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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, the terms **upwind** and **downwind** refer to the orientation of the wind turbine relative to the direction of the wind. Specifically, they describe whether the wind turbine's rotor faces into the wind (upwind) or away from the wind (downwind). These configurations play a crucial role in the design, performance, and efficiency of wind turbines.

1. Upwind Wind Turbine Systems:

An **upwind turbine** is one where the rotor (the part of the turbine with the blades) faces into the wind. This is the most common configuration used in modern wind turbines.

Key Features of Upwind Systems:

- **Rotor Facing into the Wind**: The rotor of the wind turbine is positioned such that it faces the oncoming wind directly. In this design, the blades rotate in the direction of the wind.
- **Yaw Mechanism**: In upwind turbines, a **yaw mechanism** is used to keep the rotor facing the wind. This mechanism adjusts the orientation of the turbine to ensure that the blades capture the maximum amount of wind energy. The yaw mechanism typically uses a tail vane or other control systems to detect the wind direction and turn the rotor accordingly.
- **More Efficient in Smooth Wind**: Upwind turbines generally perform better in areas with consistent and smooth wind because the blades experience minimal turbulence and wind shadow effects.
- **Noise and Mechanical Stress**: One potential downside of the upwind design is that the rotor experiences a higher degree of mechanical stress, especially in turbulent winds or areas with complex terrain. The wind direction can vary, and the blades may encounter turbulent air behind the tower.

Advantages of Upwind Systems:

- **Reduced Tower Shadow**: The rotor of the turbine faces into the wind, avoiding the aerodynamic drag caused by the tower itself. This results in more efficient energy conversion.
- **Improved Power Output**: Because the wind hits the blades head-on, upwind systems generally achieve better performance in stable and high-wind conditions.
- **Lower Turbulence**: The rotor's orientation reduces the turbulence caused by the wake of the tower, ensuring that the blades operate more smoothly.

Disadvantages of Upwind Systems:

- **Complexity of Yaw Mechanism**: The turbine's yaw system needs to be precise and reliable to ensure the rotor stays properly oriented into the wind.
- **Tower Interference**: In very turbulent wind conditions or areas with complex terrain (e.g., near mountains), wind can be channeled around the tower and cause instability, leading to inefficiency and added mechanical stress on the blades.

Examples:

- Most modern **horizontal axis wind turbines** (HAWTs) are upwind systems, where the rotor faces the wind direction, and the turbine is oriented using a yaw control system to track wind direction.

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2. Downwind Wind Turbine Systems:

In a **downwind turbine**, the rotor is oriented such that it faces away from the wind. The blades rotate in the direction of the wind, but the tower is positioned between the wind and the rotor.

Key Features of Downwind Systems:

- **Rotor Facing Away from the Wind**: The rotor of the turbine is positioned behind the tower, so it faces away from the wind. As the wind flows through the tower, it hits the rotor blades, causing them to rotate.
- **No Yaw Mechanism**: Downwind turbines do not require a yaw mechanism, as the rotor naturally aligns with the wind due to the lack of control for orientation. This can reduce the complexity and maintenance needs of the turbine.
- **Increased Turbulence**: One of the key challenges of downwind turbines is the **tower wake**. The wind experiences turbulence after passing the tower, which can create irregular wind flow across the rotor blades, reducing the efficiency and increasing mechanical wear.

Advantages of Downwind Systems:

- **Simple Design**: Since the rotor is positioned behind the tower and naturally aligns with the wind, there is no need for a yaw mechanism. This makes the system simpler and cheaper to build and maintain.
- **Reduced Mechanical Load on Yaw System**: With no need for yawing to track the wind direction, downwind turbines have fewer moving parts in their control systems, potentially reducing the risk of mechanical failure.
- **Can Tolerate More Wind Direction Variation**: Since the rotor faces away from the wind, the system can be less sensitive to changes in wind direction, which may reduce the impact of gusts and sudden shifts in wind.

Disadvantages of Downwind Systems:

- **Tower Wake**: The primary downside of a downwind turbine is the **tower wake**, where the wind passing through the tower creates turbulent airflow that affects the blades' efficiency. This turbulence leads to reduced power generation and increased mechanical stress on the blades.

- **More Mechanical Stress**: The rotor blades experience more mechanical stress due to the irregular flow of wind and the impact of turbulence from the tower. This can lead to a shorter lifespan for the blades compared to upwind turbines.
- **Less Efficient in High-Wind Conditions**: Due to the effects of the tower wake, downwind turbines can be less efficient, particularly in areas with high or fluctuating wind speeds.

Examples:

- The **Darrieus wind turbine**, a type of vertical axis wind turbine (VAWT), is a classic example of a downwind system.
- Some earlier designs of **horizontal axis wind turbines (HAWTs)** used downwind systems, but most modern commercial turbines have shifted to upwind configurations.

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3. Comparison of Upwind and Downwind Systems:

Feature	Upwind System	Downwind System
Rotor Orientation	Faces directly into the wind	Faces away from the wind (behind the tower)
Yaw Mechanism	Requires a yaw mechanism to orient the rotor	No yaw mechanism needed, rotor aligns naturally
Turbulence	Minimal turbulence, better performance in stable winds	More turbulence due to tower wake
Mechanical Stress	Higher mechanical stress in turbulent conditions	Lower mechanical stress on yaw system
Efficiency	Higher efficiency, particularly in steady winds	Lower efficiency, especially in turbulent conditions
Complexity	More complex design (yaw system, control)	Simpler design with fewer moving parts
Maintenance	Higher maintenance due to yaw system	Easier maintenance (no yaw mechanism)

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4. Applications of Upwind and Downwind Systems:

- **Upwind Systems**:
    - These are the most common in modern wind farms, especially large-scale commercial wind turbines. They are used in locations with consistent wind directions and where maximizing efficiency is crucial.
    - **Offshore wind turbines** are typically upwind designs to avoid turbulence from the tower and to ensure stable, high power output in high-wind conditions.
- **Downwind Systems**:
    - While downwind systems have mostly been replaced by upwind turbines in large-scale commercial applications, they are still relevant in some niche areas, such as **small-scale wind turbines** and specific **vertical axis wind turbine (VAWT)** designs.
    - The simplicity of the design and lack of a yaw system can make them attractive for certain applications where cost, ease of maintenance, and reduced mechanical complexity are key priorities.

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5. Conclusion:

Both **upwind** and **downwind systems** have their respective advantages and disadvantages. The upwind system is the preferred choice in modern large-scale commercial wind energy systems because it provides higher efficiency and better performance in consistent wind conditions. The downwind system, while simpler and more robust in some ways, suffers from decreased efficiency due to turbulence caused by the tower wake. However, it can still be useful in specific cases where mechanical simplicity or certain operating conditions make it advantageous. The selection of the appropriate system depends on the specific requirements of the wind energy project, including location, wind conditions, and cost considerations.