ROHINI COLLEGE OF ENGINEERING AND TECHNOLOGY

AUTONOMOUS INSTITUTION

Approved by AICTE & Affiliated to Anna University
NBA Accredited for BE (ECE, EEE, MECH) | Accredited by NAAC with A+ Grade

Anjugramam - Kanyakumari Main Road, Palkulam,Variyoor P.O. - 629 401, Kanyakumari District.

CAI 335 : SOLAR AND WIND ENERGY SYSTEMS

UNIT 3

WIND MAPPING ANALYSIS AND CHARACTERISTICS OF WIND

Prepared by:

Mr.Arunpandian.N.

Assistant Professor

Department of Agricultural Engineering

The **torque** and **power characteristics** of a wind energy system are crucial to understanding how a wind turbine converts the kinetic energy of the wind into mechanical energy and, eventually, electrical energy. These characteristics describe the relationship between the wind turbine's rotational motion and the power it produces as it interacts with the wind. In this explanation, we'll discuss the key concepts, how torque and power are generated, and how these characteristics affect the performance of a wind energy system.

1. Torque in Wind Energy Systems

Torque is the rotational force that is applied to the wind turbine blades, causing them to rotate. In the context of wind energy, torque is generated when wind flows over the blades of the turbine, creating an aerodynamic force known as **lift**. This force is responsible for turning the rotor, and torque is a measure of this turning force.

a) Aerodynamic Torque

Torque in a wind turbine is produced by the aerodynamic forces acting on the turbine blades. The basic principle is similar to how a plane's wings generate lift by interacting with airflow; wind turbines' blades generate lift and drag forces, which combine to create a turning moment (torque) on the rotor.

- **Lift and Drag Forces:**
    - **Lift** is the force generated by the difference in pressure between the upper and lower surfaces of the blades, causing the blades to rotate.
    - **Drag** is the resistance the blades experience as they move through the wind.

The net result of these forces, when combined, produces a torque that rotates the turbine rotor.

b) Torque and Wind Speed

The torque generated by a wind turbine is directly related to the wind speed and the aerodynamic design of the turbine blades. The relationship between torque (TT) and wind speed is generally nonlinear, with torque increasing as the wind speed increases, up to the rated wind speed of the turbine.

1. **At Low Wind Speeds:**
    - When the wind speed is low, the turbine blades are turning slowly, and the torque generated is relatively small. However, the turbine still produces some power, especially if it is equipped with a low cut-in speed (the minimum wind speed at which the turbine begins generating power).
2. **At Medium Wind Speeds:**
    - As the wind speed increases, the blades rotate faster, generating more torque. The aerodynamic forces (lift and drag) become more efficient at higher wind speeds, increasing the torque and power output.
3. **At High Wind Speeds (Rated Wind Speed):**

- When the wind reaches the rated speed (the maximum wind speed at which the turbine operates at full capacity), the torque output peaks. At this point, the blades are moving at their maximum speed, and the turbine generates its maximum power output.

4. **At Very High Wind Speeds:**
    - Beyond the rated wind speed, most modern turbines employ a **pitch control system** that adjusts the blade angles to prevent the turbine from exceeding its maximum power output. In this region, the torque may decrease slightly as the system limits the rotational speed to avoid damage.

c) Torque and Blade Pitch Control

Modern wind turbines often feature a **variable pitch control** system. This system adjusts the angle of the blades (the pitch) based on the wind speed, optimizing the torque and power output at different wind conditions. The pitch control helps maintain the optimal tip speed ratio (TSR) and ensures that the torque remains within safe limits, preventing overspeeding of the turbine rotor.

2. Power in Wind Energy Systems

The **power** generated by a wind turbine is the rate at which the rotor is doing work. In wind energy systems, power is typically expressed in terms of **mechanical power** (rotational power) and **electrical power** (converted by the generator). The power generated by the turbine depends on the wind speed, the rotor area, and the efficiency of the system.

a) Mechanical Power

Mechanical power is the energy transferred from the wind to the turbine rotor. It is calculated using the formula:

Pmech=12⋅ρ⋅A⋅Vwind3⋅Cp

Where:

- Pmech is the mechanical power generated by the wind turbine (in watts).
- ρ is the air density (in kilograms per cubic meter).
- AA is the swept area of the turbine blades (in square meters), which is A=πR2A, where RR is the radius of the turbine rotor.
- Vwind is the wind speed (in meters per second).
- Cp is the **power coefficient**, which is a dimensionless factor that represents the efficiency of the turbine in converting wind energy into mechanical energy.

