DIRECT REGULATION OF LARGE SPEED EXCURSIONS FOR VARIABLE SPEED WIND TURBINES

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ABSTRACT In above rated wind speed the pitch control system of a pitch regulated variable speed wind turbine aims to maintain the rotor speed within a permitted range. However, this requirement can be difficult to satisfy during extreme gusts with conventional controllers, particularly for large-scale machines where the pitch actuation capability may be quite limited. This paper investigates the design of a pitch controller for 1 MW variable speed turbine which directly responds to a strong gust by pitching the rotor blades at the maximum permissible rate, thereby exploiting the maximum capability of the actuation system. The performance assessed and compared to that of a conventional pitch controller by simulation studies.

Keywords Control Systems, Variable-Speed HAWTs, Large-Scale Machines

1. INTRODUCTION

In above rated wind speed the pitch control system of a pitch regulated variable speed wind turbine aims to maintain a constant rotor speed. However, due to the turbulent nature of the wind, the rotor speed fluctuates within some interval centred on the rated rotor speed. Nevertheless, the rotor speed must normally be prevented from exceeding some upper boundary in order to respect the structural limitations of the turbine, to minimise fatigue damage and to avoid exciting the tower structural dynamics. This requirement can prove quite demanding when the rotor speed boundary is close to the rated speed and the pitch actuation capability is limited; that is, the actuator bandwidth and the maximum rate of change of pitch angle are limited as typically occurs in the large-scale machines presently being developed. The most taxing situation is the occurrence of a strong gust which rapidly increases by a large amount then rapidly decreases again. Although strong gusts may occur relatively rarely, safety considerations nevertheless mean that the control performance under such extreme conditions cannot be neglected and, indeed, performance under such conditions may represent a primary component of the control specification. In this paper, the extreme gust performance of the pitch controller for a 1MW variable-speed wind turbine which is representative of commercial machines in its class is investigated.

2. CONVENTIONAL CONTROLLER

The dynamic characteristics of the variable-speed 1 MW machine studied are presented in the Appendix; the aerodynamic torque/rotor speed characteristics are shown in figure 1. In high wind speeds (above 12 m/s), the pitch controller is required to adjust the pitch angle of the rotor blades to maintain the peak rotor speed excursion below 15% of the rated speed. A fairly conventional type of pitch controller is considered initially. Following Leithead *et al.* (1999), it can be shown that the nonlinear relationship between the windspeed, V, rotor speed, Ω, and pitch angle, β, and aerodynamic torque generated by the rotor can be decomposed (over the operating envelope of the turbine) as

$$T(V,\beta,\Omega) = F(\beta,\Omega) + G(V)$$

where F, G are appropriate nonlinear functions. The importance of this result is that it establishes that from a control viewpoint the wind turbine can be viewed as a nonlinear system with static nonlinearity F, subject to the external wind disturbance G(V). It is emphasised that the function F is *independent* of the wind speed. This immediately suggests that the aerodynamic nonlinearity of the rotor can be accommodated by incorporating the inverse function F^{-1} within the controller (since F is independent of wind speed, implementing F^{-1} does not require any wind speed measurement). With the plant dynamics linearised in this way, the rest of the controller can be designed using linear methods. The structure of the controller is shown in figure 3 (with k_{aw}=0) and the transfer functions of the linear controller elements are given in the Appendix. The controller achieves a cross-over frequency of 1.4 rad/s with gain-margin of 10.33 dB and phase margin of 50.95°. It should be noted that the pitch actuator bandwidth of 2.5 rad/s is very low in comparison to the 1.4 rad/s bandwidth of the closed-loop system and that this is a common sitution in large-scale machines owing to the large blade inertia. Whilst there are hard limits on the position and rate which may be developed within the pitch actuator, the controller is designed such that these are not encountered during normal operation (other than the lower limit on pitch angle which is encountered when the wind speed falls below rated and so is associated with shut-down/start-up of the pitch controller). In addition, there is a restriction on the pitch velocity in order to ensure that adequate pressure levels are maintained within the hydraulic actuation system. This is a soft constraint in the sense that it does not directly limit the magnitude of quantities within the actuator, but rather places a restriction on the standard deviation of the actuator spool valve velocity (and so pitch velocity). This constraint is also not encountered by the controller during normal operation.

