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CONTROLLING STRATEGIES IN VERTICAL AXIS WIND TURBINE USING PI CONTROLLER

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Abstract

This paper addresses turbine operational control challenges for a large floating vertical axis wind turbine, with focus on the damping of the large twice-per-revolution (2p) pulsations in the aerodynamic torque. It is shown that if, as is the case for the studied design, the stator and mooring system resonance frequency is similar to the 2p frequency, these variations are almost entirely eliminated in the electrical power output without any dedicated control loop being necessary. Simulation results demonstrate this effect as well as other characteristics of the proposed control strategy. For other cases, a filtering out of 2p speed variations in the torque controller is found to give similar damping.

Keywords: Vertical axis wind turbine, floating turbine, control system, torque control

1 Introduction

Land-based vertical axis wind turbines (VAWT) have been investigated in the past and attracted a lot of attention in the 80s and early 90s before they lost ground relative to horizontal axis wind turbines which are predominant today. For very large turbines intended for offshore applications, however, this may change as the cost of installation and maintenance becomes relatively more important. New turbine concepts that offer higher reliability and simpler installation may thus be competitive even if the aerodynamic efficiency is less than for state of the art wind turbines Such considerations motivate a renewed interest in VAWTs, and a concrete example is the floating wind turbine concept studied in the European collaboration project DeepWind [1, 2, 3]. This concept includes a two-bladed Darrieus rotor with a long rotating shaft that extends into the water with the generator at the bottom end. The floating tower is stabilised by buoyancy and kept in place by mooring lines attached to the non-rotating part of the generator (the stator).

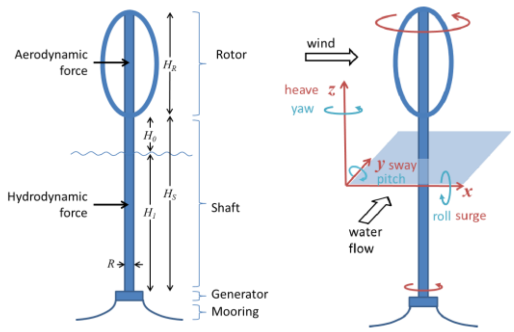

Figure 1: Schematic view of turbine and global coordinate system.

Large wind turbines require in general an active control system to maximise power extraction and minimise structural loads. A particular challenge for vertical axis turbines is the large aerodynamic torque variation which is due to the axis of rotation being perpendicular to the wind direction. Another challenge is the braking of the turbine at high winds, which without blade pitching must also be done via the torque/speed control.

In this paper we investigate a 5 MW floating VAWT modelled according to the DeepWind project preliminary design [4, 5, 6]. The most relevant turbine parameters are given in Table 1. A schematic view of the turbine and global coordinate system is shown in Figure 1.

The paper continues with a discussion of the con-

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trol challenges in Section 2. Then a description and discussion of control strategies for variable speed operation and damping of 2p variations is given in Section 3. Simulation results where the developed control system is tested under various conditions are presented in Section 4. Finally, the conclusions with a summary of the findings and remarks on limitations and future work is found in Section 5.

2 Control challenges

The objectives of the control system for this type of wind turbine are similar to the objectives for other large wind turbines. It should maximise the aerodynamic efficiency and hence the power extraction through variable speed operation. It should limit the speed and power at high wind speeds to avoid damage. It should avoid excitation of natural frequencies and possibly help stabilise structural motions. And it should ensure grid code compliance.

However, there are some important differences from standard pitch-regulated horizontal axis wind turbines. Firstly, there is no blade pitch control, which implies that all control action is through speed–torque control. Secondly, because the axis of rotation is not parallel to the wind speed, vertical axis wind turbines have large variations in the aerodynamic torque, posing an additional important control challenge. For a two-bladed turbine, these variations give a twice per revolution torque pulsation that are henceforth referred to as 2p variations. Instantaneous values of aerodynamic torque and power range from close to zero to about twice the average value, as shown in Figure 2. These large variations represent a problem both for fatigue lifetime and for the power export into the grid. This 2p effect is clearly much more severe than the 3p effect observed for 3-bladed horizontal axis wind turbines arising from tower shadow and wind shear.

