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1. DESIGN A PITCH CONTROL SCHEDULE
1.1 Pitch Control Schedule
To design an effective pitch control schedule, dynamic simulations were conducted using the RNA model in Ashes under uniform flow conditions for the WES 18-MW turbine. The schedule was designed with the operational regions: cut-in, ramp-up, rated and cut-out with wind speeds and pitch angles summarised in Table 1. The cut-in speed of 3.5m/s was selected as it was the minimum wind speed at which electrical power generation initiates from simulation, and a cut-out speed of 25m/s was determined by using similar scaled existing wind turbines and adhering to the IEC Class 1 turbine safety limits [1]. Below the cut-in speed the turbine remains idle where the blades are pitched to 0° and then increased to 3° at the cut-in speed to initiate rotation. It has a linear decrease of pitch angle from 3° to 0°. During the ramp up region, from 9m/s to 12.5m/s, the pitch angle was maintained to be 0° to maximize power coefficient (C_P) and operate at the optimum tip-speed ratio (TSR). Above the rated windspeed, the pitch angle increases to regulate power generated at 18MW to maintain constant torque and RPM. At cut-out, the blades feather to around 90° to prevent overloading the blades to protect the turbine from structural failure and fatigue loads under high wind speeds.

1.1.1 Determining the Cut-in Pitch Angle
To determine the most effective cut-in pitch angle at 3.5m/s, simulations were conducted for a range of pitch angles from 0° to 5° as shown in Figure 1. Most similar sized turbines, shown in Table 2, have a cut-in speed ranged from 3m/s to 4m/s and a cut-out speed of 25m/s as this was taken as an initial value but simulations confirmed it [2].
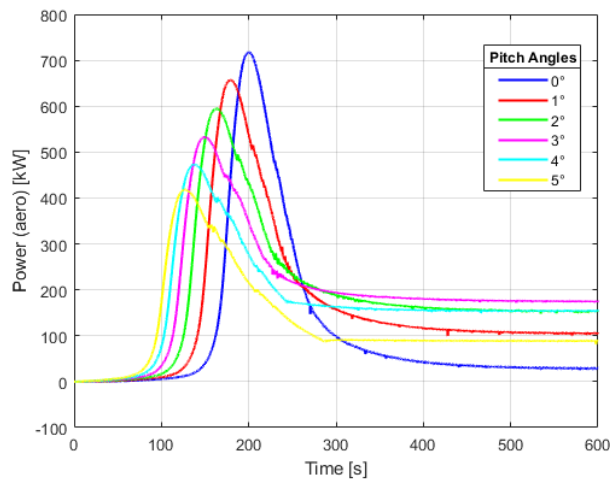

Figure 1: Cut-In Pitch Angles at 3.5m/s

Table 1: Pitch Control Schedule

Wind Speed	Region	Pitch
< 3.5m/s	Idle	0°
3.5 m/s	Cut-In	3°
9.0 m/s	Ramp-Up	0°
12.5 m/s	Rated	0°
25 m/s	Cut-Out	20.64°
> 25m/s	Feather	~90°

At 0° pitch angle the highest peak power was produced, reflecting maximum aerodynamic lift due to optimal blade alignment with the oncoming flow. However, power decayed rapidly indicating insufficient rotational momentum. The higher pitch angles exhibited lower peaks and a shorter startup time than 0° and settle at a steady power output range of 100kW-190kW showing there is some sustained energy capture. These pitch angles were evaluated to balance startup dynamics and steady-state power. The 3° pitch angle emerged as the optimal choice as it achieved a relatively short startup time of 150s, and, critically, the highest steady-state power of approximately 190 kW after 600 seconds. This angle was leveraging sufficient lift while avoiding excessive stalling or drag penalties. The selection of 3° as the cut-in pitch angle

optimizes the turbine's ability to initiate rotation and power generation at the cut-in wind speed of 3.5m/s.

