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Control System for Start-up and Shut-down of a Floating Vertical Axis Wind Turbine

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Abstract

A baseline control system for the Deepwind floating vertical axis wind turbine (VAWT) concept is analysed with emphasis on start-up and shut-down schemes. The turbine concept includes a rotating spar with a 2-bladed rotor at the top and a submerged generator at the bottom, anchored to the seabed with mooring lines attached to the stator-side of the generator. The controller is a typical PI control system with a notch filter to damp 2p torque variations. Start-up and shut-down logic is presented in detail, with simulation results demonstrating smooth start-up and shut-down at high wind speeds without severe spikes in generator torque.

Keywords: Wind turbine control, VAWT, floating wind turbine, Deepwind

1. Introduction

DeepWind is a floating vertical axis wind turbine (VAWT) with a two-bladed Darrieus rotor [1, 2]. A long rotating shaft extends into the water, with the generator at the bottom end. The floating tower is stabilised by ballast and kept in place by mooring lines attached to the non-rotating part of the generator. Potential advantages of the DeepWind concept arise from its simple design, up-scaling potential and suitability for deep sea sites. Simple design is important for cost and reliability, allowing cheaper manufacturing e.g. of blades made by pultrusion, and simpler installation and maintenance because of fewer components. Upscaling potential is important for offshore installations due to the high fixed costs per turbine, something which favours larger units. An illustration of the DeepWind turbine is shown in Fig. 1.

As is evident from availability of commercial designs, horizontal axis wind turbines are favoured to vertical axis ones for land-based application at MW scale. For very large turbines intended for offshore applications, however, this may change as the overall cost picture is significantly different. New turbine concepts that offer higher reliability and simpler installation may be competitive even if the aerodynamic efficiency is less than for state-of-the art horizontal axis turbines. In the end it is the cost of energy that matters. These considerations have motivated a renewed interest in VAWTs, such as the floating DeepWind concept.

This paper outlines a proposed control system for a 5 MW design [3, 4, 5] of the DeepWind turbine. The basic characteristic of this turbine seen from a control perspective is that it is a stall-regulated, floating

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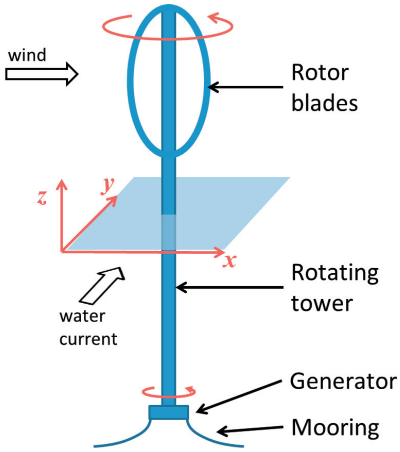

Fig. 1: A sketch of the Deepwind floating VAWT

spar-buoy type VAWT with no pitch or yaw control. A thorough discussion of the control system is being published elsewhere[1], and the emphasis of this paper is the start-up and shut-down schemes which are not treated there. The following sections include a brief overview of the model used to develop and test the control system; a detailed discussion on the start and stop logic, with simulation results demonstrating that the proposed strategy appears to work well.

1.1. Control challenges

One special feature of 2-bladed vertical axis wind turbines is the strong twice-per-revolution (2p) pulsation in the aerodynamic forces on the rotor, with values ranging from near zero to about twice the average value. With a variable speed generator, however, the aerodynamic torque variation can be isolated from the electrical side by filtering out the 2p frequency of the measured speed fed into the torque controller. In this way, the aerodynamic torque variations are absorbed by the rotational inertia of the rotor, giving a slight 2p speed variation instead. Another feature, which is special to the DeepWind turbine, is that the stator has a rotational (yaw) degree of freedom with dynamic characteristics dependent on the mooring system. Since the stator is not fixed, the generator speed is the difference between the rotor and stator speeds. In general, the generator is stiff compared to the mooring system such that the stator will track changes in rotor torque. In fact, this and the proximity of mooring–stator system eiqenfrequency with the 2p frequency in the present design gives rise to a natural damping of the 2p torque variations. Effectively, the torque variations are compensated by 2p oscillations of the stator such that the generator sees a smooth rotor speed even without the filter mentioned above. The 2p variations have previously been discussed in ref. [6].

