Individual and Collective Pitch Actuation using Lidar-Enabled Model Predictive Control

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Abstract
Research into lidar-enabled model predictive control (MPC) of wind turbines indicates clear benefits over baseline feedback controllers. However, there is little literature comparing different model predictive controllers. This work presents a comparison of the performance of collective pitch and individual pitch-enabled MPCs to an industry feedback controller as well as to each other, and confirms that MPC is able to improve both rotor speed regulation and structural load mitigation over the baseline controller. This research is presented as part of a larger, ongoing study that compares various MPC formulations in order to construct a streamlined MPC design framework.

Keywords: *Control, Lidar, Preview Measurement, Model Predictive Control, Individual Pitch Control*

Introduction

Model predictive control is an advanced control technique that involves optimizing the performance of a dynamic system over some prediction horizon. The natural inclusion of both physical system constraints and preview disturbance information makes MPC attractive for wind turbine control, especially with the development of lidar scanners that can provide measurements of the oncoming wind. Several studies have been published in the last five years presenting MPC for wind turbines; however, the MPC formulation is very general and, while studies have shown that MPC can provide performance increases over a baseline controller, few compare different MPC formulations to each other.

One significant difference between MPC studies is pitch actuation capability. Some studies [1,2] focus on collective pitch control (CPC), where the wind turbine blades all receive the same pitch command, while others [3] utilize individual pitch control (IPC), where the blades can be pitched independently to reduce structural loading. In this work, we compare lidar-enabled MPC for wind turbines using both IPC and CPC while keeping other aspects of the MPC formulation the same. By doing so, we aim to clarify the benefits and drawbacks of IPC over CPC in a MPC setting.

Methods

In this investigation of MPC we use a linear plant model. A high-fidelity, nonlinear wind turbine model implemented using the National Renewable Energy Laboratory's FAST aero-elastic code [4] is linearized to provide a discrete-time state-space model of the form

$$x_{k+1} = Ax_k + Bu_k + B_d d_k$$

where x_k, u_k, and d_k are vectors of the system states, inputs, and disturbances at time k, respectively; and A, B, and B_d are the system matrix, control input matrix, and disturbance input matrix, respectively.

The linear model, combined with a quadratic cost function, allows us to formulate the MPC problem as

$$\begin{aligned} \text{minimize} \quad & \sum_{i=1}^{N_p-1} \left(x_{k+i}^{\mathrm{T}} Q x_{k+i} + u_{k+i-1}^{\mathrm{T}} R u_{k+i-1}\right) + x_{k+N_p}^{\mathrm{T}} Q_f x_{k+N_p} \\ \text{subject to} \quad & x_{k+i} = Ax_{k+i-1} + Bu_{k+i-1} + B_d d_{\boldsymbol{k+i-1}} \\ & x_{\min} \le x_{k+i} \le x_{\max} \\ & u_{\min} \le u_{k+i-1} \le u_{\max} \qquad \text{for } i = 1,2,\dots,N_p \end{aligned}$$

where Q, R, and Q_f contain weights that are tuned to enhance certain aspects of the system's performance; N_p is the prediction horizon length; and $x_{\min}$, $x_{\max}$, $u_{\min}$, and $u_{\max}$ reflect physical constraints on the system states and control inputs. This problem can be manipulated to take the general form of a linear-constrained quadratic program by simply stacking the future states, inputs, and disturbances as well as the weight matrices.

The concept of MPC is to use this program to optimize the path of the future control inputs. Only the first of these (u_k) is applied however: when time marches forward, the controller receives new information about the current states x_k and disturbances d_k, and the optimization repeats, and thus the finite horizon is continually pushed back. The algorithm is referred to by some authors as receding horizon control for this reason.

We use estimates of future wind disturbances provided by a realistic simulation of a Windar 4-beam pulsed lidar. Finally, we simulate the closed-loop control system acting on the full nonlinear FAST model using Matlab & Simulink, with an evolved wind field providing a realistic distinction between the disturbance estimated by the lidar and the wind disturbance seen by the turbine.

Initial results

The CPC controller has been successfully implemented, as well as a baseline industrial controller for reference. Initial results from a turbulent wind field of mean wind speed 16 m/s present significant improvements in turbine performance. The results show that in a test case where rotor speed deviation, tower fore-aft motions, and pitch actuation effort were explicitly penalized in the MPC cost function, standard deviation of rotor speed error and tower displacement can be reduced by 46% and 22%, respectively, while pitch velocity standard deviation is maintained at the same level. Figure 1 provides an example of the improvement in rotor speed tracking with MPC.

The IPC controller is in the process of being implemented. Once this is complete, we will test each controller in a series of wind scenarios so that we are able to adequately compare IPC to CPC, and we will present these results at the WindTech2017 conference.

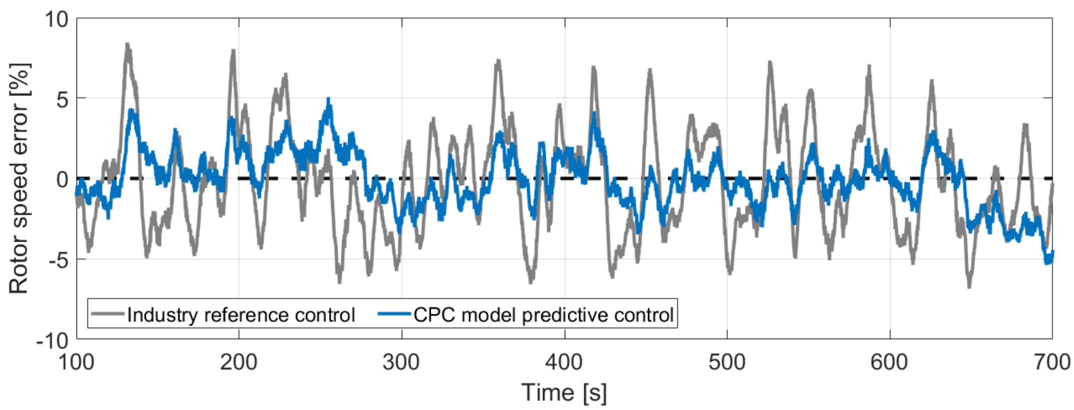

Figure 1: Comparison of rotor speed errors for the industry reference control and CPC model predictive control.

Summary

This study concurs with previous research indicating that lidar-enabled model predictive control can bring significant performance improvements for wind turbines. Further, it presents a comparison between MPC and industry controllers, and will investigate the benefits provided by IPC over CPC in a MPC implementation.

References

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