Receding horizon control (RHC) on a Lidar based preview controller design for the active wind turbine pitch system

by Leilei Shinohara[1], Shenyao Xu[2], Thorsten Beuth[1], Wilhelm Stork[1]

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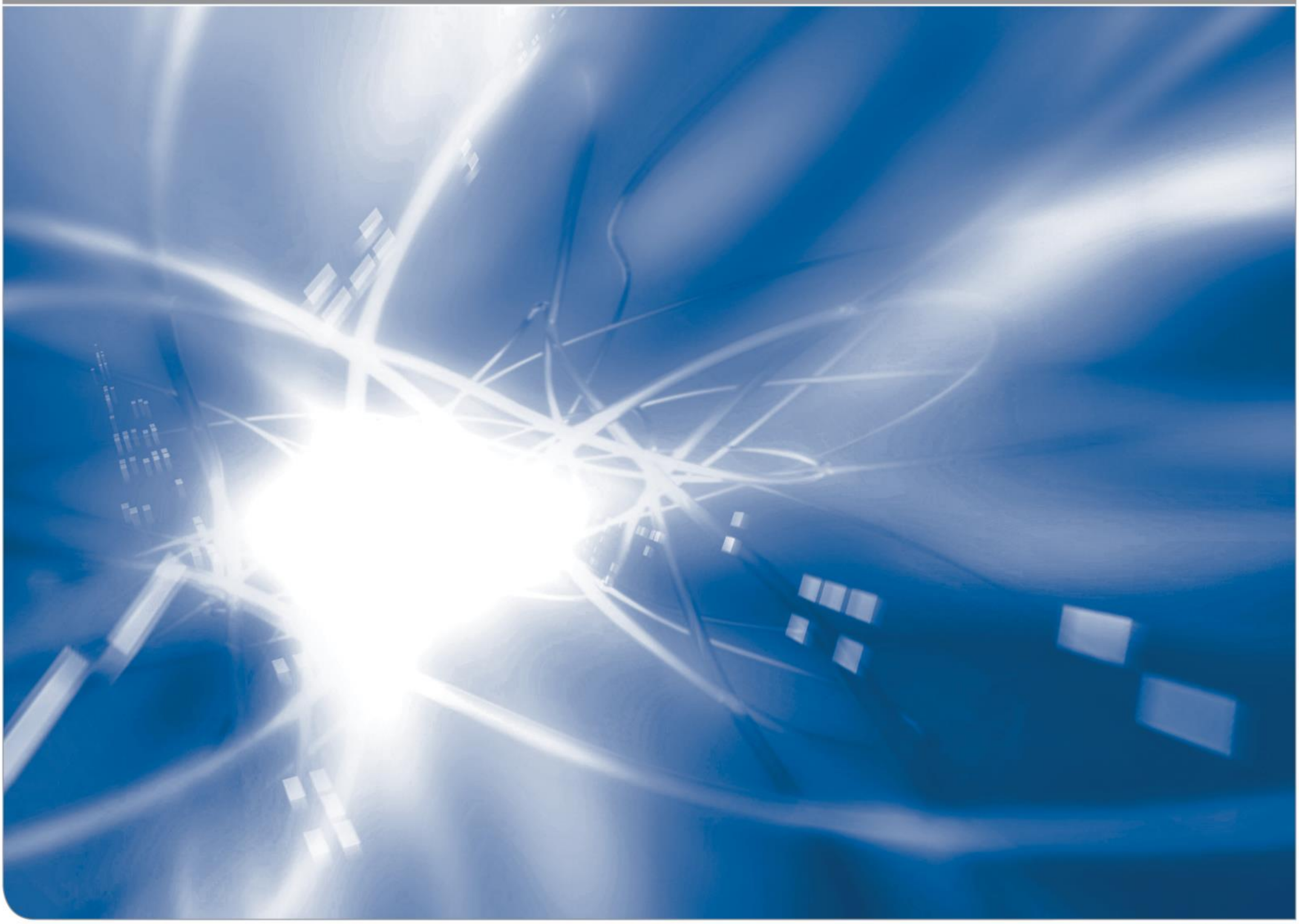