The controller is found to meet the performance specification during normal operation in simulated winds with mean speed up to 28 m/s and 20% turbulence intensity. However, in order to meet safety requirements, the controller must also ensure that the rotor speed is mantained within 15% of the rated speed while subject to an extreme gust of 6.5cos(2πt/8) superimposed onto a turbulent wind with mean 18 m/s. A simulated time history of the speed response attained with the conventional controller in response to this extreme gust is shown in figure 2. The rotor speed exceeds the rated speed by 18.9% and so does not meet the safety requirements.

3. DIRECTLY RESPONDING TO ROTOR SPEED EXCURSIONS

The spectrum of an extreme gust such as that investigated in the previous section has a considerable high frequency component. Conventional continuous pitch regulation cannot cater for such an extreme gust, as is clearly evident from the results in the previous section, since the characteristic frequencies are outside the bandwidth of the controlled system. The penalty associated with exceeding the permitted range of rotor speeds is high since safety considerations may require an emergency shut-down of the machine and, in the longer term, it is well known that it is the occasional extreme loads experienced by a wind turbine during its life which contribute most to fatigue damage (see, for example, Warren 1987). It is, therefore, attractive to consider augmenting the conventional controller to respond directly to a strong gust by pitching the blades at the maximum permissible rate, thereby exploiting the maximum capability of the actuation system. The result is a switched controller. Of course, it is not permitted to work the actuator continuously at its hard limits as this would reduce the pressure in the hydraulic actuation system below acceptable levels but it is possible to intermittently demand a high level of activity for short periods.

The following design issues must be considered when implementing this switched linear control strategy:

1. The means by which operation of the actuator at its maximum pitching rate is demanded.
2. The baseline controller is required to contain low frequency shaping, including a pure integrator term, in order to achieve acceptable disturbance rejection. These low frequency elements can lead to prolonged transients when the controller switches from demanding the maximum pitch rate back to normal continuous pitching action.
3. Whilst the baseline controller is designed such that it does not encounter the actuator rate limits during normal operation, in the augmented controller the actuator is at its hard limits when the controller switches from demanding the maximum rate back to normal continuous pitching action. If the actuator is saturated at its hard limits during operation of the baseline controller, a loss of performance and a reduction in stability margins can result from wind-up of the low-frequency control elements.
4. Since the controller must periodically switch from normal continuous pitch regulation to simply pitching with the maximum rate and *vice versa*, the controller is no longer linear even though the normal continuous regulation is linear. Consequently the stability of the controlled system can be reduced and the associated switching logic must be designed to ensure that the stability margins are maintained.

Since a hydraulic actuator is employed on the 1 MW machine considered, pitching the blades at the maximum rate is achieved by moving the spool valve directly to its end stop in response to a command from the controller. The simplicity of this approach is preferred to the alternative technique of employing a specially shaped pitch demand signal which when applied to the actuator quickly drives it to its rate limits (Leith & Leithead 1995).

In order to avoid switching transients, a minor loop is introduced (see figure 3) in the switched controller which ensures that the states of the low frequency elements have appropriate initial conditions when the controller switches from demanding the maximum pitch rate back to normal continuous pitching action. This minor loop also serves the dual purpose of providing anti-windup action to compensate for saturation of the actuator during operation of the baseline controller. It should be noted that dynamics of minor loop are nonlinear owing to the F^{-1} element in the baseline pitch controller and the gain k_{aw} is, therefore, selected to accommodate the nonlinearity (k_{aw}=200). An alternative approach (Leith & Leithead 1997) is to include the nonlinearity F in the feedback path of the minor loop to obtain linear loop dynamics but the additional complexity of this approach is not required in the present example. In addition, it should be noted that in practice, rather that using the actual pitch measurement in the minor loop feedback, models of the actuator with and without constraints (that is, linear and nonlinear models) would be used in order to avoid activity on the minor loop due to noise and/or actuator modelling errors.