The present study focusses on this difference from horizontal axis turbines, and addresses two control objectives:

- Variable speed schedule (maximise aerodynamic efficiency at low wind, limit rotational speed at high wind)
- Damp aerodynamic 2p torque variations

It will be shown that for the floating wind turbine design studied in this paper, the 2p variations are

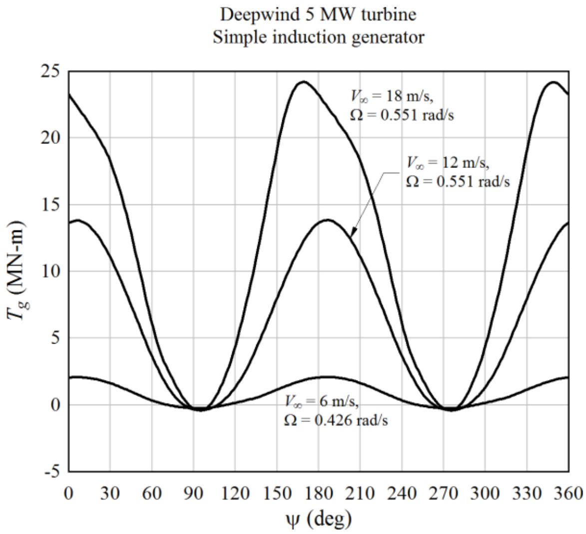

Figure 2: 2p variations of the torque T with azimuth angle Ψ for different wind speeds V_∞ and rotational speeds Ω.

damped completely by virtue of the stator/mooring system yaw motion resonance frequency being similar to the 2p frequency. In other words, the yaw motion of the stator and mooring system compensate for speed variations of the rotor.

For other designs where such a similarity in frequencies cannot be achieved, the 2p variations have to be damped by alternative approaches that do not rely on the floating nature of the turbine.

Control of land-based VAWT has been studied in the past, and it has been demonstrated that a synchronous generator with a full power converter can be used to isolate the electrical power output from 2p fluctuations in the aerodynamic torque by making the generator torsional stiffness very low [7, 8, 9]. Torque control of VAWT has similarities with torque control of fixed-pitch horizontal axis wind turbines in the stall region, which as been investigated in refs. [10, 11, 12, 13]. Ref. [14] emphasises that a good stall behaviour must be part of the rotor design optimisation process. We are not aware of any literature on floating VAWT control, but control challenges for floating horizontal axis turbines with pitch control have been discussed in refs. [15, 16, 17, 18, 19, 20, 21, 22, 23].

The basic principle for achieving a smooth electric torque and power output of the turbine discussed in this paper is to utilise the turbine itself as an energy

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storage: In order to avoid the 2p aerodynamic torque variations being transferred to the mooring system and the electrical output, the turbine must be allowed to speed up and slow down slightly, thus absorbing temporarily the associated energy variations in the rotational kinetic energy of the turbine.

The necessary speed variation ($\Delta\Omega$) at rated speed and power can be estimated through simple energy considerations as follows. Assuming that the electrical output power P_e is constant and equal to the mean value of the aerodynamic input power P_a, it is reasonable to approximate the aerodynamic power by a cosine function which captures the 2p variation, $P_a \approx P_e(1 - \cos(2\bar{\Omega}t))$, where $\bar{\Omega}$ is the revolution-average of the rotational speed Ω. The speed increase occurs when the aerodynamic power is larger than the mean value, $P_a > P_e$, which happens in the interval $t_{min} = 0$ to $t_{max} = \frac{\pi}{2\bar{\Omega}}$. In this interval, the absorbed energy is

$$\Delta E = \int_{t_{min}}^{t_{max}} (P_a - P_e)dt = \frac{P_e}{\bar{\Omega}}. \quad (1)$$

This absorbed energy is realised as an increase in kinetic energy of the rotating tower, $E_k = \frac{1}{2}J\Omega^2$, and in kinetic and potential energy of the stator/mooring system. The contribution from the stator/mooring system is negligible, so we get

$$\Delta E = \Delta E_k \approx \frac{dE_k}{d\Omega}\Delta\Omega = J\Omega\Delta\Omega \approx J\bar{\Omega}\Delta\Omega, \quad (2)$$

where J is the turbine inertia. Combined, equations (1) and (2) give the peak–to–peak speed variation,

$$\Delta\Omega \approx \frac{P_e}{J\bar{\Omega}^2} = 0.037 \text{ rad/s}. \quad (3)$$

These speed variations of ±3.6% are considered to be a small price to pay for eliminating the torque variations.