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In this paper, we present a design of a 2DOF (Degree Of Freedom) RHC/FB (FeedBack) control method for the pitch system of wind turbines based on the preview wind speed measurement by a Lidar system. This approach has higher industrial feasibilities without losing the control performance in comparison to state of the art control methods. The RHC controller is designed with the Multi-Parametric Toolbox (MPT) 3 and tested with a nonlinear wind turbine model designed via the aeroelastic simulation tool FAST (Fatigue, Aerodynamics, Structures, and Turbulence) by NREL (National Renewable Energy Laboratory) in a Simulink simulation enviroment. As a result we figure out that the new RHC control is maintaining a stable rotation speed for reducing the operational dynamic loads of the driver train especially on gust wind conditions.

Keywords: Wind Turbine, Model Predictive Control, Receding Horizon Control, FAST, Linearized Wind Turbine Model, Pitch Control

1. Introduction

With the replacement of the stall regulated wind turbine by variable pitch systems in the 1990s, the pitch control, torque control, and power quality control of wind turbine systems have become industry standard. In general the main purpose of the wind turbine control is minimizing the cost of energy (COE) [1]. The operation of wind turbine systems can be divided into two regions, below and above the rated wind speed [2]. The control strategies are depending on those operational regions. If the wind speed is below the rated speed, generator torque control provides the input to vary the rotor speed and keeps the blade pitch angle and tip speed ratio to maximize the power capturing. If the wind speed is over the rated speed, the primary objective is to maintain a constant power output by keeping the generator torque constant with the pitch control to vary the blade pitch angle [3]. The active pitch control has been proved to be an efficient way of reducing fatigue load and increasing the power capturing [4]. Since the rotor sizes increases very fast recently, the wind shear is having a stronger aerodynamical impact [5]. Therefore, there is a need for more advanced pitch control systems, as well as new designs of blades and their materials to reduce the fatigue and extreme loads. In [6] a preview based control is presented on a spline interpolation method to process the wind data and improve blade load regulation via the blade pitch angle control. The method guarantees a hard upper bound on the flap wise bending moment. In [7] an extra input is added to the control system by using an accelerometer to measure the acceleration of the tower. This new measurement is used to calculate the extra pitch contribution to the original pitch which helps to damp the tower motion in the control system. In the here presented article, a preview control based on the 2DOF FF/FB control

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is proposed for the active pitch system of wind turbines. The proposed controller is based on the 2DOF FF/FB controller, however, the FF term is designed with the RHC methods. Figure 1shows the basic idea of this concept which we called a 2DOF RHC/FB control in this article.

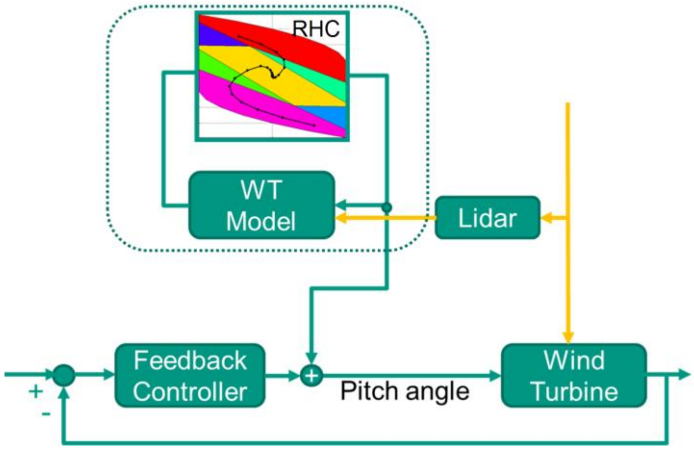

Figure 1. System diagram of the 2DOF RHC/FB controller for the active pitch control of wind turbines, green represent the control signal, yellow represents the wind signal

