energy Storage

- **Intermittency of Wind:** Wind is intermittent, and energy storage is essential for managing periods of low wind speed. However, storing energy for prolonged periods can be challenging.
 - **Cost:** Energy storage systems, particularly batteries, can be expensive to purchase and maintain, which increases the overall cost of wind energy systems.
 - **Energy Loss:** While modern batteries are efficient, they still suffer from energy losses during the charge/discharge cycles, reducing overall system efficiency.
 - **Space Requirements:** Some large-scale storage systems (like pumped hydro and CAES) require large geographical areas or specific site conditions that may not always be available.
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5. Future of Wind Energy Storage

The future of wind energy storage looks promising, with advancements in battery technology and alternative storage methods continuing to evolve. Some of the potential developments include:

- **Solid-State Batteries:** These offer higher energy density and safety compared to traditional lithium-ion batteries.
 - **Improved Flow Batteries:** Research into flow batteries may make them more cost-effective and scalable.
 - **Grid-Scale Storage Solutions:** Technologies like CAES and pumped hydro may see wider adoption as energy storage infrastructure improves.
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Conclusion

Energy storage is a crucial component of wind energy systems, particularly because wind power is intermittent. **Batteries** provide a reliable and efficient means to store excess energy for use during periods of low wind. The choice of battery depends on factors such as the scale of the system, energy needs, cost, and operational considerations. In addition to batteries, other storage technologies like pumped hydro, CAES, and flywheels are also being explored to meet the growing demand for energy storage in wind power systems. As storage technologies continue to evolve, they will play an increasingly important role in making wind energy a reliable and consistent power source for the future.

Wind Farms: Detailed Explanation

A **wind farm** (also known as a **wind power plant**) is a collection of **wind turbines** that are designed to work together to generate electricity from wind energy. Wind farms can vary in size and scale, from a few turbines to hundreds of turbines, depending on the geographical location, available wind resource, and power demand. These farms harness the kinetic energy of the wind and convert it into electrical power through a set of turbines connected to the electrical grid or to energy storage systems, depending on the configuration.

Wind farms are increasingly becoming an essential part of the global renewable energy landscape, contributing significantly to reducing greenhouse gas emissions and providing sustainable energy solutions. They can be located on land (onshore) or offshore, with each type having its own specific characteristics and advantages.

1. Components of a Wind Farm

A wind farm consists of several key components, including the wind turbines, electrical infrastructure, grid connection, and sometimes energy storage systems. Let's break them down:

a) Wind Turbines

The wind turbine is the core component of a wind farm. Each wind turbine is responsible for converting wind energy into electrical energy.

- **Blades:** Wind turbine blades are designed to capture the wind's kinetic energy. As the wind blows, the blades rotate, and this rotational energy is converted into mechanical energy through the rotor.
- **Rotor:** The rotor is made up of the blades and the hub, which connect the blades to the turbine's main shaft. The rotation of the blades drives the rotor.
- **Nacelle:** The nacelle houses the key components of the wind turbine, including the gearbox, generator, and control systems. It sits on top of the tower.
- **Gearbox:** The gearbox increases the rotational speed of the rotor to the speed necessary for the generator to produce electricity efficiently.
- **Generator:** The generator converts the mechanical energy from the spinning rotor into electrical energy (AC or DC depending on the system).
- **Yaw System:** The yaw system helps orient the turbine's rotor to face into the wind, maximizing energy capture.
- **Tower:** The tower supports the nacelle and rotor and positions the blades at an optimal height above the ground to capture the most consistent and strong winds.
- **Control Systems:** These systems monitor the turbine's performance, wind speed, and power generation. They also protect the turbine from damage by adjusting operation under extreme conditions (e.g., high winds).

b) Electrical Infrastructure

The electrical infrastructure of a wind farm is crucial for transmitting the electricity generated by the turbines to the grid or to a storage system.

- **Cables:** Cables connect the turbines to a central electrical substation where the electricity is collected.
- **Substation:** The substation is responsible for stepping up the voltage from the turbines to a level that is compatible with the local power grid. This is achieved through transformers and circuit breakers.
- **Grid Connection:** Wind farms are connected to the local electrical grid, which allows the generated electricity to be distributed to homes, businesses, and other consumers. The grid connection involves complex systems for synchronization, voltage regulation, and distribution.

- **Switchgear and Protection Systems:** These components ensure the safety and reliability of the electrical system by disconnecting faulty or damaged circuits and regulating the flow of electricity.

c) Monitoring and Control Systems

Wind farms are equipped with sophisticated **monitoring and control systems** to optimize performance and ensure operational safety.

- **SCADA (Supervisory Control and Data Acquisition):** SCADA systems are used to monitor real-time performance, track power output, and identify any malfunctions. These systems allow operators to manage the entire wind farm remotely.
 - **Data Logging and Analysis:** This involves gathering and analyzing data on wind speeds, turbine performance, and other environmental conditions to optimize turbine operation and energy production.
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2. Types of Wind Farms

Wind farms can be classified based on their location, scale, and design. The two main types of wind farms are:

a) Onshore Wind Farms

Onshore wind farms are located on land, typically in rural or coastal areas where wind speeds are higher and the terrain is suitable for the installation of turbines.