If stator/mooring system rotations are to compensate for these variations to give a constant speed input to the generator, the peak–to–peak variations in the stator yaw angle must be

$$\Delta\vartheta_{moor} \approx \frac{\Delta\Omega}{2\bar{\Omega}} = 0.036 \text{ rad}, \quad (4)$$

where a sinusoidal form of the speed variation has been assumed. This translates into a variation in the torque acting on the mooring system equal to 0.88 MNm, which is 9 % of the mean value.

Table 1: Turbine parameters

Description	Value
Rated wind speed	14 m/s
Rated rotational speed	0.52 rad/s
2p frequency	0.166 Hz
Geometry	
Tower length	253 m ($H_S + H_R$)
Darrieus rotor height	130 m (H_R)
Underwater shaft length	108 m (H_1)
Tower	
Inertia of Darrieus rotor	$4.74 \cdot 10^8$ kgm^2
Inertia of shaft	$2.12 \cdot 10^7$ kgm^2
Inertia of generator rotor	$0.5 \cdot 10^6$ kgm^2
Stator/mooring system	
Inertia	$1.6 \cdot 10^7$ kg m^2
Spring constant	$2.46 \cdot 10^7$ kgm^2/s^2
Damping coefficient	0.005
Natural frequency	0.20 Hz

3 Control strategies

This section discusses strategies that address the two control objectives that were highlighted in the previous section: enabling variable speed operation according to the aerodynamically optimal point (up to a given maximum speed limit), and damping the 2p variations.

Figure 3 shows the control system architecture proposed for the 5MW DeepWind turbine, under normal operating conditions. This is a PID control scheme, where the generator torque T_e is set based upon the error between the desired and measured rotational speed.

This model of the control system is simplified with respect to a realistic control system. The dynamics of the electrical systems – specifically, the generator and the converters – are neglected; the generator torque is assumed to instantly follow the requested value.

The state variables are the low-pass filtered torque measurement $\overline{T}_e$, the low-pass filtered speed measurements $\overline{\Omega}_r$ and $\overline{\Omega}_d$, and the integral error $\Delta\Psi_r$. Inputs are the measured generator torque T_e (inferred from electrical measurements) and the measured rotor rotational speed Ω_r.

The inputs are low-pass filtered in order to avoid high-frequency fluctuations in the controller output. The generator torque is filtered with a time constant τ_e. This is set to a relatively large value, so that

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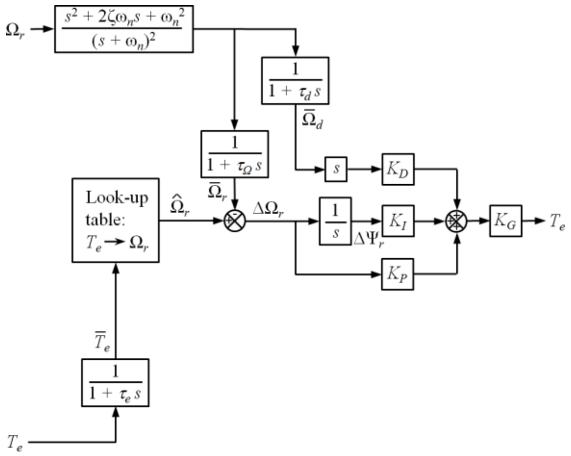

Figure 3: Control architecture.

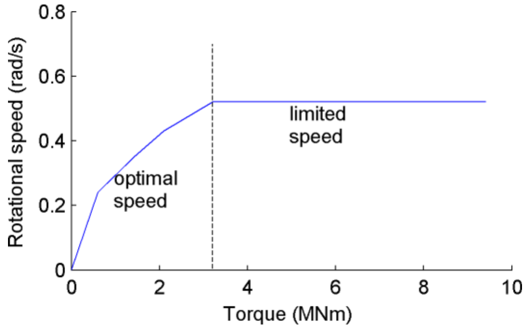

Figure 4: Torque–speed map.

