

Coordinated Control Design for Wind Turbine Control Systems

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Abstract—Increasingly, variable speed regulated wind turbine control systems are being required to alleviate structural loads. In standard approaches to alleviating tower loads, coupling of the generator speed and tower speed control causes reduced effectiveness of not only the tower speed loop itself but also the generator speed loop. Using improved representation of the wind turbine dynamics and catering specifically for the interaction of the two loops, a new configuration of control system, for a variable speed pitch regulated wind turbine is derived that, by most performance measurements, out-performs standard controllers.

Keywords: Fatigue loads, feedback, control, pitch, tuning, sensitivity function

I. INTRODUCTION

For variable speed wind turbines, the control regime is divided into an above rated mode, where the task is to modify the blade pitch angle to regulate generator speed whilst maintaining rated power output, and a below rated mode, where the task is to regulate generator speed between its minimum and maximum values to maximise power output. In this paper, the focus is on the above rated mode when the control task is multivariable. Two control actions, generator torque and blade pitch angle, are available with, typically, the former used to regulate either generator power or generator torque and the latter used to regulate generator speed, see [1], [2].

More recently, with the increase in size of wind turbines as evident in the market penetration of multi-megawatt sized machines, there is increasing interest in exploiting the pitch control capability to alleviate fatigue loads, particularly, the alleviation of tower fatigue loads. The potential for their reduction via active control has been established in previous studies, see [3]. Only fatigue associated with the fore-aft motion of the tower need be considered, since this is known to be the main fatigue driver for the tower, and only for above rated wind speeds, since it is these operating conditions that account for most of the fatigue.

A further control design issue, also related to the increase in size of wind turbines, is the influence of the tower dynamics on the performance of the control system. The interaction of the tower with the drive-train introduces a pair of right half-plane zeros (RHPZ) in the dynamics that link blade pitch angle to generator speed. These RHPZ limit the ability of the control system to regulate the generator speed through blade pitch control. As the size of wind turbines

increases, the frequencies of the tower modes become lower. Consequently, the frequencies of the RHPZ also become lower and so increasingly important in determining the achievable controller performance.

An approach to the design of above rated control, that addresses the above size-related issues, is required. A coordinated controller design (CCD) that accomplishes that task is presented in this paper. It overcomes the limitations arising from the tower induced RHPZ to achieve more effective generator speed control. Furthermore, the requirement to reduce the tower fatigue loads, although indirectly affected by the generator speed control, is simultaneously taken into account. When, subsequently considering the tower load control, a more effective controller design is possible, since the generator speed control is designed to reduce the interaction between tower load control and generator speed control. A greater fatigue reduction is thereby possible. The control analysis and design is illustrated with respect to a 2.7MW wind turbine.

II. MODELS AND DYNAMICS

The linear model for the wind turbine dynamics used in this paper is that reported in [4], [5]. For a variety of wind turbines including multi-megawatt machines, it has been validated against real data and FLEX simulations¹ see, for example, Figure 1 where the direct frequency response identification for a detailed FLEX simulation of a Multi-Megawatt wind turbine is compared to the frequency response of the linear model.

The linear model includes all the dynamic components significant for controller design and control performance assessment, in particular, two modes for the tower, two modes for the blades and two modes for the drive-train. It also includes the dynamics of the pitch actuator and the interaction of the rotor with the wind. The main difference to other linear models of wind turbine dynamics found in the control literature is the explicit inclusion of the tower and blade modes. The tower modes are of particular importance in the design of controllers for wind turbines since they introduce a pair of RHPZ which impose limitations on the generator speed control, [6], [7]. The blade modes are

¹The model is being integrated into a MATLAB Toolbox for wind turbine controller design.

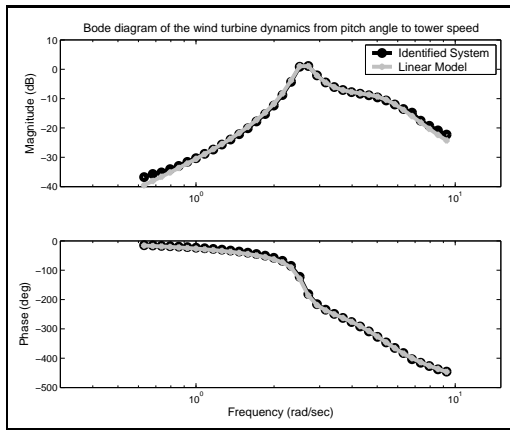


Fig. 1. Bode diagram of wind turbine dynamics from pitch angle to tower speed and direct frequency response identification for a detailed FLEX simulation

important since they interact with the tower mode and the edge mode is a major contribution to the first drive-train mode.

