Gain scheduled and robust $H_\infty$ control above rated wind speed for wind turbines

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Abstract

Two different approaches for individual pitch control for wind turbines is investigated. The first one is a gain scheduled decentralised control design and the second one is a robust $H_\infty$ loop shaping control design. Both controllers work well in the region above rated wind speed, exhibiting a response that is mostly independent of wind speed.

Introduction

For variable-speed wind turbines, the control regime is divided into an above-rated mode and a below-rated mode. Because of the increasing rotor size and the spatial load variations along the blade, it is necessary to react to turbulence in a more detailed way, with each blade separately controlled. The controllers designed in this paper are specifically designed to provide speed regulation above rated wind speed in order to reduce the blade flap motions.

The wind turbine model

The results presented in the poster correspond to the NREL 5 MW benchmark wind turbine.

Table 1: Properties for the NREL 5MW benchmark wind turbine

<table>
<thead>
<tr>
<th>Rating</th>
<th>5 MW</th>
</tr>
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<tbody>
<tr>
<td>Rotor Configuration</td>
<td>Upwind, 3 blades</td>
</tr>
<tr>
<td>Rotor diameter, Hub height</td>
<td>126 m, 90 m</td>
</tr>
<tr>
<td>Rated wind speed, rated rotor speed</td>
<td>11.4 m/s, 11.2 rpm</td>
</tr>
</tbody>
</table>

The wind turbine model has been Coleman transformed and the Coleman system and Coleman coordinates are used in the rest of the poster. The subscripts $c$, $h$, and $v$ are used for the collective, horizontal and vertical Coleman coordinates respectively. The model used is

$$T_s = G \frac{f_\alpha}{\omega_t} + \frac{f_t}{\omega_t}$$

where $G$ is the wind turbine model, $\omega_t$ is the generator speed, $f_t$ is the individual blade flap motions, i.e. collective blade flap is not used, and $\beta$ is the pitch input.

Linearization

The system has been linearized around different steady-state operating points above rated wind speed. The wind speed range under study is between 12.1 m/s and 26 m/s.

Design of a baseline controller

The linear model at 14 m/s has been used when designing a baseline controller. The Bode plot for the three control loops can be found in figure 2 (only one flap loop is shown but the other one is very similar).

Figure 2: Bode plots for the SISO loops at 14 m/s. a) The collective pitch-generator speed loop, b) The individual pitch to individual flap loop.

It is possible to use classical loop-shaping techniques on each loop. The collective pitch-generator speed loop uses a PI regulator and two notch filters with zeros at the poles of the high-frequency resonances. The same PI controller without the notch filters results in more vibrations in the drive train. The bandwidth of this loop is about 1 rad/s. A PID controller for the individual pitch-individual flap loops has been used resulting in a bandwidth of 10 rad/s.

The base line controller behaves well at wind speeds close to its design wind speed but behaves very badly at high wind speeds.

Gain scheduled controller

A simple gain scheduling approach to nonlinearities is to design a continuous set of linear controllers, $K_\alpha(s)$, that is parameterized by a scheduling variable $\omega_t$. A scheduling variable is a variable that can be measured or calculated from measured signals that determines which operating point the system works at or works close to. The controller output is then calculated by first calculating the scheduling variable, $\omega_t$, and then using the controller $K_\alpha(s)$ to calculate the output.

This has been done for the wind turbine by using the collective pitch as scheduling variable and scheduling the gain of the baseline controller designed above. The controller used is thus

$$\beta = \hat{\alpha} \hat{K}^{-1}(s)\omega_t$$

where $\hat{K}$ is the baseline controller. The scheduling is only performed for the collective speed to generator speed loop. The function $K^{-1}(s)$ is determined by first choosing new cross over frequencies for several wind speeds between 22.1 m/s and 26 m/s, followed by determining a new controller gain for each wind speed that achieves the chosen cross over frequency, and the last step is to fit a polynomial to the data points to get a continuous function. The new cross over frequencies are chosen to be lower than the cross over frequency for the base line controller below 14 m/s and the same as for the base line controller above 14 m/s. The reason for this is that the problem with the base line controller is due to a high system gain at high wind speeds and that the phase of the model is quite low at low wind speeds.

Conclusion

Two different individual pitch controllers that take into account the different behavior of a wind turbine at different wind speeds have been designed. The first one is a gain scheduled diagonal controller and the second one is a robust controller based on the $H_\infty$ loop shaping design method. Both controllers work well in the whole region above rated wind speed. The gain scheduled controller is relatively easy to design, has a low order and the individual control loops are easy to understand. One possible drawback is that it is non linear. The $H_\infty$ loop shaping controller is easy to design but it gives a controller of a large order where the individual loops is difficult to understand.