Like most VAWT, the DeepWind turbine is stall-regulated and has no blade pitching that can be used for control; all control action is done via the generator torque (and possibly additional rotor brakes). The stall behaviour is determined by the aerodynamic design of the blades, and different designs may have different control challenges. Since the final airfoil of the DeepWind 5 MW design is not yet known, our results are based upon the NACA 0018 airfoil profile at high Reynolds number, with modified drag coefficients. This blade profile gives a reasonable stall behaviour with fairly flat power output at high wind speeds.

Avoiding runaway speed or over-rated speed and torque in general is a critical challenge for the control system. Since the speed is only controlled by the torque, there is an optimal balance between reacting too fast and too slow. Fast reaction will avoid over-speed, but may lead to unwanted spikes in the generator torque. Slow reaction will at times lead to over-speed, and as aerodynamic torque increases with the rotational speed, to a subsequent increase in generator torque. Too slow response leads to rotor runaway.

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[1] Merz and Svendsen, *A Baseline Control Algorithm for the Deepwind Floating Vertical-Axis Wind Turbine* (2013)

There are two critical points in the operating range; one where the speed control changes from optimal speed to constant (rated) speed, and the other is at turbine slow-down or shut-down at high wind. The reason that these are critical is that they corresponds to situations where the deviation between measured speed and reference speed has a sharp increase, and there will therefore be a peak in the generator torque. If this happens at the same time as a wind gust accelerates the turbine, the effect is amplified. For this reason, start-up and shut-down procedures at high winds are a very important aspect of the control system, something which motivates the special treatment in this paper.

2. Modelling

The simulation model that has been used to develop and investigate control strategies includes a simplified description of aerodynamics, mechanical dynamics, and floater and mooring system. The electrical system is not included in the present model. This is reasonable, since the dynamics of the electrical components are typically very fast compared to the mechanical dynamics of the turbine. Hence, it is a good approximation to assume that the electrical torque from the generator acting on the rotating shaft equals the torque reference value obtained from the torque controller. The interaction between electrical and mechanical parts will be explored in future work. The simulation model has previously been described in refs. [7, 6].

2.1. Aerodynamical and mechanical systems

The aerodynamics of the rotor is described by a Fourier approximation that includes 2p and 4p variations, with the aerodynamic torque, T, given as:

$$T = T_0 + T_2 \cos(2\Psi + \Psi^T_{2p}) + T_4 \cos(4\Psi + \Psi^T_{4p}). \tag{1}$$

Here, Ψ is the azimuth angle of the rotor relative to the wind speed direction. The Fourier coefficients T_0, T_2 and phases Ψ^T_{2p}, and Ψ^T_{4p} have been computed for different average incoming wind speeds (V_∞) and rotational speeds (Ω) using a double-multiple streamtube blade element momentum model [8] that captures dynamic stall effects. These parameters are specified by a set of 3-dimensional look-up tables. Linear interpolation is used to get aerodynamic loads at any given incoming wind speed and rotational speed. Analogous parameters are specified for thrust forces F^x and F^y.

Regarding the hydrodynamics of the floating structure, it is assumed that the bottom end is fixed in all translational directions, but allowed to rotate (yaw) and tilt. The mooring system is included as a pure torque absorption system represented by a one-degree of freedom spring–damper in the yaw direction, acting on the stator part of the generator. There is no coupling between the tower tilting and the mooring system. The Magnus lift force acting on the under-water rotating tower is included. This force gives a fairly steady tilt moment on the tower, depending on water current and rotational speed, which makes it tilt in a direction perpendicular to the water current. Additional tower tilt results from aerodynamic thrust forces. The dynamics of the tilt in x and y directions are represented by two spring–dampers that approximate the effects of gravity, buoyancy and damping by the water.