In Figure 2, the Bode plot for the transfer function representing the dynamics linking pitch demand to generator speed is depicted for two different wind speeds. At 13m/s , the presence of the RHPZ due to the tower at about 2rad/s is evident. The acute phase loss due to these RHPZ influences strongly the maximum bandwidth that the generator speed controller can achieve. At 16m/s , the RHPZ are no longer present in the plant dynamics since they move into the left-half plane as the blade pitches. The pitching of the blades, and the change in the relationship between flap and edge mode, are also responsible for the changes in the Bode magnitude plot at mid frequencies in Figure 2.

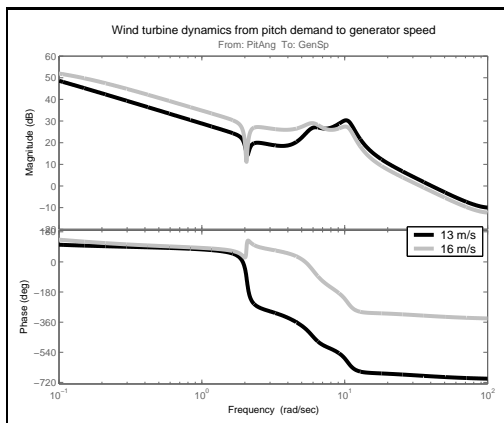


Fig. 2. Turbine dynamics from pitch angle to generator speed

In Figure 3, the Bode plot for the transfer function representing the dynamics linking pitch demand with tower speed is depicted. The first peak, at 2rad/s , corresponds to the tower mode, and the second peak, at 6rad/s , corresponds to the blade flap-wise mode. There is a marked drop in phase, 180° , between the two modes. The magnitude of the peak of the flap mode is dependent on some parameters that are

themselves wind speed dependent, but the phase loss between the modes does not alter as the parameter values change. In Figure 3, parameter values, for which the blade mode is more obvious than in Figure 1, have been chosen. Note that although the turbines depicted in Figures 1 and 3 are different, the aforementioned phase loss between the tower mode and the blade mode is present in both. Given this difference in phase between the two modes and their close proximity, any attempt to control the tower movement is constrained by the presence of the flap mode. Indeed, too strong feedback at the tower frequency may, in effect, excite the flap mode and eventually cause instability, see [8].

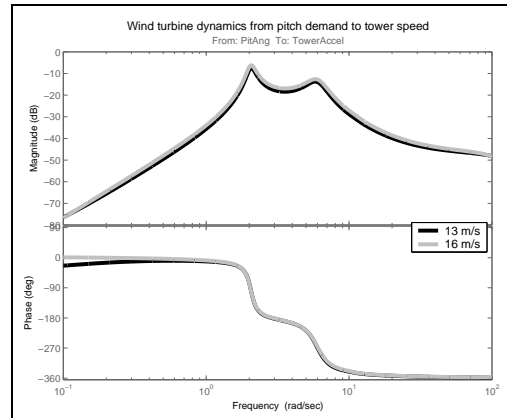


Fig. 3. Turbine dynamics from pitch angle to tower speed

Furthermore, in [9] it was observed that the fore-aft mode of the tower is relatively strongly damped, due to the aerodynamic damping of the fore-aft movement of the wind turbine rotor. Consequently, the blade fore-aft mode is not a sharp resonance but is more widely spread in frequency, see Figure 3. This strong damping, which is not present in the side-to-side mode of the tower, reduces the effectiveness of passive tower dampers for the fore-aft tower mode, since these dampers are most effective on resonant modes; that is, modes focused on a narrow frequency region, such as the side-to-side mode. For example, the addition of a passive damper to the wind turbine being studied here reduces the fatigue loads by 7% in the case of the side-to-side movement of the tower but by only 1% in the fore-aft movement of the tower. In addition to its effect on the passive damper, the non-local nature of the tower fore-aft mode requires active control based on a tower velocity measurement to be active over a wider frequency region, thereby making interaction with the flap mode more likely.

III. PERFORMANCE REQUIREMENTS

A control system is only as good as the criterion to which it is designed and without a clear statement of intent it is not possible to properly evaluate the performance [2]. It is therefore necessary to clarify the control objectives before attempting to evaluate the performance of the control system. In general, the role of the control system for wind turbines system can be summarised by the following general goals:

- regulating and smoothing the power generated
- alleviating the transient loads
- ensuring that the drive-train has the appropriate dynamics
- maximising the energy capture.

In this paper, only the first two goals are of interest. Damping of the first drive-train mode is generally taken care of by an inner feedback loop, acting on generator torque in response to generator speed measurement. This inner feedback loop, being active at higher frequency, is independent of the other control requirements. In the control systems investigated here, this inner feedback loop is always assumed to be present. The maximising of energy capture is mainly related to below rated control, which is not addressed here.