A very straightforward switching logic is employed initially: when the speed error rises more thatn 11% above the rated speed, the actuator is commanded to feather the blades at the maximum rate. Continuous pitching action is resumed when the speed error falls back below the 11% level.

The stability of the resulting switched controller is analysed using harmonic balance techniques. Whilst such techniques are, in general, only approximate, it is observed from simulation studies that the switched controller destabilises via an approximately sinusoidal limit cycle and so describing functions might be expected to provide an accurate indication of the closed-loop stability margins. Bode plots of the describing function relating pitch angle (output of the actuator) to the speed error (input to the pitch controller) are shown in figure 4 for sinusoidal perturbations of amplitudes 0.3%, 7% and 13% about the rated rotor speed. An amplitude of 0.3% of rated speed corresponds to linear operation and the describing function is identical to the transfer function of the controller/actuator. An amplitude of 7% is below the 11% threshold at which the controller demands pitching at the maximum rate but is sufficiently large that at high frequencies the actuator saturates at its rate limits. Consequently, at high frequencies (above around 1 rad/s), the gain and phase of the describing function differ from those of the nominal controller/actuator transfer function. Nevertheless, owing to the action of the minor loop, the stability margins of the closed-loop system are essentially preserved (see table 1). Indeed, the gain margin appears to increase significantly over that when the actuator does not saturate. At an amplitude of 13%, the switching action of the controller to demand pitching at the maximum rate leads to a further departure of the describing function from the transfer function of the baseline controller. It is observed that an amplitiude of 13% is close to the worst case in the sense that the gain of the controller is largest with saturation of the actuator leading to an overall decrease in the gain at higher amplitudes. With regard to the situation with an ampltide of 13%, it can be seen that, as might be expected, the switching action increases the gain of the controller at lower frequencies, thereby enhancing distrubance rejection. Perhaps more surprisingly, it is also evident that the gain of the switched controller decreases at higher frequencies, presumably owing to saturation of the actuator and the consequent action of the minor loop. As a result, the closed-loop stability margins with the switched controller are essentially preserved, with, in fact, a substantial increase indicated in the system gain-margin. The stability margins indicated by the describing function analysis are confirmed by nonlinear simulations. This behaviour is extremely interesting and certainly seems to warrant further investigation since it indicates that improvements in performance without sacrificing stability robustness are, indeed, possible by adopting a switched linear control strategy.

Amplitude (%rated)	Gain margin (dB)	Phase margin (degrees)	Cross-over freq. (rad/s)
0.3	10.34	50.95	1.39
7	14.78	47.92	1.23
13	16.68	46.03	0.99

Table 1 Stability margins indicated by describing function analysis.

Extreme gust performance of switched controller

In order to assess the performance of the switched controller when subject to the extreme gust studied in section 2, the rotor speed variations with this controller are compared to those with the continuously pitching controller described in section 2, see figure 5. The switching action reduces the speed excursion from 18.9% to 14.3% of rated speed; that is, the switched controller maintains the speed variation in response to the extreme gust below the upper bound of 15% as required. Similar improvements are noted in response to other types of extreme gust.

4. CONCLUSIONS

Whilst a conventional controller maintains the rotor speed within the required limits during normal operation, it is found that with a typical 1 MW turbine the limits maybe violated during extreme gusts. The penalty associated with exceeding the permitted range of rotor speeds is high since safety considerations may require an emergency shut-down of the machine and, in the longer term, it is well known that it is the occasional extreme loads experienced by a wind turbine during its life which contribute most to fatigue damage. The possibility of augmenting the conventional controller such that during extreme speed excursions the blades are feathered at the maximum rate allowed by the actuation system is therefore investigated. Such an approach retains the conventional controller design whilst making better use of the available actuation capability. The closed-loop stability with the augmented controller is analysed and it is confirmed that the stability margins are preserved. Nonlinear simulation results indicate that the augmented controller succeeds in maintaining the rotor speed within the required limits during an extreme gust. Although not pursued further here, it is noted that a natural extension of the proposed switching logic include the addition of a predictor to permit an earlier reaction to a speed excursion. Moreover, although not required in the present example, the possibility exists of employing co-ordinated action between blade pitching and the generator reaction torque in order to further improve performance.