The only structural dynamics which is included in the model is the tower twisting, again represented by a spring–damper. The twisting arises from the aerodynamic torque that acts at the top of the tower and the generator torque that acts at the bottom of the tower.

2.2. Control system

As discussed in the introduction, the controllable variable for this turbine is the generator torque, which is used to regulate the rotational speed of the turbine. A detailed description of the control system will be given in a separate paper, but a brief summary is as follows.

The suggested control system is fairly standard (see Fig. 2), with a proportional–integral (PI) controller that gives the reference value for the generator torque as the output. The input to the PI controller is the deviation between measured rotational speed and a reference speed. In normal operation the reference speed is obtained from the measured electrical torque via a variable speed look-up table.

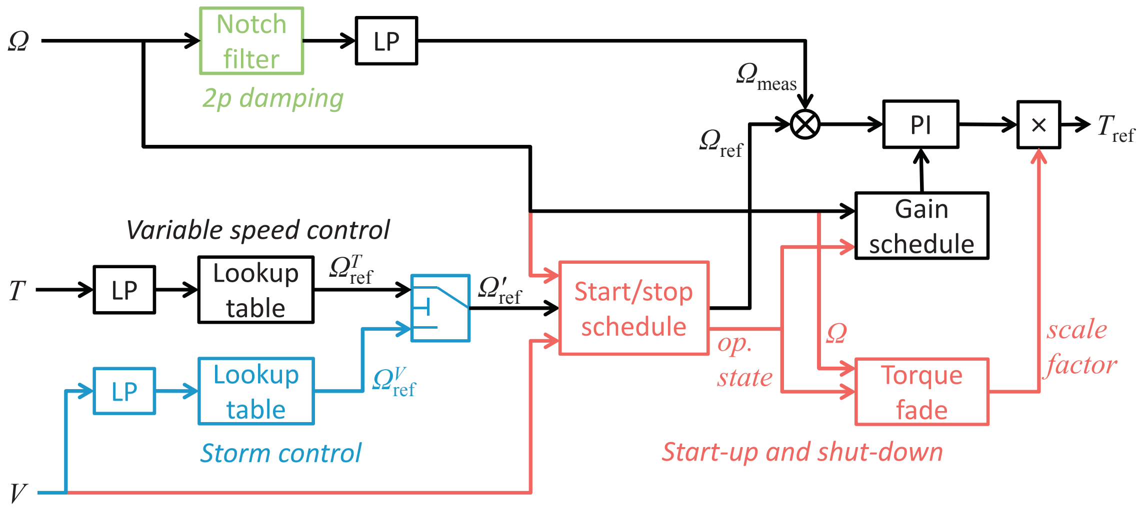
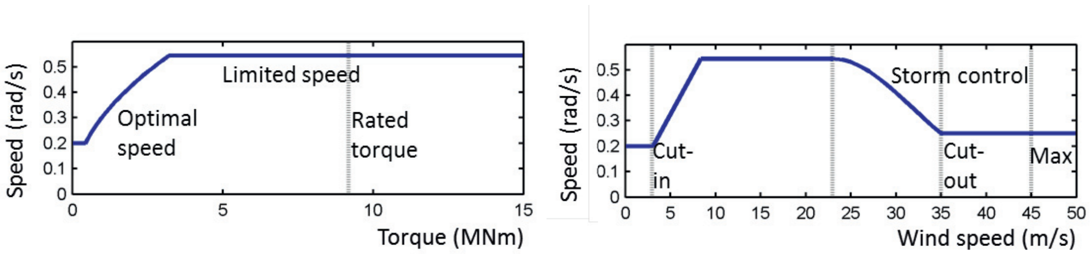


Fig. 2: Overview of the control system.



(a) Speed–torque map

(b) Speed-wind map

Fig. 3: Variable speed schedule. a) During normal operation at modest wind speeds, control is based on the torque-speed schedule. b) During high winds, storm control is activated, whereby the reference speed is reduced based on wind measurements. Also at turbine startup, wind measurements are used to determine a target value for the reference speed.