In above rated wind speed, the remaining two goals are usually achieved in the following manner. The generator torque is held constant at its rated value or varied to maintain constant generated power. However, the former is usually preferred since the latter lacks integrity; that is, on its own regulating to achieve constant power induces instability. In addition, the generator speed is controlled by varying blade pitch angle to hold the generator speed constant or within a narrow band. (In the case of constant power control, this generator speed control loop is relied on to re-establishes stability). Generally a *PI* controller or similar is sufficient. Its objective can be interpreted to be the rejection of disturbances arising from the wind speed fluctuations, see [1], [2]. A well tuned controller of the above type is used to provide a baseline for performance comparison. It is referred to as the conventional controller.

In addition, to the objectives for the conventional controller, namely regulation of torque and generator speed, the CCD is required to reduce the tower fatigue loads. To do so requires any unnecessary excitation of the tower fore-aft mode by the generator speed controller to be avoided. A high value, near the tower frequency, of the sensitivity function for the speed control loop can be symptomatic of this unwanted side-effect of generator speed control.

The suppression of the tower fore-aft mode by active control to reduce the tower fatigue loads has received a good deal of attention in recent years, [10], [11], [12], [13]. Essentially, in all the published approaches, the generator speed controller is augmented by a tower feedback loop, TFL, whilst no modification is made to the former. It acts, in response to a measurement of tower fore-aft speed typically derived from a measurement of tower acceleration, through an additive perturbation on the blade pitch angle demand as in Figure 4, where, $C(s)$ is the generator speed loop controller, WT represents the dynamics of the wind turbine from pitch angle to generator speed, $G_{act}(s)$ is the pitch actuator, $G_{tow}(s)$ represents the tower dynamics, ω_g is the generator speed, $\dot{\phi}_T$ is the tower speed output and ω_{SET} is the generator speed set point. The TFL, thereby, increases the aerodynamic damping of the tower. The different frequency ranges at which the two loops are active suggests that both loops can act simultaneously without interaction. However,

it has been observed, see [8], that the loops do interact, thereby degrading the generator speed loop performance and sometimes causing instability.

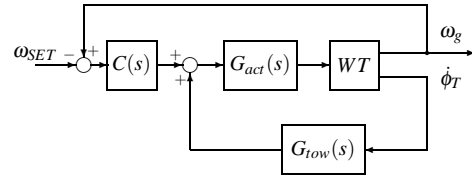


Fig. 4. Inner loop for the cancellation of the tower mode

Further to the reduction obtained by reducing the pitch actuator, the tower fatigue loads can be reduced by augmenting the CCD with a TFL.

The performance for the generator speed controller is assessed both in the frequency domain and in the time domain. In the frequency domain, the CCD should have at least the same bandwidth and the same stability margins as the conventional controller. (Good stability margins are necessary [1] to cater for the uncertainty in the wind turbine dynamics including the uncertainty in the in aerodynamics). The time domain performance is assessed in terms of the response of the generator speed loop to a step input in the wind speed and of the standard deviation of the generator speed during normal operation. The performance for the TFL is assessed by the reduction of fatigue on the tower in above rated operation. (It should be noted that this accounts for most of the tower fatigue). The fatigue is assessed by running Simulations of the wind turbine are run, with the mean wind speed wind speed varying between 16 and 24m/s, to obtain time series of the tower loads. Weighting the importance of every wind speed simulation according to the probability of its occurrence as given by the Weibull distribution, the reduction in fatigue over a 20 years period is estimated using the rain-flow counting.

A further measure of the performance to be used is related to actuator activity. Since both the generator speed control loop and the TFL act through the pitch actuator, it is important to ensure that not too great a demand is placed on the actuator. Very frequently, it is the limits on the actuator's capability that imposes constraints on the achievable control performance. This rather important role played by the actuator in controller design is often overlooked.

Ignoring the limits, arising from both hardware and software, on speed and acceleration, the actuator dynamics generally consist of a real pole, whose frequency is the actuator bandwidth, and a pair of complex conjugate poles at higher frequency, roughly a decade higher. These dynamics can normally be approximated by a first order model, see Figure 5, together with a time delay but for the discussion below the higher order model is retained. Compare the typical Bode plots, Figure 6, for the transfer functions from actuator input to actuator output position, velocity and acceleration. In the case of output velocity, there is strong amplification at intermediate frequencies and, in the case of output acceleration even stronger amplification especially at

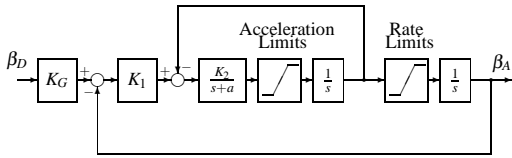


Fig. 5. Simplified actuator model

higher frequencies. Consequently, the distribution of effort over frequency for the actuator appears very different when viewed from the perspective of output position, velocity or acceleration. This difference of perspective is confirmed in Figure 7, where the output position, velocity and acceleration for the actuator model of Figure 5 corresponding to the pitch demand derived from the FLEX simulation of the wind turbine during normal operation. The amplification of the acceleration at intermediate frequencies is clear.