- **Advantages:**
 - **Lower Installation Costs:** Onshore wind farms tend to have lower capital costs compared to offshore wind farms.
 - **Easier Access:** Maintenance and operation are more accessible and cost-effective due to the location being on land.
 - **Familiar Technology:** Onshore wind farms use well-established turbine technologies.
- **Disadvantages:**
 - **Land Use and Space:** Large tracts of land are required to install onshore wind farms, which may compete with agricultural or residential land.
 - **Visual and Noise Impact:** Onshore wind farms can have visual and noise impacts on nearby communities.
 - **Intermittency:** Wind conditions can be inconsistent, and onshore sites are often subject to fluctuations in wind speed.

b) Offshore Wind Farms

Offshore wind farms are located at sea or large bodies of water, typically on the continental shelf. These wind farms have gained popularity due to the stronger and more consistent winds found offshore.

- **Advantages:**
 - **Higher Wind Speeds:** Offshore locations often have higher and more consistent wind speeds, leading to better energy generation.
 - **Less Land Use Conflict:** Offshore farms do not compete with agricultural or residential land use, reducing potential land use conflicts.
 - **Reduced Visual Impact:** Offshore turbines are located far from shore, reducing visual impacts on communities.
 - **Disadvantages:**
 - **Higher Installation and Maintenance Costs:** Offshore wind farms require specialized equipment for installation, and maintenance is more challenging due to the harsh marine environment.
 - **Environmental Impact:** Offshore wind farms can impact marine ecosystems and navigation.
 - **Transmission Costs:** The electricity generated by offshore wind farms needs to be transmitted back to shore, which requires subsea cables and additional infrastructure, increasing the cost.
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3. Wind Farm Design and Layout

The design and layout of a wind farm are critical to its efficiency. Proper turbine spacing, positioning, and consideration of local wind patterns can maximize energy output and reduce operational costs.

Key Design Considerations:

- **Wind Patterns:** Wind farms are often located in areas with consistent and strong wind patterns. Coastal areas, mountain ridges, and flat plains are common locations.
- **Spacing Between Turbines:** Turbines are typically spaced a few hundred meters apart to minimize the effects of wake turbulence. Wake turbulence can reduce the efficiency of downstream turbines because the wind speed slows down as it passes through a turbine's rotor.
- **Turbine Orientation:** Turbines are oriented to face the predominant wind direction. The yaw system helps the turbines face the wind directly, maximizing energy capture.
- **Accessibility:** Wind farms need to be easily accessible for maintenance, so access roads and transportation systems are planned around the site.

Example of Layout:

A typical wind farm layout consists of rows of turbines spaced out in a grid-like formation. The spacing allows wind to pass freely between turbines and minimizes power losses due to wake effects. The layout is also adjusted based on the terrain and wind conditions to maximize efficiency.

4. Power Generation and Output

The primary function of a wind farm is to generate electrical power. The power output of a wind farm depends on several factors:

- **Wind Speed:** Wind turbines typically generate maximum power at wind speeds between 12 and 25 m/s. Below this range, the turbine produces less power; above this range, the turbine is often shut down to avoid damage.
 - **Turbine Efficiency:** The efficiency of the turbines, including their ability to capture and convert wind energy into electricity, affects the overall output.
 - **Turbine Size:** Larger turbines can capture more wind energy, leading to higher output. Modern turbines can have capacities ranging from 1.5 MW to over 10 MW per turbine.
 - **Wind Farm Capacity:** The total capacity of a wind farm is calculated by multiplying the individual turbine capacity by the number of turbines. For example, a wind farm with 100 turbines, each rated at 2 MW, would have a total capacity of 200 MW.
 - **Capacity Factor:** The capacity factor refers to the actual output as a percentage of the maximum possible output. Wind farms typically have capacity factors between 30% and 45%, depending on local wind conditions.
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5. Economic and Environmental Impact

Economic Benefits:

- **Renewable Energy Supply:** Wind farms provide a sustainable and renewable source of energy, contributing to national and global energy security.
- **Job Creation:** Wind farms create jobs in construction, operation, and maintenance, as well as in the manufacturing of turbines and components.
- **Revenue:** Wind farms generate revenue through the sale of electricity, and some farms may also benefit from government subsidies or incentives.

Environmental Benefits:

- **Low Carbon Footprint:** Wind energy is a clean and renewable resource, producing no direct greenhouse gas emissions during operation.

- **Sustainability:** Wind is an inexhaustible resource, meaning that wind farms can continue to produce energy as long as the wind blows.

Environmental Challenges:

- **Wildlife Impact:** Wind turbines can pose a risk to local wildlife, particularly birds and bats, which may collide with turbine blades.
 - **Noise and Visual Impact:** Wind turbines generate noise, and their large presence in rural areas can affect the visual landscape, which can lead to opposition from local communities.
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6. Challenges and Future Outlook

While wind energy is an important part of the renewable energy transition, there are challenges:

- **Intermittency:** Wind is not always predictable, which can make energy supply inconsistent. To address this, energy storage systems or grid integration with other renewable sources are needed.
- **Grid Integration:** Wind farms, especially large-scale projects, require advanced infrastructure for connecting to the grid and managing energy transmission effectively.
- **Cost:** While the cost of wind energy has decreased significantly, the initial capital investment for wind farms, particularly offshore farms, is still high.
- **Land Use and Local Acceptance:** Securing land for large-scale wind farms and gaining local community support are common challenges.

Despite these challenges, the future of wind farms looks promising with continued advancements in turbine technology, energy storage, and grid management systems. As wind energy becomes more affordable and efficient, the role of wind farms in the global energy transition will continue to grow.

Conclusion

Wind farms are a cornerstone of the renewable energy revolution, offering a sustainable and clean alternative to fossil fuels. They vary in size and location (onshore and offshore), and their design and operation rely on sophisticated technology and infrastructure. Wind farms provide substantial environmental benefits by reducing carbon emissions and creating new economic opportunities. With ongoing technological advancements, wind farms will continue to be an essential part of the world's energy future.