In order to isolate the 2p variations in the aerodynamic torque from the generator and mooring systems, the turbine is allowed to absorb the associated power variations by speeding up and slowing down during the course of a revolution. This is achieved by removing the 2p frequency component in the measured speed by means of a notch filter.

The torque-based speed reference value (Ω^T_{ref}) is obtained by the speed–torque look-up table which is illustrated in Fig. 3a. The reference speed is given as the aerodynamically optimal value up to a maximum value of 0.544 rad/s. At high wind speeds, this reference value is replaced by a reference value obtained from a look-up table based on wind measurements. For wind speeds from 23 m/s to 35 m/s, the control system includes a storm control feature that reduces the reference speed (Ω^V_{ref}) gradually down to 0.25 rad/s, before shutting down the turbine, see Fig. 3b.

This variable speed reference (Ω'_{ref}) feeds into a control block that takes care of start-up and shut-down of the turbine. Start and stop is described in more detail in the next Section, but is essentially achieved by ramping up or down the reference speed. In normal operation, however, the actual speed reference equals the variable speed reference, i.e. $\Omega_{ref} = \Omega'_{ref}$.

Scheduling of the proportional gain constant K_P is used to limit over-speed by gradually increasing its value from 0.04 to 0.06 as the measured rotor speed increases from 0.55 to 0.60 rad/s. Gain scheduling of

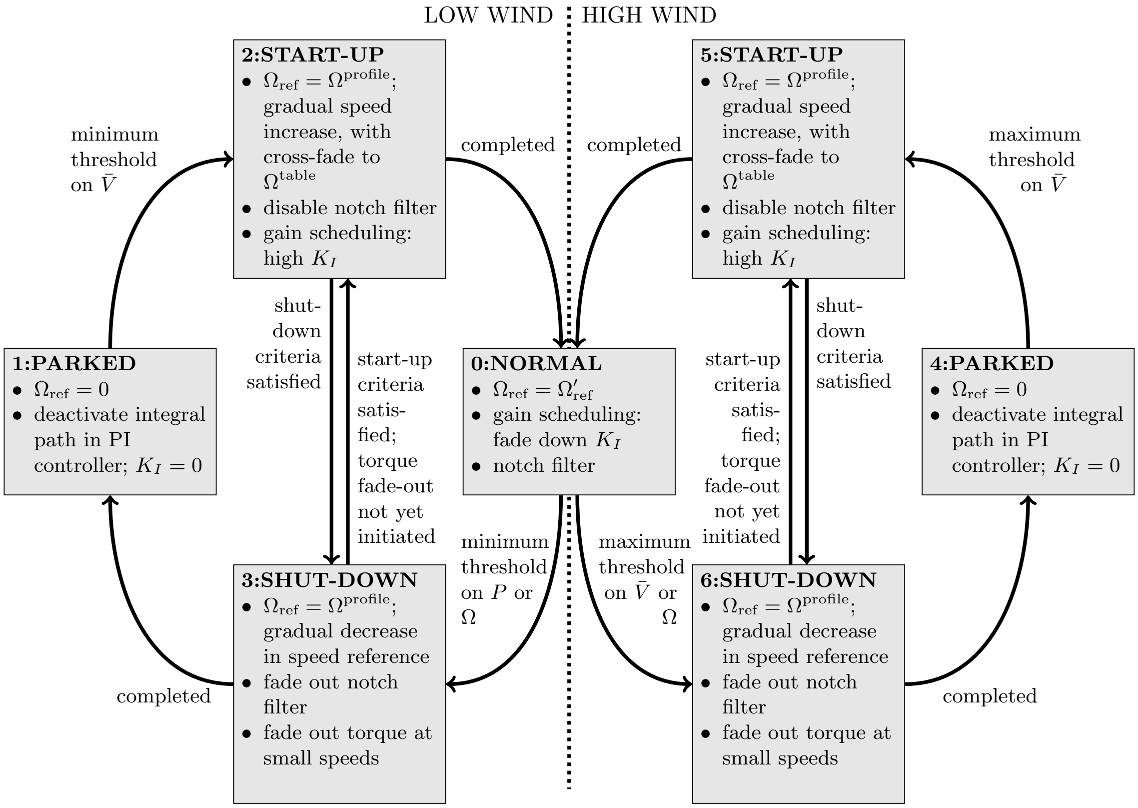


Fig. 4: Operating states; control characteristics and rules for transitions between different states.