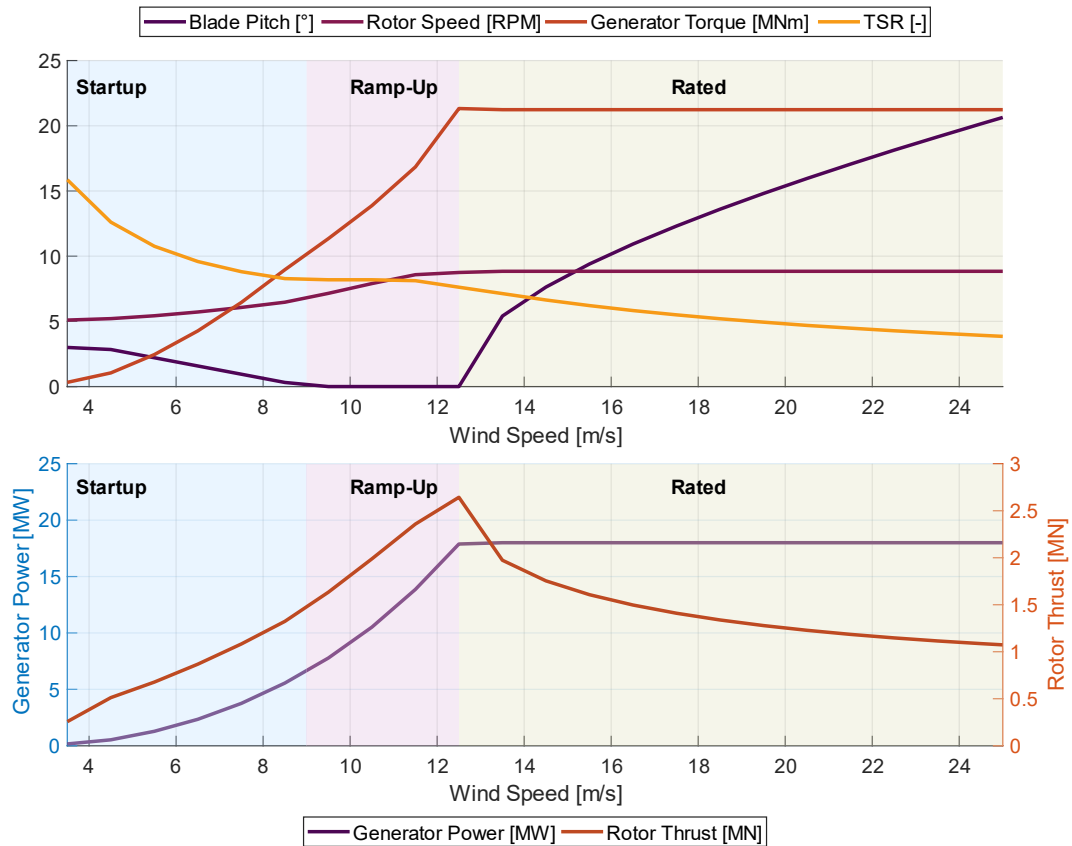## 1.1.2 Analysis of Power Curves

Figure 2: Power Curves with (a) Pitch Angle, Rotor Speed, Torque and TSR (b) Power and Thrust with respect to Wind Speed

The power curves were designed by running manual simulations across a range of windspeeds from 3.5m/s to 25m/s achieving the three shaded regions of cut-in, ramp-up and rated shown in Figure 2. This turbine has a constant pitch angle of 0° in the ramp-up region to maximize C_P of 0.44 and slowly increasing above the rated windspeed to maintain the rated power of 18MW.

1.2.1 Start-Up
Below the cut-in speed, the wind speed is not sufficient to generate any power as there is no torque from the wind to the blades, so the blades remain with a pitch angle of 0°. At the cut-in speed of 3.5m/s the pitch angle starts from 3° and gradually decreases to 0° as windspeed increases to 9m/s. This is to optimize the angle of attack to initiate the rotation as so that the TSR can be reduced and consequently increase C_P to reach a maximum value as soon as possible. The blades generate enough torque to initiate the rotation of the rotor.

1.2.2 Ramp-Up
In this region, the pitch angle stays constant as it needs to maintain the TSR to maximize power generation (C_P), as power generated increases cubically with wind speed ($P \propto u^3$). The 0° pitch maximizes the angle of attack and minimises the drag to fully exploit the aerofoil as higher wind speeds generate higher rotor speeds. The RPM increases linearly towards 8.84 RPM. Due to the increase in wind speed the thrust continues to increase.

1.2.3 Rated

Beyond the rated windspeed of 12.5m/s the objective of the turbine is to generate constant power. This is achieved by maintaining a constant torque of 21MNm and a rotor speed of 8.84 RPM by increasing the pitch angles as windspeed increases shown by $P = Q\omega$. The PID controller was used to control the pitch angles so that the angle of attack of the blade will increase and thus decrease the lift force so that the thrust reduces. When the windspeed exceeds the cut-out speed the turbine will shut down and the blades will pitch to a near 90° angle to feather and to minimise the aerodynamic loads and prevent excessive loading to ensure the structural integrity of the turbine.

1.3 Rotor Diameter Suitability

This rotor diameter of 208m is suited to high wind speed sites because of the cubic dependence of the power output on the wind speed as shown in Equation 1.3. At 12.5m/s the turbine achieves its rated power of 18MW but at lower speeds at 10.5m/s the power output drops to 10.5MW. A larger rotor will capture more wind energy but also needs a sufficient windspeed to generate to the rated power efficiently.

$$P = \frac{1}{2}\rho A v^3 \text{ (1.3)}$$

At lower wind speed sites, the turbine will struggle to reach the rated power as the cubic relationship is powerful. Thus, the turbine is said to be underutilized and wouldn't reach provide the rated power of 18MW. Moreover, it will also be unable to reach the rated power because of the insufficient aerodynamic force acting on the blades. TSR must be maintained within an optimal range to ensure efficiency but at lower wind speeds the turbine must either require excessive pitch control or spin at a lower RPM to achieve a high TSR. For this rated power of 18 MW, similar turbines are much larger with a rotor diameter of around 260m. This turbine is much smaller compared to it and proving it to be better at capturing energy as it has a higher power density. Power density is how much power a turbine produces over the swept area and is shown in Table 2. This turbine is the most efficient as it produces the most energy with respect to its size. Thus, it is more suited to a higher wind speed area as the bigger swept area of a turbine has the ability to capture more energy at lower wind speeds.