The system consists of a normative model of a wind turbine (WT Model) to generate a full states output, then a RHC controller to calculate the pitch commands for the normative model. The wind field is generated by the TurbSim and reprocessed by a Lidar model for the WT Model and controller. The RHC controller takes the Lidar data for predicting the future pitch commands. The feedback controller takes the states error to generate the correcting pitch commands and add into the RHC commands for the real nonlinear wind turbine model (Wind Turbine) created by the FAST tool. Reference signal can be the states at the linearization setting point or the output from the normative model. This concept is first introduced by T. Hatanaka et. al. for the control of an electrodynamics shaker (Figure 2) [8], where P_m is the nominal model of plant, P_r is the real plant, .K_f is disturbance-force compensator, $\hat{d}_f$ is the estimated disturbance force, G_E is the disturbance estimator.

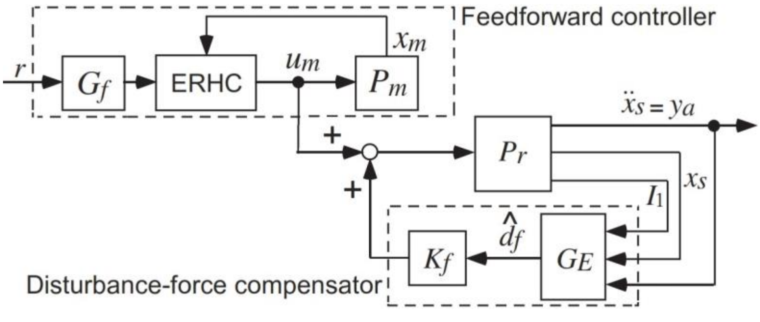

Figure 2. Block diagram of the 2DOF electrodynamics shaker controller [8]

2. Modeling of the wind turbine

A FAST nonlinear model for the simulation of a 5 MW offshore reference turbine from NREL is used [3]. However, the FAST model is too complex and so it is not possible to integrate into the control loop. Therefore, a reduced linear model is designed based on the study by C. L. Bottasso et. al [9]. The simple model can be divided into an aerodynamic model and a servo-elastic model. The aerodynamic model simulates the forces affected by the airflow around the wind turbine body. The servo-elastic dynamic model can be further separated into different sub-models: drivetrain model, generator model, tower model, blades model, pitch actuator model, and torque actuator model. In this article, we only consider the drivetrain and the generator.

The aerodynamics torque and thrust force on the turbine rotor are given as a nonlinear function

$$\tau_{\mathrm{Rotor}} = \frac{1}{2}\rho\pi R_{\mathrm{Rotor}}^{3} U_{\infty}^{2} C_{Q}(\lambda_{\mathrm{TSR}}, \beta_{\mathrm{Pitch}}),$$
$$f_{T} = \frac{1}{2}\rho\pi R_{\mathrm{Rotor}}^{2} U_{\mathrm{REWS}}^{2} C_{T}(\lambda_{\mathrm{TSR}}, \beta_{\mathrm{Pitch}}).$$

Where ρ is the air density, A_D is the rotor swept area, R_{rotor} is the rotor radius, $U_{\infty} = \frac{U_{\mathrm{REWS}}}{(1-a)}$ is the wind speed at the far upstream side and C_P is the power coefficient. $\lambda_{\mathrm{TSR}} = \frac{\Omega_{\mathrm{Rotor}} \cdot R_{\mathrm{Rotor}}}{U_{\mathrm{wind}}}$ is the tip-speed ratio, $C_Q = \frac{C_P}{\lambda_{\mathrm{TSR}}}$ is the torque coefficient, C_T is the thrust force coefficient. The servo-elastic dynamic model of the rotor and the drive train are represented with the equation of motion (EoM) as