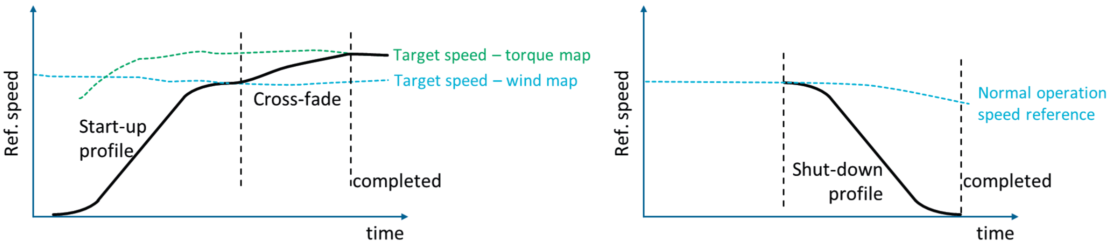
the integral gain constant $K_I = \frac{K_P}{\tau_i}$ is used to allow faster torque response during start-up and shut-down. Torque fade which is indicated in Fig 2 refers to a scaling down of the torque reference during shut-down, to arrive smoothly at a zero value.

3. Start-up and shut-down scheme

3.1. Operating states

The start-up and shut-down procedures are important, especially in high winds, because peaks in the required torque tend to occur at the end of the start-up sequence or upon initiation of the shut-down sequence. Low wind speeds are less critical, with the goal being to minimise the number of shut-downs and maximise energy production. Fig. 4 summarises the operating states of the turbine and the logic used to switch between states. The arrows indicate possible transitions between operating states. The symbol P refers to measured electrical power, Ω the rotational speed, and $\bar{V}$ refers to a filtered wind speed measurement. Subtly different logic is used in low and high wind speeds. The transition between low and high wind speeds is determined by a 300 s average anemometer measurement, with the transition occurring when the measured wind speed crosses 12 m/s.

The main difference between the seven operating states is how the reference speed Ω_{ref} is specified. A second difference is the scheduling of the integral gain constant K_I. Note that in the parked condition, the integral path is disabled completely to ensure that the turbine aligns itself in a position with minimal aerodynamic torque. A third difference is the notch filter, which is activated only in normal operation since it leads to instability in the other states. Finally, during shut-down the reference torque is faded out to obtain a smooth stop.



(a) Start-up profile (b) Shut-down profile

Fig. 5: Illustration of start-up and shut-down speed profiles.

The start-up and shut-down profiles Ω^{profile} are specified explicitly as illustrated in Fig. 5. The speed at initiation of start-up or shut-down is used as an initial condition. On shut-down, the target speed is zero (Fig. 5b), whereas on start-up, the target speed is determined based upon the speed–wind curve in Fig. 3b. The wind speed is estimated by an anemometer measurement, low-pass filtered with a time constant of 300 s. As the target speed is approached, a fade function is employed for a smooth transition to the normal operating schedule based on torque measurements (Fig. 5a).

Following the results of refs. [9, 10], shut-down in low wind speeds is initiated when the low-pass filtered generator power drops below a minimum value. The minimum power was set to 50 kW, corresponding to a nominal wind speed of 2.5 m/s, and the time constant on the low-pass filter is 300 s. Once shut down, the turbine starts up when the low-pass filtered anemometer measurement exceeds the cut-in wind speed of 4 m/s; here the time constant is also 300 s. These settings were obtained by trial-and-error, and seem to function well, never initiating a shut-down when the mean wind speed was 3 m/s or higher. However, we did not optimise the low wind speed logic, focusing instead on high wind speed start-up and shut-down.

