

Internal Assessment Test – 3

Sub: Solar and Wind Energy (Professional Elective)				Code: 18EE731
Date: 27/01/2022	Duration: 90 mins	Max Marks: 50	Sem: 7	Section: A&B [EEE]
Answer ANY FIVE full questions. Explain your notations explicitly and clearly. Sketch figures wherever necessary. Good luck!				
			Marks	OBE CO RBT
Q1. Derive an expression for the maximum power output (P_{max}) of a horizontal axis wind turbine.	[10]			CO4 L3
Q2a. List out the different guidelines in selecting a site for wind generators.	[5]			CO4 L2
Q2b. Write a short note on environmental benefits and problems of wind energy.	[5]			CO4 L2
Q3a. With a neat block diagram, explain the basic principle of wind energy conversion system.	[8]			CO4 L3
Q3b. The rotor diameter of a horizontal axis wind turbine generator is 126 m. The velocity of wind is 13.5 m/s and density of air is 1.23 kg/m ³ . Calculate the power in the wind.	[2]			CO4 L2
Q4a. List and explain various classification of wind energy conversion systems.	[5]			CO5 L2
Q4b. Explain various environmental aspects of wind energy conversion systems.	[5]			CO5 L2
Q5. With the help of a neat sketch, explain the main components of a horizontal axis wind turbine (HAWT).	[10]			CO5 L3
Q6. Derive the relationship between the torque coefficient (C_T), power coefficient (C_P) and the tip speed ratio (λ).	[10]			CO5 L3

Solution

1. Derive an expression for the maximum power output (P_{max}) of a horizontal axis wind turbine.

MAXIMUM POWER (P_{MAX})

- × HAWT is considered
- × Betz model of expanding air stream tube is shown
- × Air mass flow rate is the mass of substance which passes per unit time

$$\dot{m} = \frac{dm}{dt}$$

- × The air mass flow rate remains same throughout the stream tube

$$\dot{m} = \rho A_1 V_1 = \rho A_2 V_2 = \rho A V$$

Where V_1 or V_i velocity at the upstream (incoming) of the turbine
 V_2 or V_e velocity at the downstream (exit) of the turbine
 A area of the wind turbine rotor

- × Force exerted on the wind by the rotor is

$$F = ma = m \frac{dv}{dt} = \rho A V (V_1 - V_2) \text{ ----- (1)}$$

- × Work done to move the rotor to dx distance by the force of the air at uniform speed is

$$dE = F \times dx$$

- × The power extracted by the turbine is

$$P = \frac{dE}{dt} = F \frac{dx}{dt} = FV \text{ ----- (2)}$$




x (1) in (2)

$$P = \rho AV^2(V_1 - V_2) \text{ ----- (3)}$$

x Power can be computed using kinetic energy as

$$P = \frac{\Delta E}{\Delta t} = \frac{1}{2} \dot{m} V_1^2 - \frac{1}{2} \dot{m} V_2^2 = \frac{1}{2} \dot{m} (V_1^2 - V_2^2) = \frac{1}{2} \rho AV (V_1^2 - V_2^2) \text{ ----- (4)}$$

x Equating (3) and (4)

$$\rho AV^2(V_1 - V_2) = \frac{1}{2} \rho AV (V_1^2 - V_2^2)$$

$$\rho AV^2(V_1 - V_2) = \frac{1}{2} \rho AV (V_1 + V_2) (V_1 - V_2)$$

$$V = \frac{V_1 + V_2}{2} \text{ ----- (5)}$$

x Hence wind velocity of the rotor is taken as the average of upstream and downstream velocities

x (5) in (4)

$$P = \frac{1}{4} \rho A (V_1 + V_2) (V_1^2 - V_2^2) \text{ ----- (6)}$$

$$P = \frac{1}{4} \rho A (V_1 + V_2) (V_1^2 - V_2^2) \text{ ----- (6)}$$

$$P = \frac{1}{4} \rho A (V_1^3 - V_1 V_2^2 + V_2 V_1^2 - V_2^3)$$

x From (6) it is observed that V_2 is +ve in one term and -ve in the other because of which too low or too high value of V_2 will result in reduced power

x Hence there is an optimum exit velocity V_2 which results in maximum power P_{\max} obtained by

$$\frac{dP}{dV_2} = 0$$

$$-V_1 2V_2 + V_1^2 - 3V_2^2 = 0$$

$$3V_2^2 + 2V_1V_2 - V_1^2 = 0 \text{ ----- (7)}$$

x Solution for (7) is $V_2 = V_1$ or $V_2 = \frac{1}{3}V_1$

x Only second solution is physically acceptable giving the optimum exit velocity of

