Q.1 What are the components in a HAWT type wind turbine system? Describe the function of each component.

HAWT Components

1. Blade Pitch System
2. Yaw System
3. Gearbox
4. Generator

Gearbox: Increases rotational speed, converting low-speed rotation to a speed suitable for the generator.
Generator: Converts mechanical energy into electrical energy.
Yaw system: Adjusts the direction of the wind rotor to face the wind.
Blade Pitch System: Controls power output and protects the turbine in strong winds by adjusting the blade's angle of attack.

Q.2 Why are wind turbine rotor blades twisted towards the end?

The twist in wind turbine rotor blades is designed to optimize the aerodynamic properties at different radii along the blade. Near the root of the blade, where the speed is slower, a larger angle is required to capture wind energy effectively. At the blade tips, where the speed is much faster, the twist reduces drag and improves efficiency.

Q.3 What is the specific power in wind at a location with wind speed of 5m/s? Determine the theoretical maximum power output of a 40-m diameter wind turbine generator at this location. Assume density of air to be 1.225Kg/m3. 直径.

$V = 5\,m/s \quad \rho = 1.225\,kg/m^3 \quad D = 40\,m \quad A = \frac{\pi}{4}D^2$

① $P = \frac{1}{2}\rho v^3 = \frac{1}{2} \times 1.225 \times 5^3 = 76.56\,W$

② $P_w = \frac{1}{2}\rho A V^3 = \frac{1}{2} \times 1.225 \times \frac{\pi}{4}(40)^2 \times 5^3 = 96211.28\,W$

HAWT: $A = (\pi/4)D^2$ VAWT: $A = \frac{2}{3}D \cdot H$

Power density (specific power) = power per square meter (Watts/m²)

Q.4 The wind speed in a city area is 5 m/s at a height of 10m. The location has a friction coefficient of 0.4. What is the specific power at a height of 50m? Assume density of air to be 1.225Kg/m3.

$H = 10\,m \quad V = 5\,m/s \quad \alpha = 0.4 \quad \rho = 1.225\,kg/m^3$

$H_0 = 50\,m \quad V_0 = ?$

$\left(\frac{V}{V_0}\right) = \left(\frac{H}{H_0}\right)^\alpha \Rightarrow V_0 = \frac{V}{\left(\frac{H}{H_0}\right)^\alpha} = \frac{5}{\left(\frac{10}{50}\right)^{0.4}} = 9.52\,m/s$

$P_w = \frac{1}{2}\rho V_0^3 = \frac{1}{2} \times 1.225 \times (9.52)^3 = 528.47\,W$

$\left(\frac{P}{P_0}\right) = \left(\frac{V}{V_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha}$

Q.5 At tip-speed-ratio of 5, what is the rpm of the wind turbine rotor with a diameter of 40m, if the wind speed is 10m/s?

$\text{tip speed ratio} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{rpm \times \pi D}{60V}$

$rpm = \frac{5 \times \cancel{60}^{15} \times 10}{\pi \times \cancel{40}} = 23.87$

Q.6 Explain how the rotor blades in a wind turbine get the required thrust to rotate.

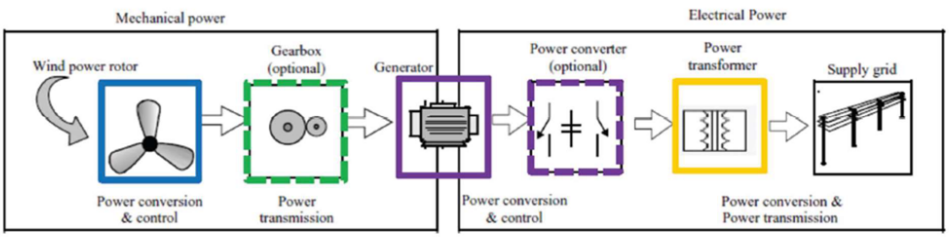
Air moving over top of airfoil has more distance to travel →Air pressure on top is lower than under airfoil
→ "Lift" is created

Q.7 What are the various methods used for varying the wind turbine rotor speed based on wind speed?

How: • Adjust angle of attack at the turbine blades • Stall or pitch control	How: • Multiple gearboxes design for different rotor speed to generator speed ratios. • Different generator designs and power converters are used to adjust the voltage frequency to be the same at the grid frequency.