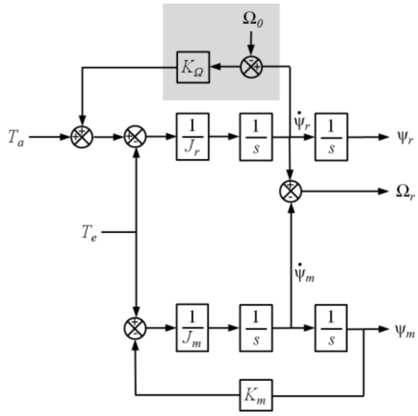

Figure 5: Simple shaft model.

the speed set-point $\hat{\Omega}_r$ varies slowly. The rotational speed is filtered with time constants τ_Ω and τ_d. These are relatively small, so that the generator torque reacts rapidly to deviations in speed. A fast reaction is especially important when operating above the rated windspeed, because the aerodynamic torque increases rapidly with rotor speed; the generator must "catch" the rotor in order to prevent runaway.

The measured rotational speed Ω_r may also be passed through a band-stop (notch) filter, with notch frequency ω_n equal to 2p. The purpose of this filter is to eliminate 2p variations in the electrical torque if this is not achieved naturally by the stator/mooring system resonant motion.

3.1 Variable speed operation

Variable speed operation that ensures optimal aerodynamic efficiency is obtained by the suggested control system in the same way as for horizontal wind turbines, using a pre-defined map between optimal rotational speed and torque as outlined above. This torque–speed map is used to set the reference speed $\hat{\Omega}_r$ based on measured values of torque T_e since each value of the torque is associated with a unique optimal speed (but not vice versa). The exact form of the relationship depends on the design of the turbine. In this paper we only consider operation in the optimal speed and the limited speed regions, see Figure 4. The speed limitation region starts at around 8 m/s in the present case

3.2 Damping of 2p variations

Figure 5 shows a simple model that was used to determine the influence of the control system on generator torque fluctuations. The rotor shaft and stator are modelled as rigid bodies, with only a torsional degree-of-freedom. The rotor and stator are connected by the generator torque. The stator is connected to ground by a torsional spring representing the mooring system.

The control system of Figure 3 was coupled to the shaft torsion model of Figure 5, and the aerodynamics and torque-speed look-up table were linearised about different operating points. Typical tuning strategies were then used to find appropriate gains and filter time constants. Different gains are needed in the optimal speed and limited speed regions.

Figure 6 shows an example, at a windspeed of

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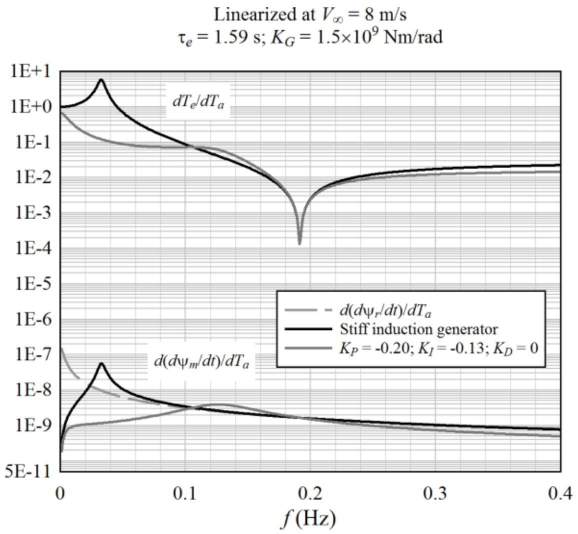

Figure 6: Frequency transfer functions for electrical and mooring system torque (top) and mooring system yaw motion (bottom) relative to aerodynamic torque.

8 m/s, of the frequency transfer functions for generator torque and mooring system rotation as a function of aerodynamic torque. The 2p frequency is roughly 0.17 Hz. It is evident that if the natural frequency of the stator and mooring system, with no rotor, is in the vicinity of 2p, then the 2p aerodynamic torque fluctuations will not appear in the generator torque. Also, the corresponding oscillations of the mooring system will not be severe.