$$V_{2 \text{ opt}} = \frac{1}{3}V_1 \text{ ----- (8)}$$

x (8) in (6)

$$P_{\max} \text{ or } P_T = \frac{1}{4} \rho A (V_1 + \frac{1}{3}V_1) (V_1^2 - \frac{1}{9}V_1^2)$$

$$= \frac{1}{4} \rho A \left(\frac{4V_1}{3} \right) \left(\frac{8V_1^2}{9} \right)$$

$$P_{\max} = \frac{8}{27} \rho AV_1^3$$

$$= \frac{16}{27} \times \frac{1}{2} \rho AV_1^3$$

$$= 0.593 P_a = 0.593 P_{\text{total}}$$

Hence, Power extracted from the turbine, $P_{\max} = C_P P_a$

Q2a. List out the different guidelines in selecting a site for wind generators.

GUIDELINES	
<ul style="list-style-type: none"> × Turbines work well at height and exposed sites × Narrow mountain gaps through which wind is channeled × Top of smooth well-rounded hill with gentle slopes (about 1:3 or less) on a flat plain × Coastal site areas are good choice × Town centers and highly populated residential areas are not suitable × Avoid roof mounted turbines as its vibrations may damage property × Farther distance between turbine and power requirement location causes loss of power in cables 	<ul style="list-style-type: none"> × Cabling distance impacts cost as well × Ensure height of turbine being twice the height of the nearest obstacle to avoid turbulence × No tall obstructions for some distance (about 3 km) in upwind direction (i.e., the direction of incoming wind) and also as low a roughness as possible in the same direction × Small turbines require average wind speed of 4.5 m/s to give efficient electricity × In remote areas off-grid connection is preferable as connecting remote areas WT to grid becomes expensive × Soil conditions must be such that building of foundations of the turbines and transport of road construction material loaded on heavy trucks must be feasible

Q2b. Write a short note on environmental benefits and problems of wind energy.

Environmental benefits of Wind Energy



- Wind energy is a source of renewable energy. It does not contaminate, it is inexhaustible and reduces the use of fossil fuels, which are the origin of greenhouse gasses that cause global warming.
- In addition, wind energy is a "native" energy, because it is available practically everywhere on the planet, which contributes to reducing energy imports and to creating wealth and local employment.
- Wind energy is space efficient. The largest wind turbines can take care of a large number of domestic needs. The land between these wind turbines can be utilized for agricultural purposes.
- Wind energy currently supplies over 3 % of global electricity consumption. In the longer term (by 2040), the International Energy Agency forecasts that wind energy could meet 9 % of global electricity demand. By the end of 2015, wind power capacity topped out at 400,000 MW in the world.

Winds are caused by:

- heating of atmosphere by the sun
- rotation of the Earth
- the irregularities on the Earth's surface.

As long as Sun continues to shine(6-7 billion years), wind will be produced and wind energy can be harnessed.

Problems of Wind Energy

1. Avian issues

Birds and bats may collide with wind turbines, as they do with any structures on their route.

In many cases, careful planning can avoid the risk to bird population due to wind turbines.

Noise can also be used as an effective tool for making the turbine more detectable for birds, especially during the night hours. Modern turbines are less noisy and the inherent noise level of these turbines does not keep the birds away.

2. Noise emission

Like any other rotating mechanical systems, wind turbines also create some noise during their operation.

Systematic acoustic analysis during the project planning stage can avoid possible noise annoyance from wind turbines.

Noise pollution from wind turbines is not a serious issue as it is being considered.

3. Visual impact

Another environmental concern of wind farm development is its impact on scenic beauty of the landscapes. Wind turbines are tall structures installed in open areas which make them visually prominent in the landscape. The turbines may dominate our sight up to 2 km or even more.

Carefully designed and cleverly constructed wind farms can be a positive addition to the landscapes. Wind farms with layouts, naturally blending with the prevailing scenery and turbines designed with aesthetic sense can add to the scenic beauty of the landscape.