$$J_{\mathrm{tot}}\dot{\Omega}_{\mathrm{Rotor}} = \tau_{\mathrm{Rotor}} - N_{\mathrm{Gear}}(\tau_{\mathrm{Gen}} + \Delta\tau_{\mathrm{EM}}),$$
$$\dot{\Omega}_{\mathrm{DT}} = \frac{\tau_{\mathrm{Rotor}}}{J_{\mathrm{Rotor}}} - \left(\frac{1}{J_{\mathrm{Rotor}}} + \frac{1}{N_{\mathrm{Gear}}^{2} J_{\mathrm{Gen}}}\right)(k_{\mathrm{DT}} \cdot \theta_{\mathrm{DT}} + c_{\mathrm{DT}} \cdot \Omega_{\mathrm{DT}}) + \frac{\tau_{\mathrm{Gen}} - \Delta\tau_{\mathrm{EM}}}{N_{\mathrm{Gear}} J_{\mathrm{Gen}}}.$$

where, $J_{\mathrm{tot}} = J_{\mathrm{Rotor}} + N_{\mathrm{Gear}}^{2} J_{\mathrm{Gen}}$ is the overall rotational inertia of the drivetrain system, θ_{DT} and Ω_{DT} denotes the drive train shaft torsion angle and rates, $\theta_{\mathrm{DT}} = \theta_{\mathrm{Rotor}} - \frac{\theta_{\mathrm{Gen}}}{N_{\mathrm{Gear}}}$, $\Omega_{\mathrm{DT}} = \Omega_{\mathrm{Rotor}} - \frac{\Omega_{\mathrm{Gen}}}{N_{\mathrm{Gear}}}$, with $\dot{\theta} = \Omega$. A linear time-invariant (LTI) model is used to derive the RHC controller from the MPT toolbox. Therefore, a linearization process is applied with FAST. The model in state space is reprenseted as

$$\Delta\dot{x} = A\Delta x + B\Delta u + \Gamma\Delta v, \quad \Delta y = C \cdot \Delta x + D \cdot \Delta u + D_d \cdot \Delta v$$

where, Δx, $\Delta\dot{x}$, Δu, Δv are the system states and its first order deliverable, system control input and wind disturbance input which are defined as

$$\Delta x = [\delta\Omega_{\mathrm{Rotor}} \quad \delta\theta_{\mathrm{DT}} \quad \delta\Omega_{\mathrm{DT}}]^{\mathrm{T}}, \ \Delta u = [\Delta\tau_{\mathrm{EM}} \quad \delta\beta_{\mathrm{Pitch}}]^{\mathrm{T}}.$$

Parameters A, B, C, D, Γ, and D_d are the parameter matrices which are

$$A = \begin{bmatrix} \frac{\delta\tau_{\mathrm{Rotor}}/\delta\Omega_{\mathrm{Rotor}}}{J_{\mathrm{Rotor}}} & -\frac{k_{\mathrm{DT}}}{J_{\mathrm{Rotor}}} & -\frac{c_{\mathrm{DT}}}{J_{\mathrm{Rotor}}} \\ 0 & 0 & 1 \\ -\frac{\delta\tau_{\mathrm{Rotor}}/\delta\Omega_{\mathrm{Rotor}}}{J_{\mathrm{Rotor}}} & -\left(\frac{k_{\mathrm{DT}}}{J_{\mathrm{Rotor}}} + \frac{k_{\mathrm{DT}}}{N_{\mathrm{Gear}}^{2} J_{\mathrm{Gen}}}\right) & -\left(\frac{c_{\mathrm{DT}}}{J_{\mathrm{Rotor}}} + \frac{c_{\mathrm{DT}}}{N_{\mathrm{Gear}}^{2} J_{\mathrm{Gen}}}\right) \end{bmatrix},$$
$$B = \begin{bmatrix} 0 & -\frac{\delta\tau_{\mathrm{Rotor}}/\delta\beta_{\mathrm{Pitch}}}{J_{\mathrm{Rotor}}} \\ 0 & 0 \\ -\frac{1}{N_{\mathrm{Gear}} J_{\mathrm{Gen}}} & \frac{\delta\tau_{\mathrm{Rotor}}/\delta\beta_{\mathrm{Pitch}}}{J_{\mathrm{Rotor}}} \end{bmatrix},$$
$$\Gamma = \begin{bmatrix} \frac{\delta\tau_{\mathrm{Rotor}}/\delta U}{J_{\mathrm{Rotor}}} & 0 & \frac{\delta\tau_{\mathrm{Rotor}}/\delta U}{J_{\mathrm{Rotor}}} \end{bmatrix}^{\mathrm{T}}.$$