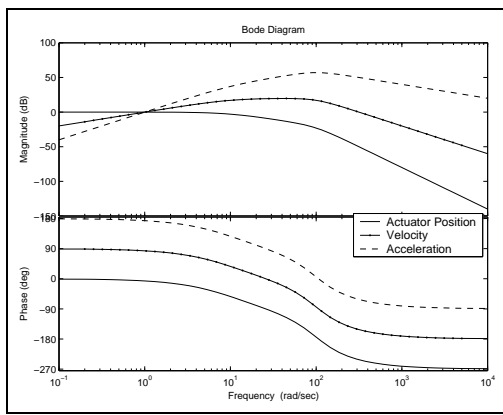


Fig. 6. Bode diagrams of the actuator transfer function, from pitch demand to pitch position, velocity and acceleration

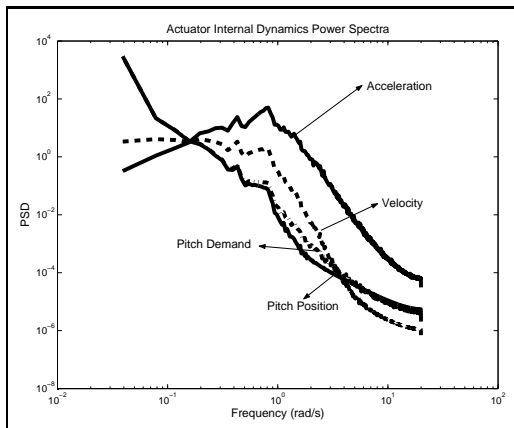


Fig. 7. pitch actuator acceleration spectra

From the perspective of the actuator output position, much of the effort, typically 50%, is expended at low frequency; that is, in the frequency range over which effective control action is required. From the perspective of output velocity, little effort, typically 10%, is expended at low frequency and it is the intermediate frequency components that can

cause the actuator rate limit to saturate. From the perspective of output acceleration, negligible effort, typically 1%, is expended at low frequency and it is the intermediate and high frequency components that can cause the actuator acceleration limit to saturate. Given that the power consumed by the actuator is proportional to the product of the speed times the acceleration, only a very small fraction of the power consumed by the actuator is actually invested in control action. The rest will be dissipated in accommodating the noise at medium and high frequencies. Hence, the actuator capability and so the controller performance is dictated by the intermediate and high frequency components of the input demand signal to the actuator.

For the above reasons, the controller performance is also assessed from the actuator output acceleration.

IV. COORDINATED CONTROLLER DESIGN

A major part of any controller design concerns the choice of controller structure to meet the full operational envelope requirements. For variable speed wind turbines, these include switching between below and above rated modes, actuator saturation and nonlinear aspects of the dynamics, in particular, the aerodynamics. An appropriate choice of structure ensures that no reduction in performance is caused by these aspects of the controller. The choice of controller structure should be assessed with respect to the response of the wind turbine to large transient loads, for example, the response of generator speed and tower speed to a large step disturbance in wind input and with respect to the extent to which stability margins derived from linear analysis are maintained without compromising performance. Being concerned with above rated control, with one exception, this aspect of controller design is not considered here. The controller structure already implemented on the wind turbine is kept unchanged. To realise the CCD, modifications are made to existing filters in the controller.

The one aspect of controller structure considered here is the accommodation of the aerodynamic nonlinearity. The dynamics that link pitch angle to generator speed change with wind speed, as can be seen in Figure 2. A change in the low frequency gain of the Bode plots is evident. Because the aerodynamics are nonlinear, it is caused by the aerodynamic gain incorporated into the dynamics depicted in Figure 2 being wind speed dependent. Consequently, a fixed controller design is not valid for the whole range of wind speeds. It would appear that the controller needs to be scheduled with a wind speed dependent gain. However, it is best to avoid using a direct measurement of wind speed. Instead, the scheduling should be done on an indirect measure of wind speed. The stability of the system with the nonlinear scheduled controller is inferred from the stability of the linear systems at each equilibrium operating point. This gain scheduling approach, which is commonly used, is valid provided that the system is weakly nonlinear or the system remains sufficiently close to the locus of equilibrium points. However, the condition of being weakly non-linear does not really apply to wind turbines. Since the wind speed fluctuations are stochastic,

the operating point varies rapidly and continuously over the whole operating envelope. Moreover, large fluctuations in wind speed are common, which persist for relatively long periods and produce substantial and prolonged perturbations from equilibrium. Yet, gain-scheduling can work well when applied to wind turbine control.

