INTRODUCTION TO WIND TURBINE TECHNOLOGY

21WSP034

January 2022 (1b) Exam paper

This is a (1b) online examination, meaning you have a total of **2 hours plus an additional 30 minutes** to complete and submit this paper. The additional 30 minutes are for downloading the paper and uploading your answers when you have finished. If you have extra time or rest breaks as part of a Reasonable Adjustment, you will have further additional time as indicated on your exam timetable.

It is your responsibility to submit your work by the deadline for this examination. You must make sure you leave yourself enough time to do so.

It is also your responsibility to check that you have submitted the correct file.

<u>Exam Help</u>
If you are experiencing difficulties in accessing or uploading files during the exam period you should contact the exam helpdesk. For urgent queries please call **01509 222900**.
For other queries email examhelp@lboro.ac.uk

You may handwrite and/or word process your answers, as you see fit.

You may use any calculator (not just those on the University's approved list).

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(21WSP034)

January 2022 | 2 Hours

Answer **ALL FIVE** questions.

All questions carry equal marks.

1.

a) Draw a velocity triangle to illustrate the concept of angle-of-attack for a wind turbine blade, showing how it relates to the relative wind speed, blade pitch angle and rotational speed of the rotor. With the aid of this vector diagram, explain why most modern turbine blades incorporate a twist from root to tip, assuming a constant lift coefficient along the blade. Define all symbols used. [7 marks]

b) A three-bladed turbine has a diameter of 150 m and a rotational speed of 12 RPM at a wind speed of 10 m/s. The axial flow induction factor is 0.28 and the tangential induction factor is 0.04. Calculate the relative wind speed at a radius 75% of the way out from the centre of the hub towards the blade tip. [4 marks]

c) With the aid of a flow diagram, explain the steps involved in detailed wind turbine blade structural design process. [4 marks]

2.

a) Consider the 5 MW Reference Wind Turbine data shown below:

Property	Dimension	Value
Rating	MW	5
No of blades		3
Rotor Diameter	m	126
Tip Radius	m	63
Hub Diameter	m	3.0
Hub Radius	m	1.5
Hub Height	m	90
Hub Inertia About Shaft Axis	Kgm^2	115926
Max Rotor Speed	rpm	12
Max Generator Speed	rpm	1173.7
Max Tip Speed	m/s	80
Overhang	m	5.0
Shaft Tilt	deg	4.0
Rotor Mass	kg	110000
Nacelle Mass	kg	240000
Tower Mass	kg	347460

By applying an up-scaling method, a 9 MW wind turbine will be designed. The considered up-scaling method is realized assuming geometric similarity rules. At the same time, aerodynamic similarity calls for the preservation of the blades' tip-speed.

i. What is the linear scaling factor required to scale up from 5 MW to 9 MW? [2 marks]

ii. Calculate the rotor diameter, shaft tilt angle, and hub inertia about the shaft axis for the 9 MW turbine. [3 marks]

b) Explain a commonly used industry methodology for providing an estimate of the long-term energy yield. [7 marks]

c) Briefly describe the underlying principles of the method of measuring the wind speed at a site with lidar. [3 marks]

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3.

a) Referring to relevant equations, explain how you would control a wind turbine to achieve optimal power tracking in low wind speeds and describe the meaning of optimal power tracking. [4 marks]

b) Sketch in a qualitative way the torque performance versus tip-speed-ratio for a low solidity and a high solidity wind turbine. With reference to the curves in these diagrams, indicate a stable part and unstable part for controlling the wind turbine and explain the reasons. [7 marks]

c) Explain passive stall regulated control, using the velocity triangle, lift coefficient vs. angle of attack curve, and power curve to support your answer. [4 marks]

4.

a) A meteorological mast has been installed at a potential wind turbine site and has measured wind speed for over 12 months at 10 m and 85 m heights above the ground. Table 1 shows the mean wind speed and frequency recorded over the 12 months, sub-divided into two 180-degree direction sectors.