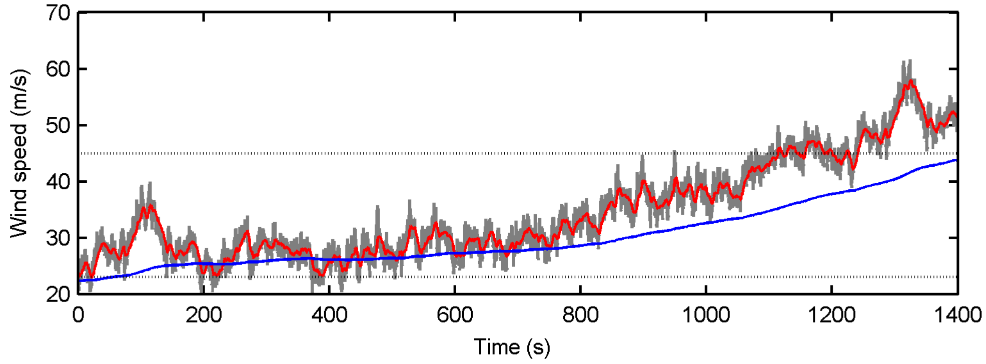
Start-up at high wind speeds is challenging, as the turbine tends to over-speed at the transition between start-up and normal operation. Two modifications to the basic control scheme were implemented to limit the overshoot to a small value. The first was the increase of the proportional gain K_P at rotational speeds above 0.55 rad/s, as described above. Second, on transition from start-up to normal operation, a fade function was implemented such that the integral path time constant τ_i increases gradually. During start-up, τ_i is given a low value of 15 s so that the ramping speed trajectory can be followed without a persistent offset. After reaching the target speed, τ_i increases linearly from 15 s to 120 s, over a timespan of 120 s. This gives the integrated error sufficient time to stabilise at an appropriate value.

In high wind speeds, shut-down is initiated if a slow-filtered (τ = 120 s) anemometer measurement exceeds the cut-out wind speed V_{co} = 35 m/s, if the fast-filtered (τ = 5 s) anemometer measurement exceeds a maximum gust wind speed $V_{\max}$ = 45 m/s, or if the rotational speed exceeds a maximum over-speed value $\Omega_{\max}$ = 0.6 rad/s. The setting of the cut-out and maximum gust wind speeds depends upon the storm control strategy. The turbine restarts if both the slow-filtered and fast-filtered anemometer measurements fall below 23 m/s.

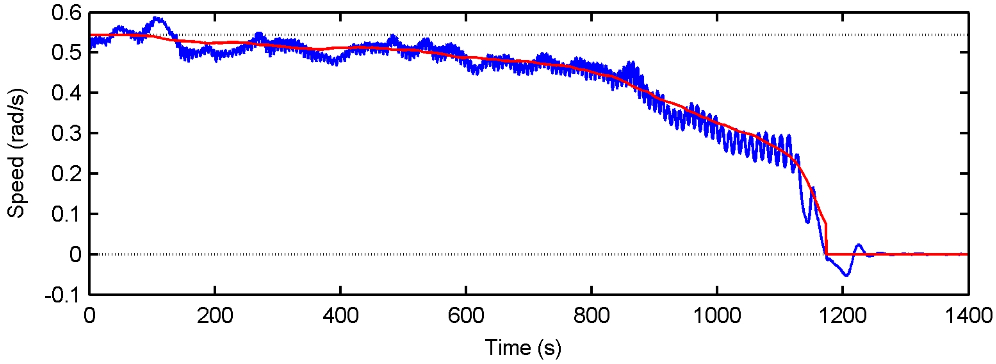
3.2. Simulation results

This section includes results from computer simulations that illustrate turbine behaviour during operation in high wind speeds, including turbine shut-down and start-up.