4. Manufacturing a wind turbine consumes more energy than the machine will be able to generate.

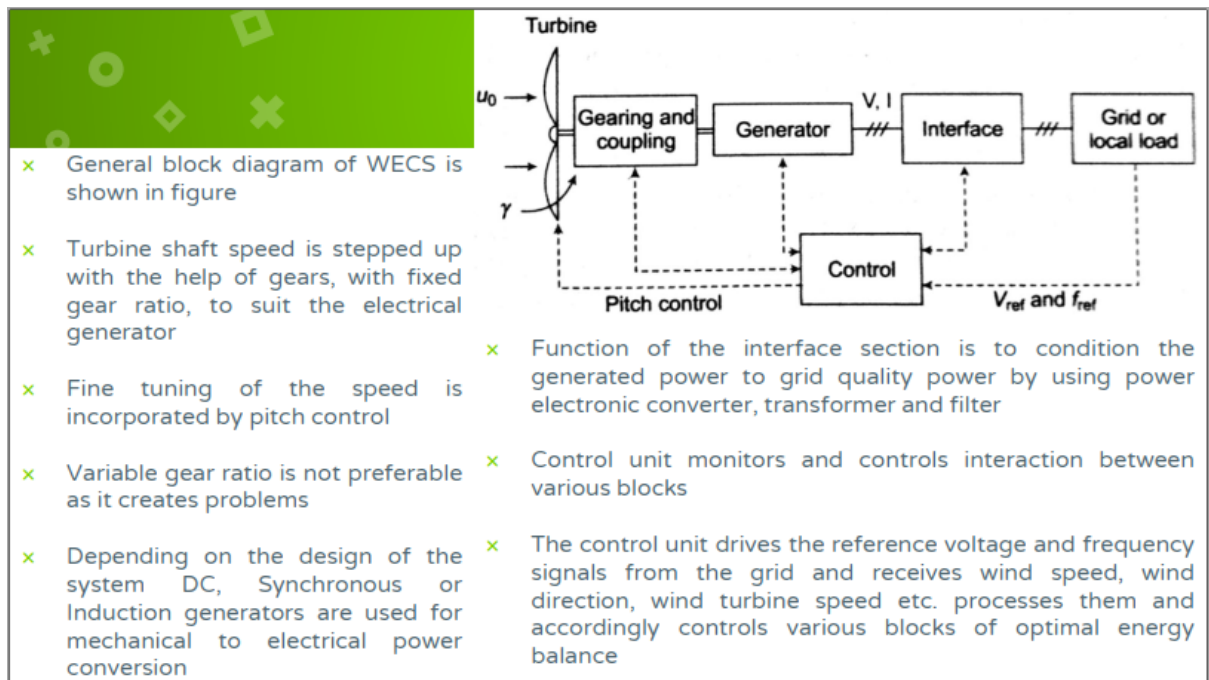
5. Bending of the wind blades

6. Transportation Difficulty

7. High maintenance cost

Q3a. With a neat block diagram, explain the basic principle of wind energy conversion system.

- × Basic principle of wind energy conversion is to convert kinetic energy of the wind to mechanical energy
- × This mechanical energy is used in farm appliances, water pumping or is converted to electricity using aero generator
- × Aero generator/wind generator/ wind energy conversion system (WECS) is a generator coupled wind turbine
- × A step up transmission is required to match relatively slow speed of the wind rotor to the higher speed of an electric generator



- × General block diagram of WECS is shown in figure
- × Turbine shaft speed is stepped up with the help of gears, with fixed gear ratio, to suit the electrical generator
- × Fine tuning of the speed is incorporated by pitch control
- × Variable gear ratio is not preferable as it creates problems
- × Depending on the design of the system DC, Synchronous or Induction generators are used for mechanical to electrical power conversion

- × Function of the interface section is to condition the generated power to grid quality power by using power electronic converter, transformer and filter
- × Control unit monitors and controls interaction between various blocks
- × The control unit drives the reference voltage and frequency signals from the grid and receives wind speed, wind direction, wind turbine speed etc. processes them and accordingly controls various blocks of optimal energy balance

Q3b. The rotor diameter of a horizontal axis wind turbine generator is 126 m. The velocity of wind is 13.5 m/s and density of air is 1.23 kg/m³. Calculate the power in the wind.

$$D = 126 \text{ m} ; V = 13.5 \text{ m/s} ; \rho = 1.23 \text{ kg/m}^3$$

$$P_a = \frac{1}{8} \rho \pi D^2 V^3$$

$$= \frac{1}{8} \times \pi \times (126)^2 \times (13.5)^3 \times 1.23$$

$$= 18.867 \text{ MW}$$

Q4a. List and explain various classification of wind energy conversion systems.