However, given the separability of the aerodynamic torque, $T(p, \Omega, V)$, see [14], where p is the pitch angle, Ω is the rotor speed and V is the wind speed, it is possible to write the aerodynamic torque as

$$T(p, \Omega, V) = h(p, \Omega) - g(V) \quad (1)$$

for some non-linear functions h and g . Note that, because of this separation, the wind speed dependent component is an additive disturbance to the control system and so does not influence the dynamics. The dynamics depend only on h , a nonlinear function of p and Ω , both of which are easily accessible. A global cancellation of the nonlinear dependence of the dynamics on p and Ω is now possible, [14], as depicted in Figure 8, where $C(s)$ is the linear controller; $G_{act}(s)$ is the actual pitch actuator dynamics and $\hat{G}_{act}(s)$ is a simple model, usually first order, for the actuator. In practice, the integrator and the transfer function for the inverse of $\hat{G}_{act}(s)$ would be combined into a proper transfer function. Similarly, $C(s)$, $\hat{G}_{act}(s)$ and the derivative would be combined. When the controller, $C(s)$, includes integral action, which it almost always does, it would cancel with the derivative. Several simplifications can be made to the scheme depicted in Figure 8. The bandwidth of the actuator is generally high and so both $\hat{G}_{act}(s)$ and its inverse can be omitted. In addition, because the wind turbine rotor speed varies slowly, the additive insertion of the rotor acceleration is not required. All that remains is the nonlinear gain between the combined transfer function, for $C(s)$ and the derivative, and the integrator. This nonlinear gain depends on p and Ω but the latter dependence can be ignored since it varies slowly. The resulting control scheme now has a very similar appearance to a gain-scheduled controller. However, it is a global controller that is not dependent on a weak nonlinearity condition for validity. The positioning of the nonlinear gain is important and must be kept between the derivative and the integrator. The above analysis, the use of a varying gain in the controller to counter the aerodynamic nonlinearity. Note, that the gain is a function of pitch angle and not wind speed so no wind speed measurement is required.

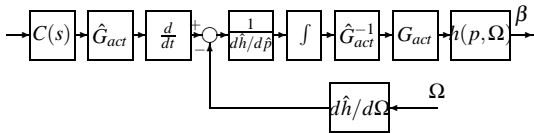


Fig. 8. Gain Scheduling

A consequence of the global validity of the above scheme for cancelling the aerodynamic nonlinearity is that controller design need only be considered at one wind speed. Here the controller is designed at $13m/s$.

The CCD is based on a parallel path modification of the plant, see [15], using both blade pitch and generator torque demand. Although its basic structure is similar to the conventional controller, maintaining elements such as the nonlinear gain, described above, the parallel path modification enables the RHPZ, due to the tower, to be counteracted. The Bode plots for the transfer functions representing the dynamics from generator speed error to generator speed in both the conventional controller case and the CCD are depicted in Figure 9 for a wind speed of $13m/s$. In the latter the RHPZ, due to the tower, are no longer present. In addition, the parallel path modification is exploited to decouple the tower fatigue loads from the generator speed control.

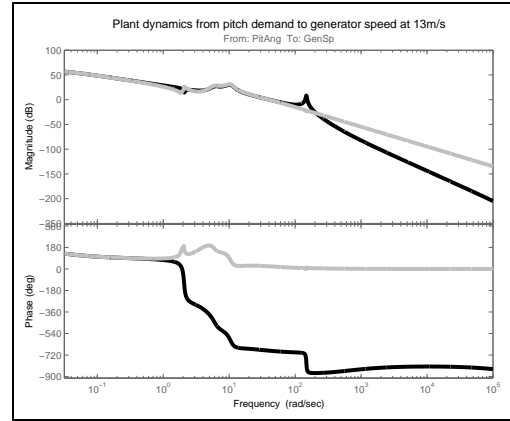


Fig. 9. Effective Plant and Real Plant

With the removal of the non-minimum phase dynamics from the control loop, the controller design is freed from the restrictions on bandwidth imposed by the RHPZ. In the CCD, a PI controller is combined with the parallel path modification to achieve the same bandwidth as the conventional controller. The open loop system Bode plots and Nyquist plots for both the conventional controller and the CCD are shown in Figure 10. As would be expected in the absence of the RHPZ, the stability margins are improved. The Gain Margin (GM) has increased from $7.2dB$ to $16.8dB$ and the Phase Margin (PM) from 37° to 44° . Rather than simply maintaining the bandwidth of the controller, this increase in the stability margins could be exploited to increase the controller bandwidth, whilst keeping within acceptable stability margins, thereby increasing the performance of the controller. However, that is not done here. As pointed out above, the wind speed acts as a disturbance on the controller feedback loops, see for example the TFL in Figure 11, where WT_{cl} and WT_{ol} are, respectively, the closed loop and open loop wind turbine dynamics linking wind speed to tower speed, and Φ_T is the tower speed. Hence, the sensitivity function, since it is a measure of disturbance rejection, is an important indicator of the effectiveness of the controller design. The sensitivity function with the CCD, is an improvement on the sensitivity function for the conventional controller. The peak magnitude is 33% less, see Figure 12. (Positive values of the sensitivity function indicate harmful