Q.8 Draw the complete block diagram of the wind energy conversion system to convert wind energy to electricity for the grid. Briefly explain the function of each block.

Main Components of Wind Energy Conversion Systems (WECS)



Power extracted by the rotor at low rotational speed, typically at 10-15 rpm.

Gearbox is used to increase rotational speed to a higher rpm to generate 50/60Hz electricity.

Generators and power converters are the main components to make sure that WECS produce high quality voltage supplies.

Transformers are used to step-up the voltage to connect the generator to the grid.

Q.9 Using appropriate equations, explain why it is economical to increase the size of the wind turbine rotor.

$$\boxed{P_w = \frac{1}{2}\rho A v^3}$$

The power output of a wind turbine is directly proportional to the swept area of the rotor, which is given by: This means that doubling the blade length results in a fourfold increase in power output, while the cost only increases roughly by a factor of two. Therefore, larger rotors provide significantly higher energy production per unit cost, making them more economical.

The larger the rotor, the more energy it can capture

Q.10 Explain the cause of rotor stress in large wind turbines.

Rotor Stress

As seen in the previous example, the blade at the top of its rotation can experience much higher wind speeds than at the bottom of its rotation. This results in flexing of the blade.

It can also:

- Increase noise.
- Contribute to blade fatigue, which can lead to blade failure.

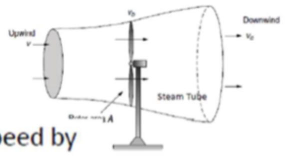
Q.11 From first principle, derive Betz's Law for retrieving maximum energy from wind using a wind turbine.

1

Power Extracted

Assume that the velocity of wind v_b is just the average of the upwind and downwind speed,

$$P_b = \frac{1}{2}\rho A\left(\frac{v + v_d}{2}\right)(v^2 - v_d^2)$$



Denote the ratio between upwind and downwind speed by

$$\lambda = \left(\frac{v_d}{v}\right)$$

Substitute v_d, then we have,

$$P_b = \frac{1}{2}\rho A\left(\frac{v + \lambda v}{2}\right)(v^2 - \lambda^2 v^2)$$

$$= \underbrace{\frac{1}{2}\rho A v^3}_{\text{Power in the wind}} \cdot \boxed{\underbrace{\left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]}_{\text{Fraction extracted}}}$$

2

Rotor Efficiency

Define Rotor efficiency as,

$$C_P = \tfrac{1}{2}(1+\lambda)(1-\lambda^2)$$

Fundamental relationship for power delivered by the rotor,

$$\boxed{P_b = \tfrac{1}{2}\rho A v^3 \cdot C_p}$$

3

Maximum Rotor Efficiency

$$\frac{dC_p}{d\lambda} = \frac{1}{2}[(1+\lambda)(-2\lambda) + (1-\lambda^2)] = 0$$

$$= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)]$$

$$= \frac{1}{2}(1+\lambda)(1-3\lambda) = 0$$

The blade efficiency will be maximum if it slows the wind to one-third of the upwind speed.

$$\lambda = \frac{v_d}{v} = \frac{1}{3}$$

4

We can now find the maximum rotor efficiency,

Substituting $\lambda = 1/3$ in Efficiency $= \tfrac{1}{2}(1+\lambda)(1-\lambda^2)$

$$\text{Maximum rotor efficiency} = \frac{1}{2}\left(1 + \frac{1}{3}\right)\left(1 - \frac{1}{3^2}\right)$$

$$= \frac{16}{27} = 0.593 = 59.3\%$$

Q.12 What is the tip seed ratio (TSR) of wind turbine? How does TSR affect the rotor efficiency of a wind turbine?

TSR is the speed at rotor tip divided by the wind speed.

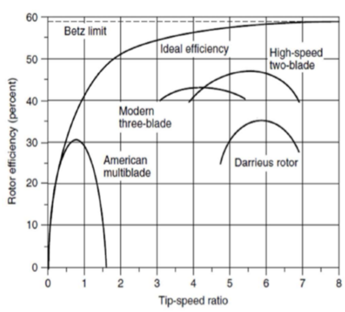
$$\frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

D: diameter (m)
v: wind speed (m/s)

The optimal TSR gives the maximum efficiency that a turbine can extract wind energy.