Table1: Mean wind speed and frequency by direction sector as measured on the meteorological mast at two heights.

		Sector	
		0-180 [deg]	180-360 [deg]
Mean Wind Speed [m/s]	at 10 m	4.4	5.3
	at 85 m	7.8	8.7
Frequency [%]		60	40

Show that the roughness lengths are 0.627 and 0.356 for the 0-180 and 180-360 sectors, respectively. [2 marks]

b) A 3 MW wind turbine is erected at the site described in a) for the same year that the meteorological mast had been measuring. It has a hub height 95 m, cut-in at 3 m/s, is rated at 11 m/s, and cut-out at 24 m/s. Table 2 contains the power curve data for the wind turbine.

Table 2: Turbine power curve data.

Wind speed [m/s]	Power [kW]
0 – 3	0
3 – 6	245
6 – 9	1015
9 – 11	2300
11 – 24	3000

Starting with completing the missing values from Table 3, go on to calculate the annual energy yield at the given site from the wind turbine. Assume the reliability of the turbine is 98%.

Table 3: Complete the missing data.

Parameter	0-180 degree	180-360 degree	Units
z1	10	10	m
z2	85	85	m
zhub	95	95	m
U(10m)	4.4	5.3	m/s
U(85m)	7.8	8.7	m/s
Zo	0.627	0.356	m
U(hub)	7.98		m/s
Frequency	60	40	%
C		10.02	m/s
K	2.00	2.00	
Q(U>3)	0.895	0.914	
Q(U>6)	0.641	0.698	
Q(U>9)	0.368	0.446	
Q(U>11)	0.225		
Q(U>24)		0.003	
Power (3<U<6)	62.14	52.85	kW
Power (6<U<9)	277.39	256.25	kW
Power (9<U<11)	329.76	337.31	kW
Power (11<U<24)		888.49	kW

Note: The probability Q that a wind speed u exceeds a value v (assuming the measurements fit a Weibull distribution with scale parameter C and shape parameter k) is given by:

$$Q(u > v) = exp(-(v/C)^k)$$

The value of C can be estimated using $C = 2\bar{u}/\sqrt{\pi}$, where $\bar{u}$ is the mean wind speed at the hub height. You can use $k = 2.0$. [8 marks]

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c) An onshore wind turbine of rotor diameter 100 m and hub height of 85 m is to be sited close to the edge of a forest, which has a roughness length 0.1 m.

Estimate how far away the turbine should be from the edge of forest so it no longer feels its influence. Assume the turbine is sited in flat terrain surrounded by short grass (roughness length: 0.033 m) and clearly state any further assumptions that you make.

Hint: The quantity δ_1 is the height of an internal boundary layer which grows a distance r downwind of a roughness change and is given by the expression:

$$\frac{\delta_1}{z_0} = 0.75\left(\frac{r}{z_0}\right)^{0.8}$$

Where z_0 is the downwind roughness length. [5 marks]

5.

a) An offshore wind turbine generates 4 MW at 11 m/s. It has a 140 m rotor. Calculate its power coefficient (air density is 1.225 kg/m^3). [2 marks]

b) Sketch a $C_p - \lambda$ curve for a low solidity wind turbine and explain what is happening to a wind turbine rotor aerodynamically as λ varies. [5 marks]

c) Sketch in a qualitative way the power performance curves for a series of wind turbines with increasing numbers of blades from 1 to 5. With reference to this diagram, explain the different uses of a high solidity and low solidity wind turbine. [4 marks]

d) The C_P depends on only solidity and tangential force coefficient when the tip-speed-ratio, axial induction factor, and tangential induction factor are kept constant. Assume that the power should be maintained, and the number of blades is the same.

Referring to relevant equations, explain the relationship between solidity and tangential force coefficient in designing the blade to be more slender. [4 marks]

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