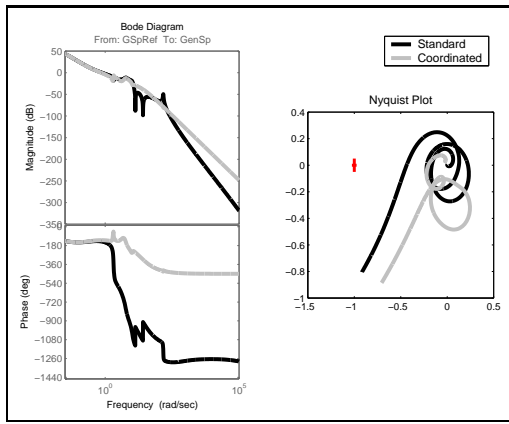


Fig. 10. Traditional approach and CCD open loop Bode plot

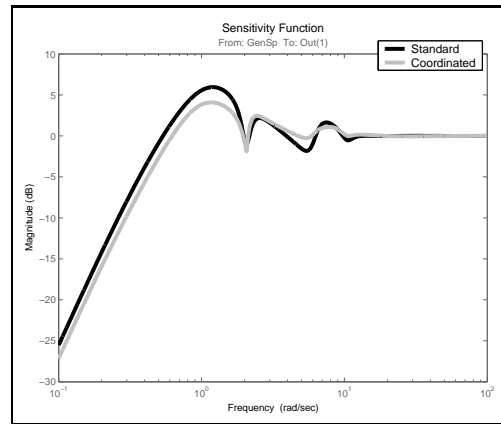


Fig. 12. Sensitivity Function

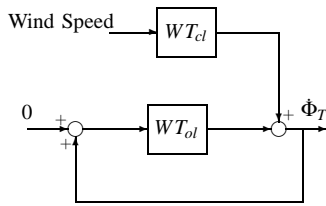


Fig. 11. Block diagram for the TFL

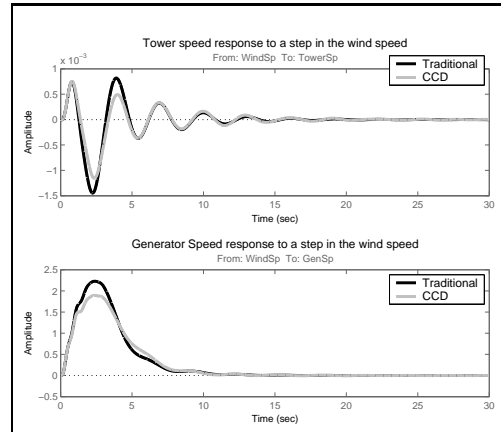


Fig. 13. Response of tower and generator speed to an input step disturbance in the wind input

positive feedback rather than beneficial negative feedback). In addition, at low frequencies the gain is lower ensuring better disturbance rejection. This is not unexpected since a consequence of Bode's Theorem is that the sensitivity function for a minimum phase system is always better than for an equivalent non-minimum phase system. The lower magnitude of the sensitivity function near the tower frequency indicates lower pitch activity at these frequencies. This is beneficial since the tower fore-aft movement and, therefore, the tower fatigue, is related to the pitch activity, [8]. The response of both generator speed and tower speed to a step in the wind input, is shown in Figure 13. The improvement in performance is clear. It should be noted that this increase in performance is done with a tuning for the controller that only aims to maintain the same bandwidth as the conventional controller. There, therefore, remains room for improvement in controller performance, given the increased stability margins, should it be considered necessary.

Representative spectra of the pitch demand with the conventional controller and the CCD are compared in Figure 14. The pitch demand is reduced over the intermediate frequency range. The corresponding spectra for actuator output acceleration are depicted in Figure 15 and the cumulative spectra in Figure 16. The actuator output acceleration is obtained by using the time series of pitch demand from FLEX, from which the spectra in Figure 14 are constructed, as input to the actuator model in Figure 5. The actuator output acceleration is greatly reduced in the intermediate frequency range. Indeed, the standard deviation of the actuator output acceleration is reduced by 70%. The reduction in actuator activity is clear.