4 Simulation results

This section demonstrates by means of time simulations different aspects of the floating vertical axis turbine and the control system.

4.1 Model

A modestly detailed simulation model [24] with additional degrees of freedom that capture the most important characteristics of the floating vertical axis turbine has been implemented in Matlab/Simulink. An overview of the various sub-modules and interactions between different parts of the system is shown in Figure 7.

The aerodynamics is approximated by a Fourier ex-

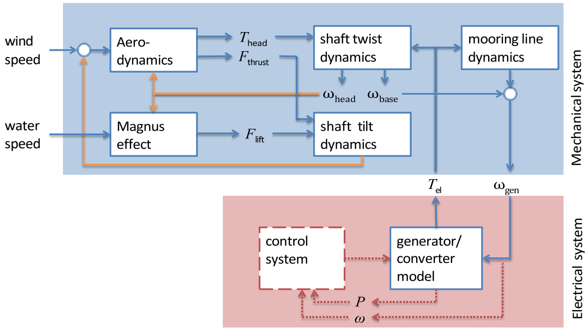

Figure 7: Simulation model modules and interfaces.

pansion that includes 2p and 4p variations:

$$T = T_0 + T_2\cos(2\Psi + \Psi^T_{2p}) + T_4\cos(4\Psi + \Psi^T_{4p}),$$
$$F^x = F^x_0 + F^x_2\cos(2\Psi + \Psi^x_{2p}) + F^x_4\cos(4\Psi + \Psi^x_{4p}),$$
$$F^y = F^y_0 + F^y_2\cos(2\Psi + \Psi^y_{2p}) + F^y_4\cos(4\Psi + \Psi^y_{4p}), \quad (5)$$

where Ψ is the azimuth angle of the rotor relative to the wind speed direction. The Fourier coefficients $\{T_0, T_2, \Psi^T_{2p}, \Psi^T_{4p}, F^x_0, F^x_2, \Psi^x_{2p}, \Psi^x_{4p}, F^y_0, F^y_2, \Psi^y_{2p}, \Psi^y_{4p}\}$ have been computed for different speeds (V_∞) and rotational speeds (Ω) using a double-multiple streamtube blade element momentum model [25], and are specified as a set of look-up tables. This approach is justified in ref. [25].

The tower twisting is represented by a two-mass spring–damper model ("shaft twist dynamics"), with the blade inertia and half the shaft inertia lumped together at the top, and the other half of the shaft inertia and the generator rotor lumped together at the bottom. Similarly, the yaw dynamics of the stator and mooring system is represented by a single-mass spring–damper model ("mooring line dynamics").

Hydrodynamics is included in two ways. First, since the tower rotates in the water, it will experience a Magnus lift force when there is a water current. This effect gives a fairly constant tilting of the entire tower in a direction perpendicular to the current. The Magnus effect in this context has been further explored in ref. [26]. The other effect that is included is the dynamics of this tilting, which is represented by independent spring–damper models in x and y directions. Since aerodynamic thrust forces have a large 2p variation just as the torque, the top of the turbine will move around a circle. This motion results in 2p

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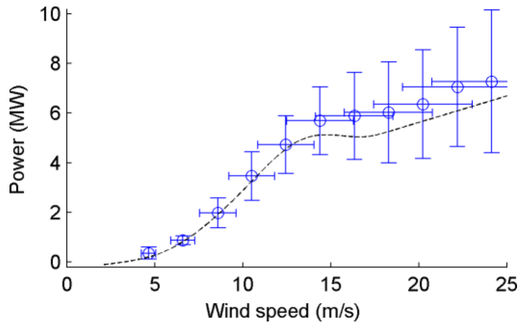

Figure 8: Simulated electrical power output versus wind speed for different stochastic wind series. Error bars indicate variability, and black dotted line represents the theoretical value.