Table 2: Comparison with similar rated turbines [3][4][5]

Model	Rated Power	Rotor Diameter	Swept Area	Power Density
WES 18-MW	18 MW	208 m	33987 m²	0.53 kW/m²
MingYang MySE	16 MW	242 m	45995 m²	0.35 kW/m²
GE Haliade-X	14 MW	220 m	38013 m²	0.37 kW/m²
Siemens Gamesa	14 MW	222 m	38655 m²	0.36 kW/m²

1.3.1 Potential Rotor Design Changes for Lower Wind Speed Sites

To make this turbine more suitable for lower wind speed sites, the rotor diameter could be increased and consequently enlarging the swept area so that it can capture more energy at lower wind speeds. A small increase in rotor diameter will lead to a greater swept area because the turbine intercepts more wind even at lower speeds to generate power. Longer and larger blades create more torque due to the increase in the moment arm. Thus, it is easier for the turbine to rotate at lower wind speeds and will also reduce the cut-in speed. Using longer and slimmer blades to reduce drag at lower wind speeds and consequently increasing the lift to drag ratio for lower windspeeds. Also, the blades mass can be reduced by using carbon fibre instead of fibreglass, so that the turbine can start easier with lower wind speeds. Using carbon fibre composites instead of traditional fiberglass reduces the blade mass despite the increase in length.

1.3.2 Design Implications on the Tower and Foundation

As the swept area increases there is more thrust loading on the tower especially in the ramp-up region. Moreover because of the longer blades it will also create a larger bending moment at the hub which will transfer to the tower. To mitigate this, the tower must be taller and stiffer so stronger materials or thicker steel sections will be required to withstand the increased flapwise loads. The tower has to be taller to increase the tip blade clearance because the blades are longer. Dynamic stability becomes more critical as larger blades create more aerodynamic forces. Increased fatigue loads will also be experienced due to larger and more frequent blade deflections. A larger rotor lowers the natural frequency of the turbine which may align with the wind or wave induced excitation frequencies and this would lead to resonance and structural fatigue. The rotor's increased torque and the taller, heavier tower significantly raise the loading on the foundation. As this is an offshore turbine, larger wave and wind drag forces will affect the structure. As a result, larger and deeper monopiles are required with more seabed penetration to sustain the increased loads. Considering all these, the taller tower and deeper foundation demand more materials as the initial investment (CAPEX) for larger diameter turbines is significantly higher as cost increases cubically with diameter. However, this initial cost could be offset by higher energy yield at lower wind speeds. At the same time, it is more viable financially to place this turbine in high wind speed sites where power generation is predictable.

1.4 BEMT vs CFD

Ashes implements Blade Element Momentum Theory (BEMT) to model the aerodynamic loads sustained by the rotor by dividing each blade into aerodynamic stations and computes the lift and drag forces based on local flow conditions. Another approach is to use Computational Fluid Dynamics (CFD) and both of these approaches differ in modelling fidelity and speed for aerodynamic analyses for an isolated wind turbine.

BEMT is used in ASHES to calculate the aerodynamic forces by assuming the flow over the rotor disk is uniform and axisymmetric as it segments blades into independent 2D elements. The flow on each blade element is independent of other sections and relies on 2D aerofoil data which leads to underpredicting the actual power output and the torque of the turbine. Moreover, it neglects 3D effects such as radial flow and tip vortices. This method also cannot model a turbulent region behind the rotor and dynamic stall condition thus cannot be used in wind farm modelling [6].

In contrast CFD offers higher fidelity by solving the full Navier Stokes equations, accurately capturing the 3D flow field, such as turbulence, boundary layer effects and wake structures around the turbine. It provides detailed information on pressure distribution, flow separation and unsteady effects making it suitable to analyse turbulent interactions between turbines in a wind farm. For an isolated wind turbine, CFD can resolve tip vortex structures as BEMT approximates it, these improved predictions of power output by 8% in ramp-up regions [7].

BEMT analysis is significantly faster because of the assumptions of the flow physics stated above. Simulating an isolated turbine can be completed in seconds to minutes on a standard computer. Due to this low computational cost this is ideal for the preliminary design stage as it requires many iterations and simulations. This speed essentially stems from avoiding detailed flow field calculations.

CFD on the other hand is computationally expensive and time consuming. Simulating a turbine can take hours or even days on a supercomputer as it greatly depends on the mesh resolution and the iterative manner of solving. Although CFD offers more detailed and accurate results, the computational demands make it impractical to do iterative design studies as well as the slow speed. However, this method is mainly used for validation and detailed design stages.