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APPENDIX

Nominal plant dynamics

Plant transfer function from aerodynamic torque, T, to generator speed, ω_g,

$$\frac{0.0372}{s^4 + 0.25s^3 + 753.03s + 1.73}$$

The bandwidth of the blade pitch actuator is approximately 2.5 rad/s with transfer function

$$\frac{1022.7}{s^3 + 28.57s^2 + 531.82s + 1022.7}$$

The aerodynamic nonlinearity relating the aerodynamic torque generated by the rotor to the windspeed, V, rotor speed, Ω, and pitch angle, β, is of the separable form

$$T(V,\beta,\Omega) = F(\beta,\Omega) + G(V)$$

where F, G are nonlinear functions.

High wind speed controller (speed regulation by blade pitching, power regulation by generator torque)

The controller transfer functions are

$$C_i = 250\frac{(s + 4570971)(s^2 + s + 750)}{(s + 2.187719)(s^2 + 38s + 750)}$$

$$C_o = -99.21\frac{(s+0.5)(s^6+19.074s^5+64.71s^4+55.22s^3+18.011s^2+2.2785s+0.0749)}{s(s+0.3)(s^8+32.187s^7+305.33s^6+1390.3s^5+3328.5s^4+3328.1s^3+1389.8s^2+224.16s+11.527)}$$

$$C^* = 19922.2\ \frac{s^3 + 9.0s^2 + 26.0s + 30.0}{s^3 + 43s^2 + 820s + 6000}$$

The pitch controller incorporates an approximate model of the pitch actuator dynamics, $A = \frac{0.1s + 1}{0.4s + 1}$ and an approximate model of the inverse of the actuator dynamics, $A^{-1} = \frac{0.4s + 1}{0.1s + 1}$. The closed-loop stability margins are: gain margin 10.33 dB, phase margin 50.95° with open-loop cross-over frequency of 1.39 rad/s.