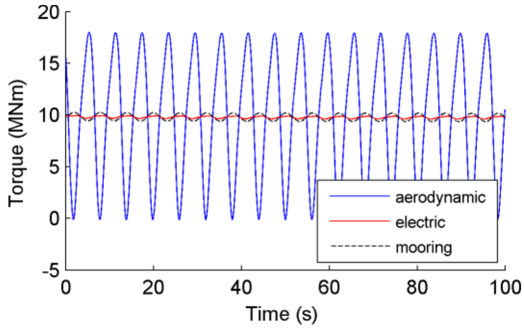

Figure 9: Variations in electric torque and torque acting on mooring system compared to input aerodynamic torque. Mean wind speed 14 m/s.

ripples in the effective wind speed. Wave forces are presently not included.

The electrical system is not modelled. Instead, it is assumed that the electrical torque equals the controller set-point value. This approximation is justified since the electrical system has a dynamics that is much faster than the 2p variations we are focussing on.

4.2 Variable speed operation

Figure 8 shows simulated relationship between wind speed and power output. The plot is based on a number of simulations with stochastic wind variations around different mean wind speeds. The points represents mean values of wind speeds and power for the different simulated time series. The variability in the wind and the power output is indicated by error bars showing one standard deviation from the mean. The fact that the simulated behaviour is close to the theoretical curve indicates that the turbine with the suggested control system is able to follow the desired speed–torque map (Figure 4) reasonably well. At high winds the mean is above the theoretical curve. This is due to periods with over-speed, which in the limited speed region are not balanced by less likely under-speed periods.

4.3 Damping of 2p

The damping of the aerodynamic 2p torque variations is illustrated in Figure 9 for a situation with

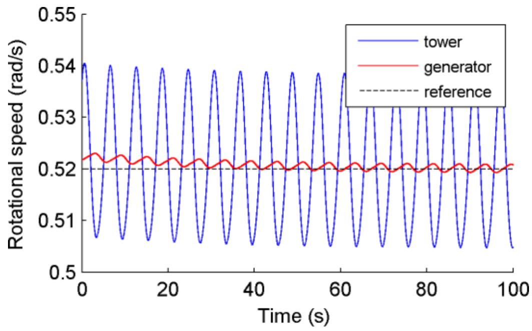

Figure 10: Rotational speed of shaft and generator rotor relative to stator. Mean wind speed 14 m/s.

14 m/s constant wind speed. As the figure clearly shows, the electric torque has virtually no 2p variations. The torque acting on the mooring system does have small 2p variations. This is inevitable, as it is the stator/mooring system rotations that absorb the 2p variations, as explained in Section 2. Close inspection of the figure reveals that the 2p variations in the mooring line torque is about 0.88 MNm, which equals the expected value derived in Section 2.

Figure 10 shows the rotational speed of the shaft and the generator rotor relative to the speed of the stator for the same case as above. It is clear from this figure that 2p variations in the shaft speed are indeed absorbed by the stator/mooring system such that the generator sees an almost smooth speed. The 2p variations in the tower rotational speed are seen to be 0.034 rad/s, which is again as expected according

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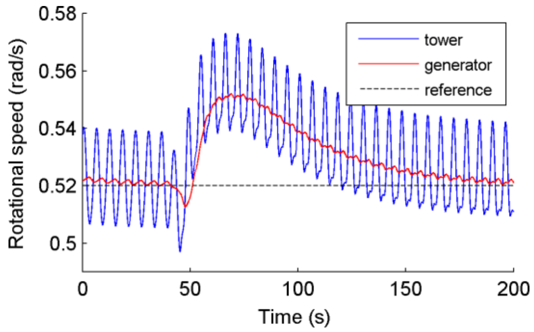

Figure 11: Rotatioal speed response to a deterministic wind gust that increases the wind speed from 14 m/s to about 22 m/s in the time interval 40–48 seconds.

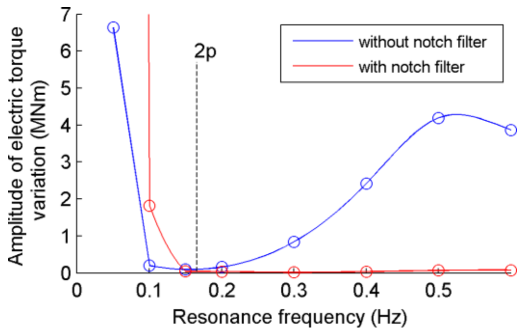

Figure 12: Amplitude of 2p variations in electrical torque as a function of stator/mooring system natural frequency. Simulated results at constant 14 m/s wind.

to the discussion in Section 2.