- × **Broad Classifications**
 - ❖ Horizontal Axis Wind Turbines (HAWT)
 - ❖ Vertical Axis Wind Turbines (VAWT)
- × **According to Size**
 - ❖ Small size machine (up to 2 kW) – used in farm, remote applications and places requiring low power
 - ❖ Medium size machine (2 kW to 100 kW) – residential or local use
 - ❖ Large size machine (100 kW and above) – used to generate power for distribution in central power grids. Two subclasses – (a) Single generator at single site (b) Multiple generator sited at several places over an area
- × **According to Output Power**
 - ❖ DC Output – (a) DC generator (b) Alternator Rectifier
 - ❖ AC Output – (a) Variable frequency, variable or constant voltage AC (b) Constant frequency, variable or constant voltage AC
- × **According to Rotational Speed of Aeroturbines**
 - ❖ Constant speed with variable pitch blades – uses synchronous generator with constant frequency output
 - ❖ Nearly constant speed with fixed pitch blades – uses induction generator
 - ❖ Variable speed with fixed pitch blades – uses constant frequency output system such as Field Modulated System, AC-DC-AC Link, Double Output Induction Generator, AC Commutator generators etc.
- × **According to Utilization of Output**
 - ❖ Battery storage
 - ❖ Direct connection to an electromagnetic energy converter
 - ❖ Other forms such as thermal potential etc. of storage
 - ❖ Interconnection with conventional electric utility grids

Q4b. Explain various environmental aspects of wind energy conversion systems.

<p>ELECTROMAGNETIC INTERFERENCE</p> <ul style="list-style-type: none"> × Interference with TV and other electromagnetic communication systems × Wind turbines can be in good position to receive and scatter the signals × Interference is overcome by sending TV signals with cables 	<p>BIRD LIFE</p> <ul style="list-style-type: none"> × Tall structures are potential collision hazard to bird life especially in night × Smaller, faster turning machines are more hazardous than very large motors
<p>NOISE</p> <ul style="list-style-type: none"> × Two categories of noise produced by wind farms ❖ Mechanical noise from gear box, generating equipment and linkages – it is a broadband noise ranging up to several kilo hertz ❖ Second noise is aerodynamic in nature produced by the movement of turbine blades – it is a low frequency noise of 15 to 20 Hz. Revolving blades generate noise which can be heard in the immediate vicinity of the installation and it will not travel far 	<p>RISK</p> <ul style="list-style-type: none"> × Detachment of blade or blade fragment which could be thrown at considerable distance and could damage people or property × Reliable control system to detect fault rapidly and braking system to bring rotor safely to rest, regular inspection are some measures to prevent this × As wind farms are usually in rural areas it is less likely that anyone would be injured or killed by flying debris
<p>VISUAL EFFECTS</p> <ul style="list-style-type: none"> × Adjust characteristics like color pattern, shape, speed, reflectance of blade material to modify visual effect WT including landscape where they are installed 	

Q5. With the help of a neat sketch, explain the main components of a horizontal axis wind turbine (HAWT).

WINDMILL HEAD

TURBINE BLADES

- × Made of high density wood or glass fiber and epoxy composites
- × Airfoil type cross section
- × Twisted from outer tip to the root
- × Twisted to reduce tendency to stall
- × Stall – motor stops rotating due to load torque greater than motor shaft torque
- × Diameter of modern rotor 100 m for MW range
- × Two/three blades in modern WT
- × Two/three blade rotor HAWT are also called Propeller Type WT

BLADE COUNT

- × Blades rotation leads to emission of noise
- × Small increase in tip of blade leads to large noise
- × Increasing blade count from one to two increases 6% aerodynamic efficiency
- × Aerodynamic efficiency (lift to drag ratio) is thrust force for rotation of blades
- × Increasing blade count from two to three increases aerodynamic efficiency by 3% only
- × Higher blades minimal increment in efficiency

- × Less blades, means less cost and high speed
- × Hence low solidity WT give good efficiency
- × Thin blades with respect to their width are low solidity WTs
- × Three blades usually used as they have low solidity and are less disturbing

BLADE MATERIALS

- × Wood and canvas sails were used earlier due to low price and availability
- × New turbines with 10 MW range have larger blades of up to 100 m
- × Typically can be 110 m to 120 m
- × Fiber glass composite is used in 40 m to 50 m blades
- × Carbon fiber in 60 m blades reduces blade mass by 38% and cost by 14%