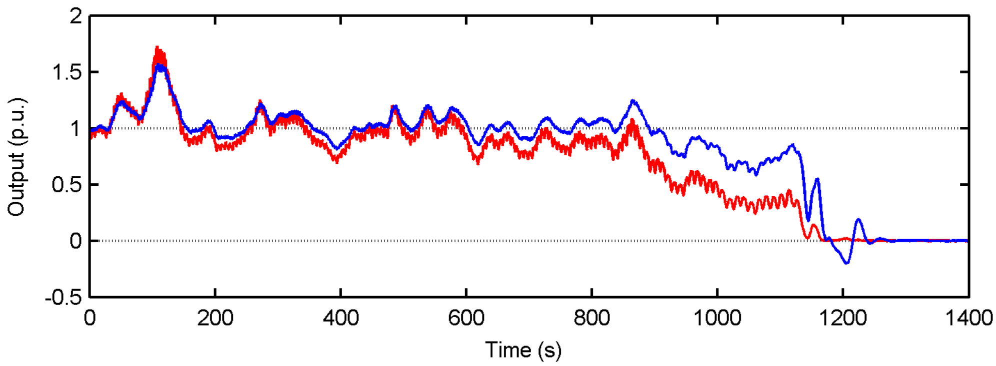
Fig. 6 shows a time series simulation with high and increasing wind that illustrates the turbine performance during storm control and shut-down. The storm control is activated at around 80 s as the slow filtered wind crosses the threshold value of 23 m/s. At around 100 s there is a rather severe wind gust that gives a significant spike in electrical torque and power output. This illustrates the “worst case” situation with a wind gust that accelerates the turbine at the same time as the reference speed is reducing due to storm control or shut-down. Shut-down is initiated at about 1100 s as the fast filtered wind speed exceeds the maximum value of 45 m/s. The turbine is then brought to rest without any severe spikes in speed or power.



(a) Incoming wind speed; measured value (gray), fast-filtered (red) and slow-filtered (blue).

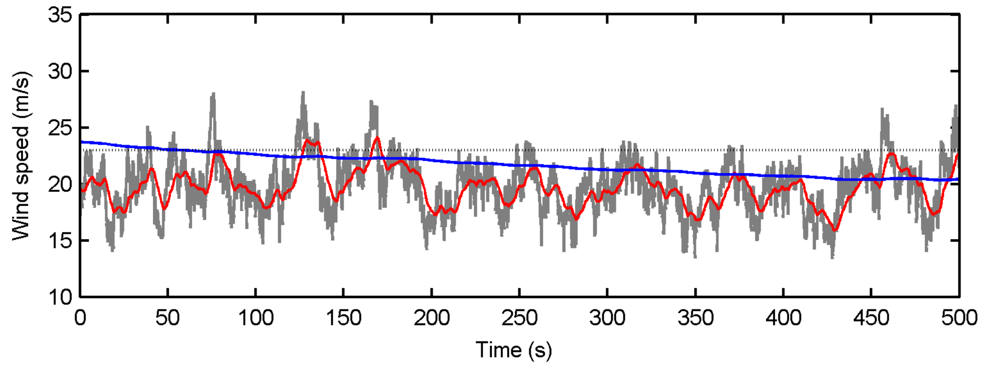


(b) Rotational speed; measured value (blue) and reference value (red)

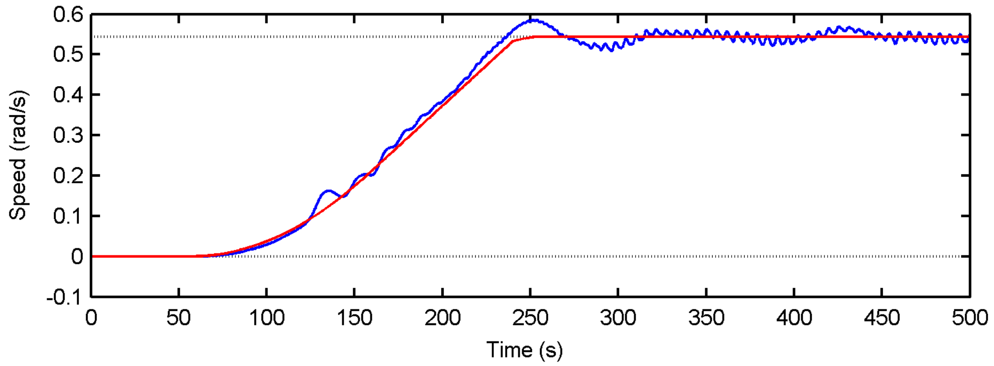


(c) Generator output; torque in units of 9.2 MNm (blue) and power in units of 5 MW (red)