The reduction in blade pitch activity at frequencies close to the tower mode implies, as discussed previously, a reduction in the tower fore-aft movement and, therefore, the tower fatigue. Representative spectra of the fore-aft tower base bending moment with the conventional controller and the CCD are compared in Figure 17 and the cumulative spectra in Figure 18. The cumulative spectra, the first moment of the PSD with respect to frequency, can be used to obtain a quick estimate of the fatigue reduction and the contribution of each frequency mode to the total fatigue [12]. Although these estimates are not precise, they can be considered to be a reasonable guide to the relative magnitude of the fatigue loads. Comparing Figures 14 and 17, the correlation between the regions of pitch activity increase/reduction and the correspondent increase/reduction of the tower base moment is clear. With the CCD, there is a small increase in the spectrum of the tower base moments at low frequencies but this does not have a major affect on the overall fatigue. The life-time estimate of fatigue, indicates a reduction of as much as 13% in the fatigue tower loads; more precisely, in the constant amplitude cyclic loads that would produce the same fatigue damage over the full operational life of the wind turbine.

Representative spectra of the generator speed with the

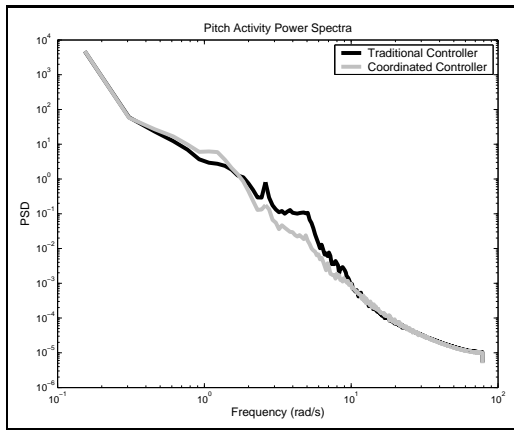


Fig. 14. Pitch Activity Power Spectra

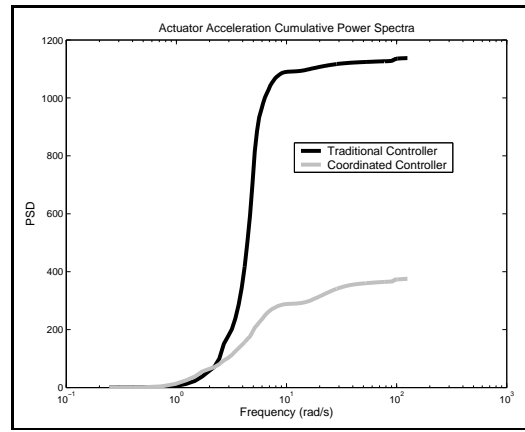


Fig. 16. pitch actuator acceleration spectra

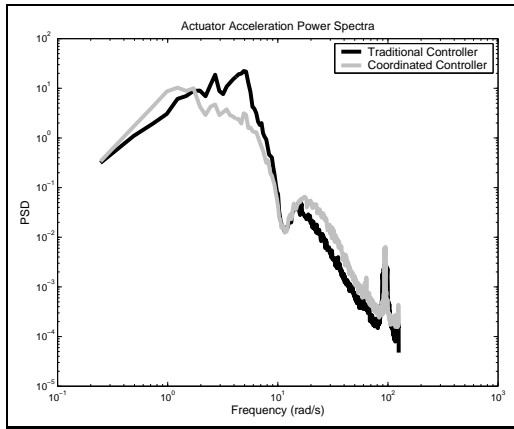


Fig. 15. pitch actuator acceleration spectra

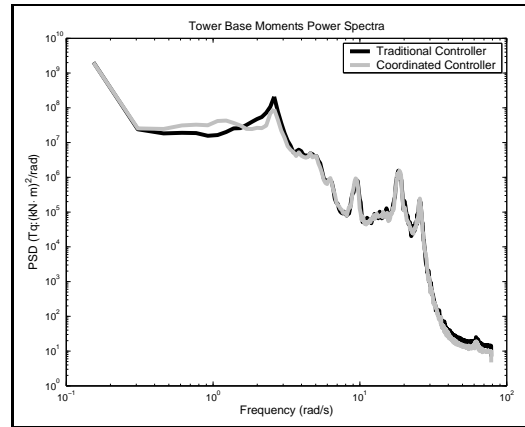


Fig. 17. Tower base moments power spectra

conventional controller and the CCD are compared in Figure 19 and representative spectra for generated power in Figure 20. It can be seen that the reduction in the tower fatigue loads is achieved without degrading the generator speed control loop. Although, no attempt is made to exploit the increased stability margins to increase the bandwidth of generator speed control, a small improvement in speed control is evident.

From the preceding discussion, the performance of the CCD is markedly better than the conventional controller.

The CCD can be augmented by a TFL, as described in [8], to further reduce the tower fatigue loads. Representative spectra of the fore-aft tower base bending moment with the conventional controller, the CCD and the CCD augmented with a TFL are compared in Figure 21 and the cumulative spectra in Figure 22. The life-time fatigue load reduction for the CCD augmented with a TFL is of the order of 12-18% depending on the wind turbine. The effectiveness of the augmented CCD is clear.