HUB

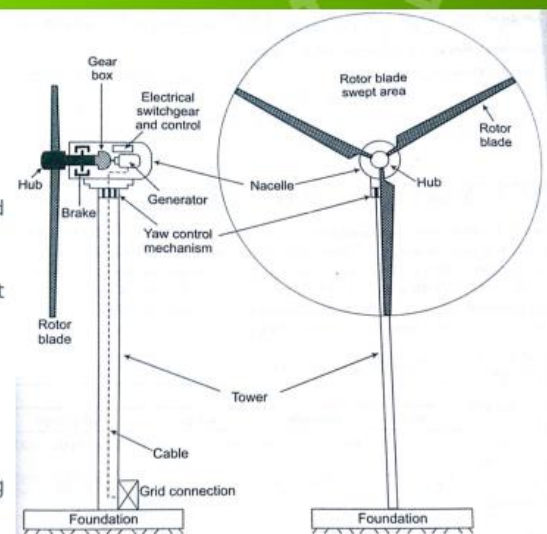
- × Center solid portion of the rotor wheel
- × All blades are attached to it

NACELLE

- × Houses rotor brakes, gearbox, generator and switchgear and control
- × Mounted on top of the tower
- × Rotor brakes – stops rotor when generation is not desired
- × Gearbox – steps up shaft rpm to suit generator
- × Switchgear and control – protection and control
- × Cables to get generated power to ground

YAW CONTROL

- × Adjusts nacelle around vertical axis to keep it facing the wind



TRANSMISSION

- × The rate of rotation of large wind turbine generators operating at rated capacity or below, is conveniently controlled by varying the pitch of the rotor blades
- × For optimum generator output much greater rates of rotation such as 1800 rpm is required
- × Also it is necessary to increase greatly the low rotor rate of turning
- × The Transmission options are mechanical systems involving fixed ratio gears, belts and chains, singly or in combination or hydraulic systems involving fluid pumps and motors
- × There is a high degree of design flexibility and large potential savings

GENERATOR

- × Either constant or variable speed generators are used
- × Constant speed generators which are in use are Synchronous Induction motor and Permanent magnet motor types

- × Protection for the generator, the utility accepting the generator and prime mover

- × Maintenance mode

CONTROLS

Wind Turbine requires a reliable control system to perform the following functions :

- × The orientation of the rotor into the wind
- × Power control of the rotor by varying the pitch of the blades
- × Generator output monitoring – status, data computation, and storage
- × Shut down and cut out owing to the malfunction or very high winds

- × Components in the control system
 - ❖ Sensor – mechanical, electrical or pneumatic
 - ❖ Decision elements – relays, logic modules, analog circuits, microprocessor, mechanical unit
 - ❖ Actuators – hydraulic, electric or pneumatic

TOWER

- ✘ Supports nacelle and rotor
- ✘ Its taller than rotor diameter for medium and large sized turbines
- ✘ In small size turbines towers are larger than rotor diameter because air is erratic at lower heights
- ✘ Made of steel or concrete
- ✘ Can be tubular or lattice type





Steel tubular
Steel lattice (truss)
Concrete

Q6. Derive the relationship between the torque coefficient (C_T), power coefficient (C_P) and the tip speed ratio (λ).

❖ RELATIONSHIP BETWEEN C_T , C_P , and TSR (λ)

$$C_T = \frac{T}{T_{max}}$$

$$T = C_T T_{max} \quad (1)$$

Maximum torque occurs if maximum thrust is applied at the blade tip furthest from the axis

$$T_{max} = F_{max} R; \quad \text{where } R \text{ is radius of propeller turbine}$$

$$F_{max} = \frac{1}{2} \rho A V_1^2$$

$$T_{max} = \frac{1}{2} \rho A V_1^2 R \quad (2)$$

Tip speed ratio (TSR) $\lambda = \frac{V_{tip}}{V_1} = \frac{R\omega}{V_1}$

Where R is outer blade radius and ω rotational frequency

$$R = \frac{\lambda V_1}{\omega} \quad (3)$$

(3) In (2)

$$T_{max} = \frac{1}{2\omega} \rho A V_1^2 \lambda V_1 = \frac{1}{2} \rho A V_1^3 \frac{\lambda}{\omega} = P_a \frac{\lambda}{\omega} \quad (4); \quad \text{where } P_a = \text{available power in wind}$$

Shaft power is the power derived from the turbine P_t , so

$$P_t = \tau \omega = T \omega \quad (5)$$

Also,

$$P_t = C_P P_a \quad (6)$$

Putting (6) and (1) in (5)

$$C_P P_a = C_T T_{\max} \omega$$

From (4)

$$C_P P_a = C_T P_a \lambda$$

$$C_P = \lambda C_T$$

Note that in practice C_P and C_T will be function of λ and not constants

By Betz criterion for ideal case C_P maximum value is 0.593 hence,

$$C_{T \max} = \frac{0.593}{\lambda}$$

- × High solidity machines have high starting than running torque while starting torque of low solidity machine is lower than their already low running torque