We linearize the system at the operation point in the middle of the above rated speed region with $U_{\mathrm{REW}} = 18\ \mathrm{m/s}$, $\beta_{\mathrm{Pitch}} = 14.9^{\circ}$, $\Omega_{\mathrm{Rotor}} = 12.1$ rpm. Therefore, the linearized LTI system parameters are given as

$$A|_{U_{\mathrm{REW}}=18} = \begin{bmatrix} 3.32 \times 10^{-4} & 172.83 & 1.2382 \\ 0 & 0 & 1 \\ -0.2742 & -195.21 & -1.6724 \end{bmatrix},$$

$$B|_{U_{\text{REW}}=18} = \begin{bmatrix} 0 & -1.93\times10^{-5} \\ 0 & 0 \\ -1.3364 & 1.93\times10^{-5} \end{bmatrix}, \quad \Gamma|_{U_{\text{REW}}=18} = [0 \quad 0 \quad 0.0313]^{\text{T}}.$$

Figure 3 shows the bode diagram of the drivetrain open loop response. The input and outputs are defined as: In(1) contralable electrical magnatic torque of generator, In(2) collective blade pitch angle, In(3) wind speed disturbance, Out(1) rotor speed, Out(2) drivetrain torsion angle, Out(3) drivetrain torsion angular rates. Since the control objective is to keep the rotor speed stable, the responses from inputs to the output 1 are most important.