Rotor Efficiency vs TSR

- For a given wind speed, rotor efficiency is a function of the rate at which a rotor turns.
  - If Rotor turns too slow letting too much wind to pass
    => efficiency drops.
  - If Rotor turns too fast causing turbulence
    =>efficiency drops.



Q.13 Describe the various types of wind turbine generators based on type of speed control used.

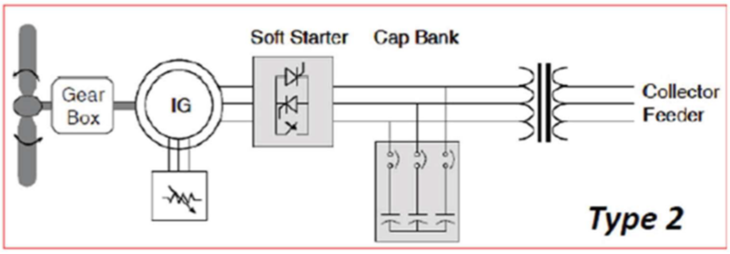
WTGs Classification by Speed Control

Wind turbine generators can be divided into 5 types.

1. Type 1: Fixed speed (1-2% variation)
2. Type 2: Limited variable speed (10% variation)
3. Type 3: Variable speed with partial power electronic conversion (30% variation)
4. Type 4: Variable speed with full power electronic conversion (full variation)
5. Type 5: Variable speed with mechanical torque converter to control synchronous speed (full variation)

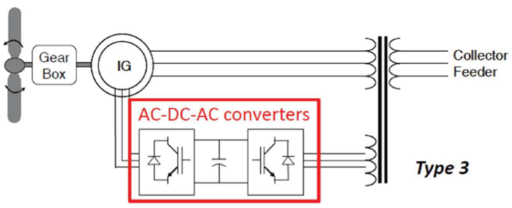
Q.14 Using block diagram, describe the various types of variable speed wind turbine generator systems with electrical control on generator side.

Type 2: Variable Speed Systems

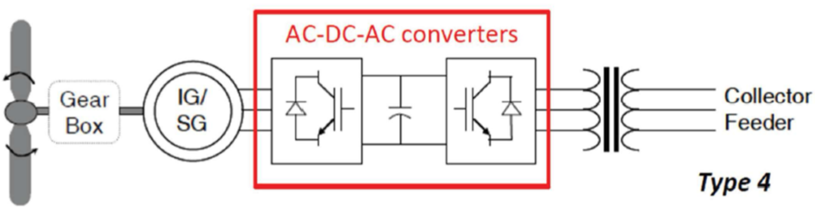


- Variable speed induction generators (VSIG) are often used in wind energy conversion systems to harness energy efficiently from varying wind speeds.
- The rotor resistance control method involves adjusting rotor circuit's resistance to control the generator's speed

Type 3: Doubly Fed Induction Generator(DFIG)

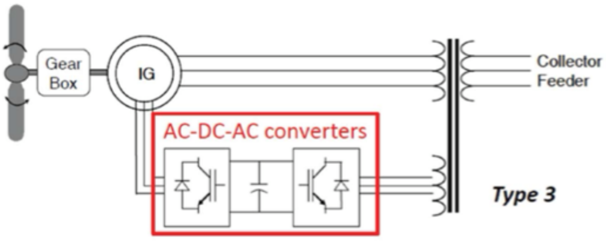


Type 4: Indirect Grid Connection



Q.15 Using block diagram, explain the operation of wind turbine system with a doubly fed induction generator (DFIG).

Type 3: Doubly Fed Induction Generator(DFIG)



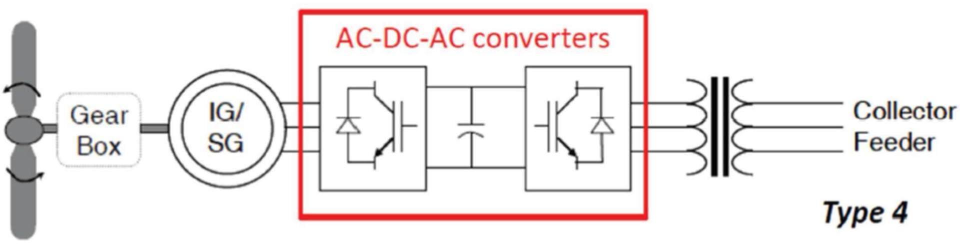
- Instead of variable resistors in Type 2, this Type 3 design adds AC-DC-AC converters to the rotor circuit.
- Rotor frequency is decoupled from grid frequency.
- The machine can still be synchronized with the grid while the wind speed varies.