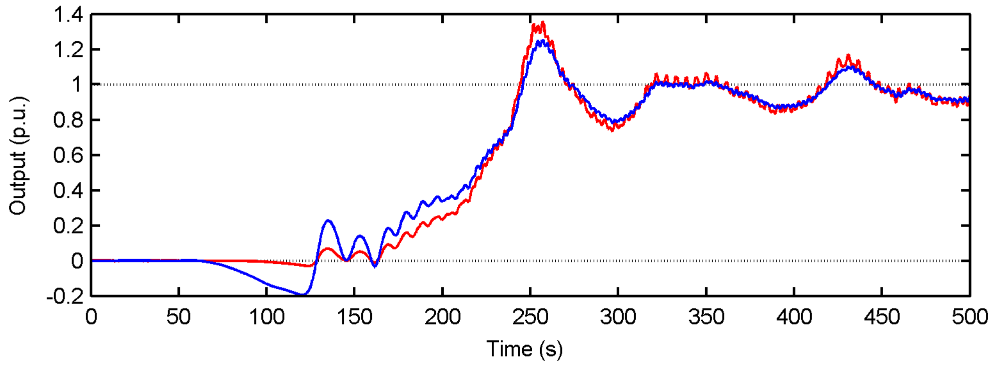
Fig. 6: Simulation results of turbine storm control and shut-down in high wind



(a) Incoming wind speed; measured value (gray), fast-filtered (red) and slow-filtered (blue).



(b) Rotational speed; measured value (blue) and reference value (red)



(c) Generator output; torque in units of 9.2 MNm (blue) and power in units of 5 MW (red)

Fig. 7: Simulation results of turbine start-up in high wind.

Fig. 7 shows a time series simulation with high, but decreasing wind that illustrates the turbine performance during start-up in high wind. The (slow- filtered) measured wind drops below the threshold value of 23 m/s at around 50 s. From this point, the reference speed is smoothly increased, following a speed profile as discussed above. Since the turbine is not self-starting, the initial phase of the start-up requires a negative generator torque. The transition from increasing to constant reference speed at around 250 s is the critical point, and a certain amount of over-speed and over-torque is evident in this simulation. After start-up has been completed, the 2p damping is activated, giving rise to 2p oscillations in the rotational speed which are visible from about 300 s in Fig. 7b.

4. Conclusions

A control system for a floating vertical axis wind turbine has been outlined, with emphasis on start-up and shut-down schemes, which are seen as critical for safe operation of the turbine. Control for start-up and shut-down of the turbine was achieved by defining operating states that correspond to different stages in the start and stop cycle. Each operating state is associated with different control parameters, and rules for how a transition to another operating state can occur.

The control system was implemented in a simplified computer model of the floating turbine and simulations were presented that demonstrate the turbine performance during shut-down and start-up at wind speeds near the cut-out speed.

In general, these simulation results found the behaviour of the turbine during start and stop to be fairly smooth. They also demonstrate that start and stop are indeed critical events with significant peaks in rotational speed and generator torque during the transition from start-up to normal operation at rated speed, and during initiation of turbine slow-down, especially if this happens simultaneously as a wind gust as we saw in these simulations. Other simulations, not presented in this paper, with different wind speed profiles confirm these results.

The observed amount of over-speed and over-torque is significant, but can still be characterised as moderate and not dramatic. The maximum rotational speed is avoided and the torque peak is not dramatically different from what is seen in normal operation due to turbulent wind variations. Since the torque is the only control variable, it is inevitable that peaks in the torque above the nominal value occurs with short duration. It is important that this is taken into account for the dimensioning the generator.

It must also be noted that these simulations were based on a preliminary design of the DeepWind 5 MW turbine with quite good stall behaviour. Modifications to the design will naturally have implications for the control system design, and the results presented here.

Acknowledgement

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