V. CONCLUSION

A new wind turbine controller for above rated operation is presented. In contrast to other published controllers, it is not subject to the size related constraints on performance

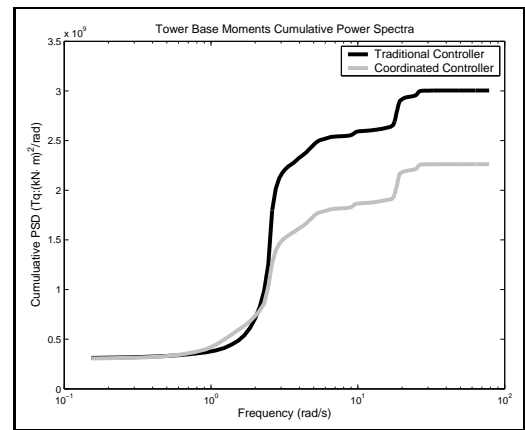


Fig. 18. Tower base moments cumulative power spectra

that arise in multi-megawatt wind turbines. A more general approach to tower fatigue load reduction is adopted. Whilst maintaining performance, the generator speed control loop is redesigned to minimise the blade pitch activity at frequencies close to the tower frequency, thereby lessening the generator speed control interaction with the tower fatigue loads. When augmented with a tower feedback loop, this controller

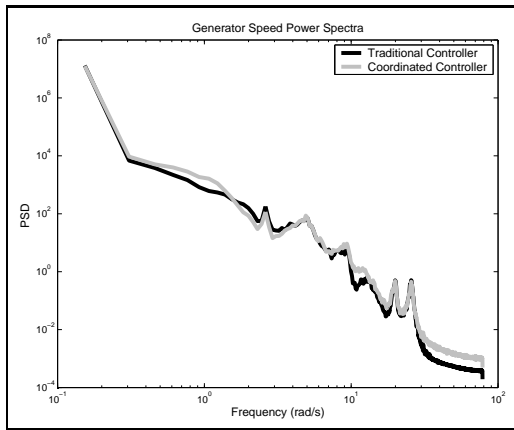


Fig. 19. Generator speed power spectra

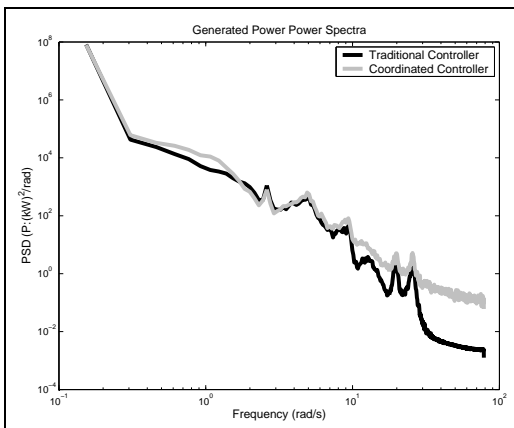


Fig. 20. Generated power power spectra

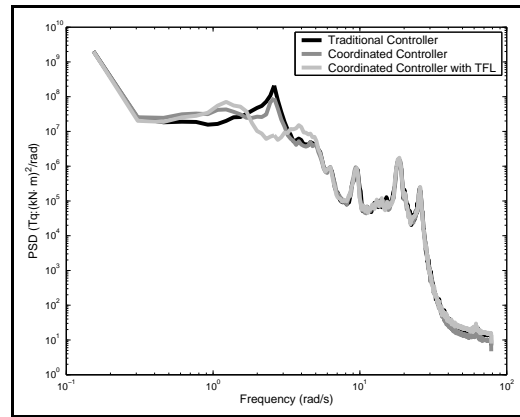


Fig. 21. Tower base moments power spectra

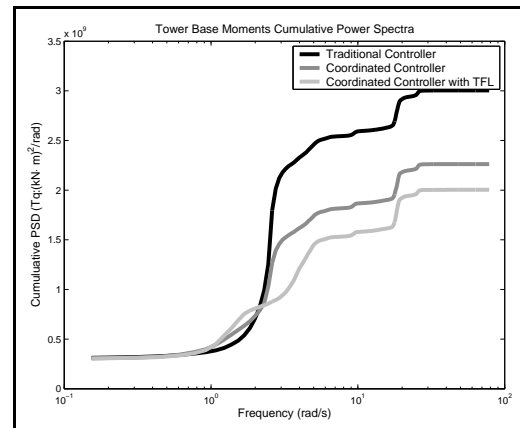


Fig. 22. Tower base moments cumulative power spectra

achieves a reduction in the life-time tower fatigue loads of up to 18%.

The controller is designed on the basis of a thoroughly validated linear model that is easily modified to represent most wind turbines. Although the linear model includes all relevant dynamic features for controller design, it uses the minimum possible number of wind turbine parameters. Consequently, the relationship between the main dynamic features and the wind turbine parameters are transparent, thus providing clear insight into the dynamics and supporting better controller design. The controller itself is easily tuned for different wind turbines.

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