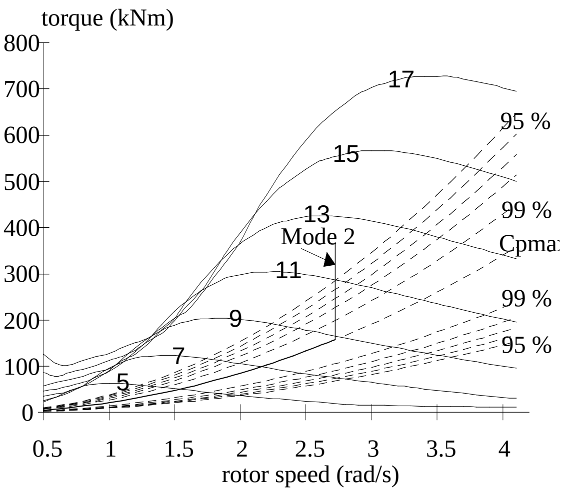

Figure 1 Operational strategy

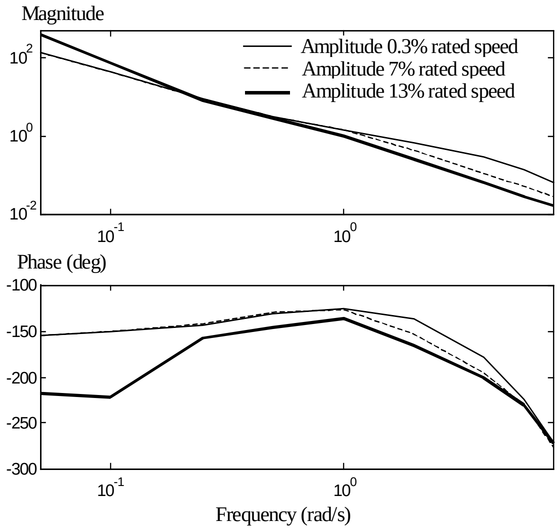

Figure 4 Describing functions of open-loop with modified conroller

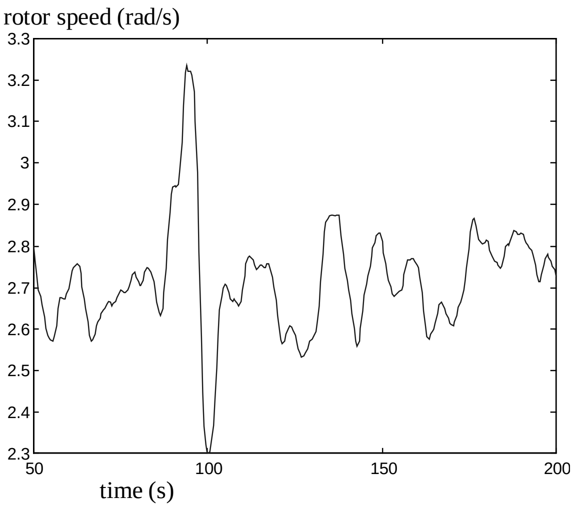

Figure 2 Extreme gust performance of original controller

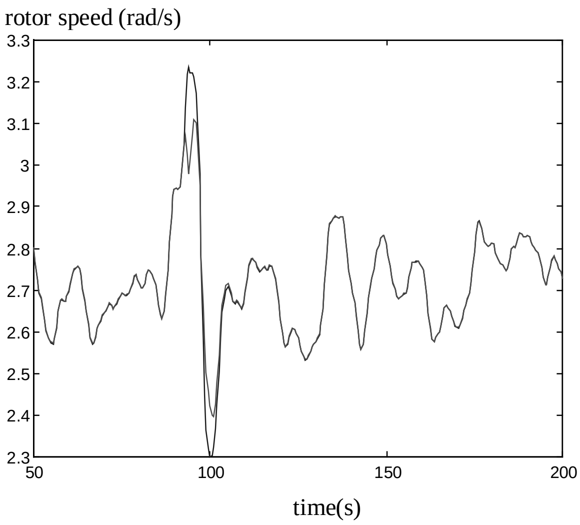

Figure 5 Comparison of extreme gust performance of original and modified controllers

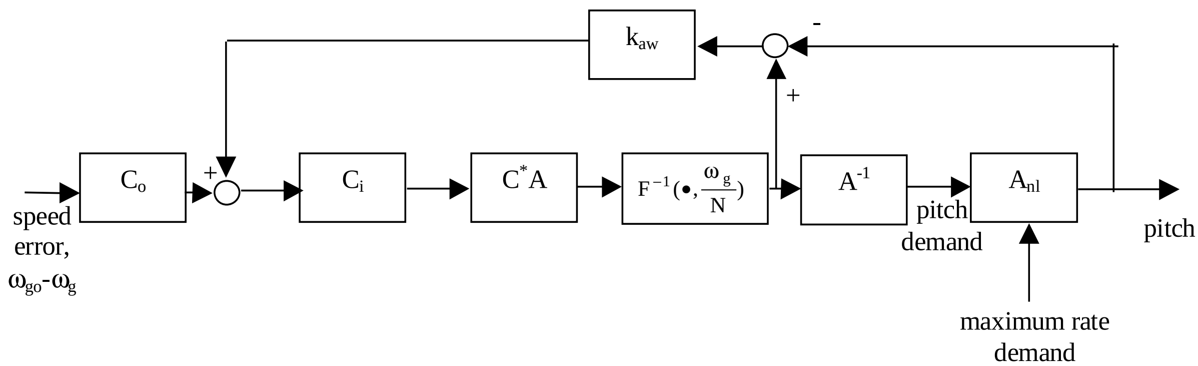

Figure 3 Controller implementation