Q.16 Using block diagram, explain the operation of variable turbine speed, type 4 wind turbine system with a Synchronous generator.

Q.17 Draw the ideal power delivered vs wind speed curve for a wind turbine generator. Clearly explain the operation at different wind speed.

Type 4: Indirect Grid Connection

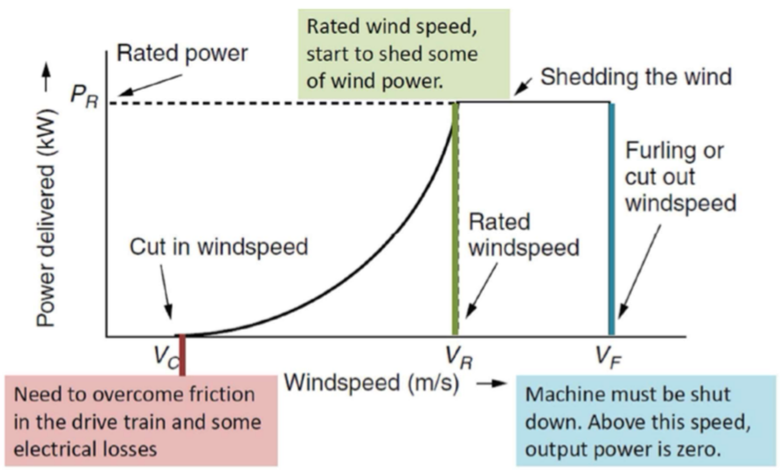
16



- Allows the turbine to rotate at its optimal speed.
- AC output from generator frequency is different and decoupled from grid frequency.
- AC-DC-AC converter is used to connect the AC output to the grid.
- Full control and flexibility in the design and operation of wind turbine.
- The ratings of power electronics are higher than Type 3.

Ideal Power Curve

17



Q.18 What is meant by wind shedding? Explain the various methods for shedding wind power?

Wind shedding refers to the intentional reduction of power output to protect the turbine during high winds. Methods include:

How to Shed Wind Power

Pitch-controlled turbines

– Active control by reducing 'angle of attack'

Stall-controlled turbines.

– Passive control using pure aerodynamic design.

Active stall control.

– Induce stall for large wind turbine by increasing 'angle of attack'.

Passive yaw control

– Small kW size turbine, causing axis of turbine to move off the wind.

Q.19 The table below gives the measurement of wind speed during one day. Calculate the total energy generated for the day using a 40-m diameter rotor wind turbine generator with rotor efficiency of 40% and generator efficiency of 85%. The cut-in speed is 3 m/s and cut-out speed is 9 m/s. Assume there is no wind shedding.

$D = 40\,m$

$\rho = 1.225\ kg/m^2$

$A = \frac{\pi}{4} D^2 = 400\pi\ m^2$

	Wind speed (m/s)	Number of hours recorded during the day
<3	1	5
	2	3
3~9	4 $i=1$	4
	7 $i=2$	6
	8 $i=3$	4
>9	10	2

$P_w = \frac{1}{2} \rho A v^3$ $P_{w_1} = 49.26\ kW$ $P_{w_2} = 264\ kW$ $P_{w_3} = 394.08\ kW$

$P_{out} = P_w \cdot 0.4 \cdot 0.85$ $P_{out_1} = 16.75\ kW$ $P_{out_2} = 89.76\ kW$ $P_{out_3} = 133.99\ kW$

$E = P_{out} \cdot hours$ $E_1 = 66.99\ kwh$ $E_2 = 538.57\ kwh$ $E_3 = 535.95\ kwh$

$E_{all} = \sum_{1 \le i \le 3} E$ $E_{all} = E_1 + E_2 + E_3 = 1141.51\ kwh$