The **power coefficient** Cp is a key factor in determining the turbine's efficiency. The theoretical maximum value for Cp is **0.59** (known as the **Betz Limit**), which means that no turbine can capture more than 59% of the kinetic energy in the wind.

b) Electrical Power

Once the mechanical power is generated by the turbine, it is converted into electrical power by the **generator**. The efficiency of the generator, as well as the overall drivetrain (including the gearbox and power electronics), affects the amount of mechanical power that is ultimately converted into usable electrical power. The electrical power output is given by:

$P_{elec}=P_{mech}\cdot\eta_{gen}$

Where:

- P_{elec} is the electrical power output (in watts).
- η_{gen} is the efficiency of the generator.

c) Power Curve of a Wind Turbine

The **power curve** is a graph that shows the relationship between wind speed and the electrical power output of a wind turbine. It typically has the following phases:

1. **Cut-in Wind Speed:** The wind speed at which the turbine begins generating power (typically around 3-4 m/s). Below this wind speed, the turbine does not produce power.
2. **Rated Wind Speed:** The wind speed at which the turbine reaches its maximum power output. This is typically between 10 and 15 m/s, depending on the turbine design.
3. **Cut-out Wind Speed:** The wind speed at which the turbine is shut down to prevent damage, usually around 25 m/s. Above this speed, the turbine may experience mechanical stress, and the power generation is cut off.

d) Relationship Between Torque and Power

Since power is the rate at which work is done, and torque is the rotational force causing this work, the relationship between power and torque is given by the following equation:

$P=T\cdot\omega$

Where:

- PP is the mechanical power (in watts).
- TT is the torque (in newton-meters).
- ω\omega is the angular velocity (in radians per second).

For wind turbines, this equation means that the power generated is the result of the torque generated by the aerodynamic forces on the blades multiplied by the angular speed of the blades. The torque and angular speed change depending on the wind speed and the turbine's operating conditions.

3. Factors Affecting Torque and Power Characteristics

Several factors influence the torque and power characteristics of a wind energy system:

a) Wind Speed:

The amount of power generated by a wind turbine is highly dependent on wind speed. Wind energy follows a **cubical relationship** with wind speed, meaning that small increases in wind speed result in large increases in power output. For example, doubling the wind speed increases the power output by a factor of eight.

b) Blade Design:

The shape, size, and material of the blades directly affect both torque and power. The aerodynamic efficiency of the blades determines how much torque can be generated from the wind. Blade **pitch control**, which adjusts the angle of the blades, also plays a significant role in regulating torque and power output.

c) Generator Efficiency:

The efficiency of the generator in converting mechanical power into electrical power affects the overall system performance. Losses in the drivetrain, bearings, and generator can reduce the electrical power produced.

d) Cut-In, Rated, and Cut-Out Speeds:

As mentioned earlier, wind turbines have specific cut-in, rated, and cut-out wind speeds, which define the operating ranges for power generation. The torque and power characteristics of the turbine are governed by these speeds, with the turbine producing little or no power below the cut-in wind speed, maximum power at rated wind speed, and no power above the cut-out speed.

e) Control Systems:

Modern wind turbines use sophisticated control systems to adjust the blade pitch and yaw (the direction of the blades relative to the wind) to optimize torque and power output. These systems help ensure that the turbine operates at its peak efficiency under varying wind conditions.

Conclusion

The **torque** and **power characteristics** of a wind energy system are crucial for understanding how wind turbines generate energy. Torque is the rotational force that is generated by the aerodynamic forces acting on the blades, and it is directly related to the wind speed and blade design. The power output of a wind turbine is determined by the torque and the angular speed of the rotor, and it follows a nonlinear relationship with wind speed. By optimizing factors such as blade design, pitch control, and generator efficiency, wind energy systems can maximize their power output and operate efficiently across a range of wind conditions.