4.4 Wind gust

An interesting case to study is the turbine response to a wind gust. The effect on the rotational speed of the turbine is shown in Figure 11 for a "step-up" gust that takes the wind speed from 14 m/s up to 22 m/s in 7 seconds. There is a period of over-speed, but otherwise no dramatic behaviour. Shortening the response time is possible, but must be done with care to avoid other negative effects. As stated previously, the present control system has not been optimised for all operating conditions, but is meant to outline promising methods for control of floating vertical axis turbines like DeepWind. The effect on the turbine is minimal, which is partly due to the large size and inertia that smooths such short-lasting effects.

4.5 Dependence on stator/mooring system natural frequency

As is clear from Figure 6, the stator/mooring system will damp 2p variations also if its natural frequency is shifted farther away from the 2p frequency, albeit to a lesser degree. In order to verify this with simulations, a number of cases have been run where the mooring line stiffness has been gradually changed to give stator/mooring systems with different natural frequencies, while keeping all other parts of the model unchanged. The observed amplitudes of 2p electrical torque variations for constant 14 m/s wind speed have been plotted in Figure 12. The result confirms that the damping (without notch filter) is still good in a frequency range around the 2p frequency. For larger deviations, however, the damping is insufficient.

If the natural frequency is sufficiently different from the 2p frequency, additional control logic has to be added in order to eliminate the 2p variations. One such approach which has been tested with promising results is a control system with an added notch filter that takes out the 2p variation in the speed deviation signal in the torque controller. As indicated in Figure 12, this notch filter reduces electrical torque variations outside the 2p band dramatically. The robustness of this approach is currently being investigated.

A time series comparison of the original system (without notch filter), and a modified system with natural frequency at 0.44 Hz with and without the notch filter is shown in Figure 13. The response should be compared to that seen in Figure 9 for the original system.

5 Conclusions

Two control objectives have been addressed in the present work. The first is to operate the turbine at variable speed (up to a maximum value) that gives optimal aerodynamic efficiency whilst avoiding damage due to over-speed. The second is to avoid 2p aerodynamic torque variations being transmitted into the electrical system and to the mooring system.

For designs where the stator/mooring system yaw resonance frequency matches the 2p frequency, the

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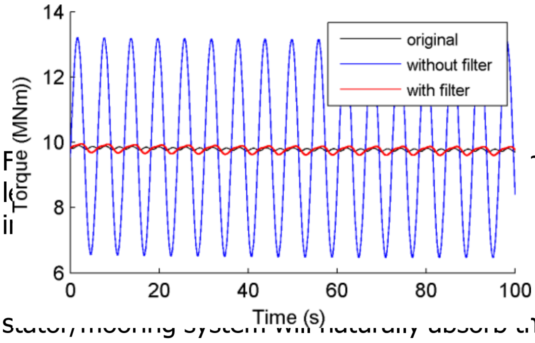

ntrol- with

he 2p aerodynamic variations. Shaft speed variations are followed by stator rotations such that the generator sees a constant rotor speed, giving a constant electrical torque and power output. The stator rotations are small and give rise to only small variations in the mooring line forces.

If the design is such that the stator/mooring system has higher resonance frequency than the 2p frequency, extra mass can be added in order to reduce the resonance frequency. If this is undesired for other reasons, or if the frequency is already lower than the 2p frequency, damping of the 2p variations have to rely on other approaches. An approach employing a notch filter was briefly discussed and shown to give a good damping, at least under conditions studied so far.

The results presented here are still at a preliminary stage, and refinement and thorough tuning of parameters and validation of the suggested control strategies is needed. Also, additional control objectives that have not yet been addressed need to be considered. These include turbine shut-down at high speeds, a more thorough investigation of mechanical natural frequencies, analysis of the coupling between electrical dynamics and structural dynamics, and relevant issues related to grid connection such as behaviours during voltage dips (fault ride-through). These topics are included in planned future work.

It would also be interesting to know how the control challenges may change with the size of the turbine, e.g. if there are fundamental differences for a 20 MW machine.

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