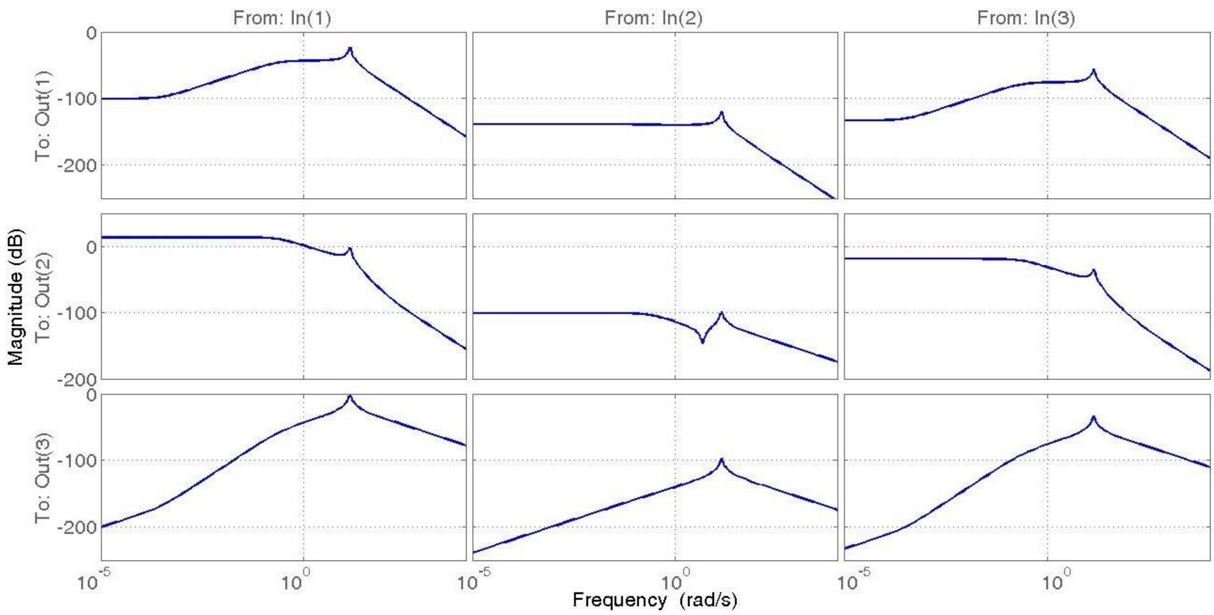

Figure 3. Bode diagram of the drivetrain open loop response

3. RHC controller design

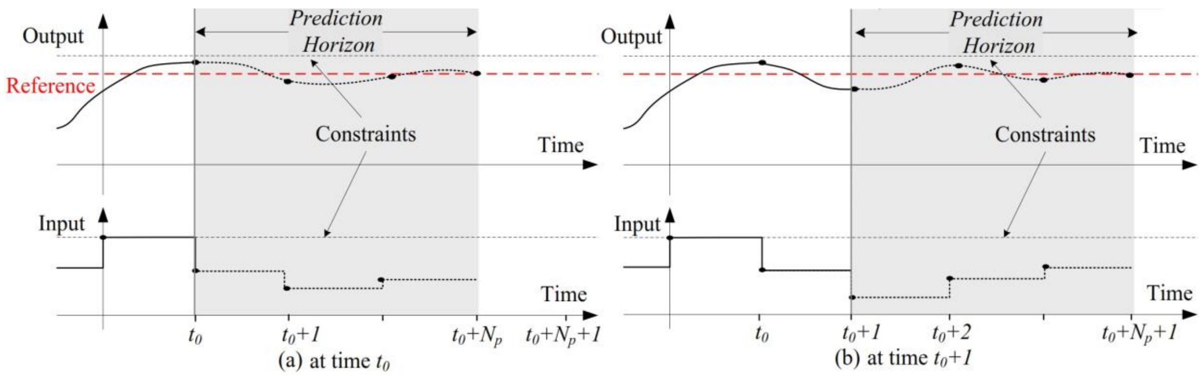

Figure 4. Illustration of the receding horizon of RHC methods [10]

RHC is based on iterative, finite horizon optimization of a plant model. At time k the current plant state is sampled and an optimal predicted output is calculated for a fixed time horizon in the future: [k, k+p]. Then a corresponding control input for the plant is calculated by the controller. Only the selected steps of the control output are implemented, then the plant is sampled again and the calculations are repeated from the current states, yielding a new control and prediction. The prediction horizon is continously shifted forward and for this reason MPC is called receding horizon control. Figure 4 illustrates the working principle of the RHC methods.

RHC controller performs an optimization on the predicted output of the plant. Assume now the time is k, $\Delta u(k+j|k)$ denotes the input of Δu at time $(k+j)$ in the future, so the same expressed of $x(k+j|k)$, $z(k+j|k)$. For the optimization, a cost function is defined where the different outputs and control inputs can be weighted to decide the objectives of the controller. The cost function is given as a quadratic equation:

$$J_k[x(k), u] = \sum_{j=1}^{N} \|z(k+j|k) - z_r(k+j|k)\|^2_{Q(j)} + \sum_{j=0}^{N_c-1} \|\Delta u(k+j|k)\|^2_{R(j)}.$$

System constraints are given as

$$z_{min} \le z(k+j|k) \le z_{max},\ j = 1, \cdots, N,$$
$$\Delta u_{min} \le \Delta u(k+j|k) \le \Delta u_{max},\ j = 0, \cdots, N_c - 1.$$

Here $z(k+j|k)$ is the predicted output from the plant, $z_r(k+j|k)$ is the reference for the output and $\Delta u(k+j|k)$ is the predicted control input. $[z(k+j|k) - z_r(k+j|k)]$ is the tracking error which is weighted and minimized in the optimization. The weight of the tracking error is determined by the matrix Q. The last part of the cost function is the calculation of the cost for the control input, which is weighted by the matrix R.

4. Controller validation via simulation

The controller is tested with the simulation setup in Simulink as shown on Figure 1. The RHC controller is designed with a full state model output. Assuming a perfect model of the real wind turbine, the calculated turbine control input for the norminal model is exactly the same which can be used for the real turbine model. However due to the simplified norminal model, error occurs in between the norminal and real turbine model. To evaluate the controller performance, a gust wind profile for testing of the extreme load and an IEC turbulence wind profile for testing the operational fatigue load is applied. For the comparison, a standard industrial PI (Proportional Integral) FB controller and a 2DOF FF/FB controller are used.

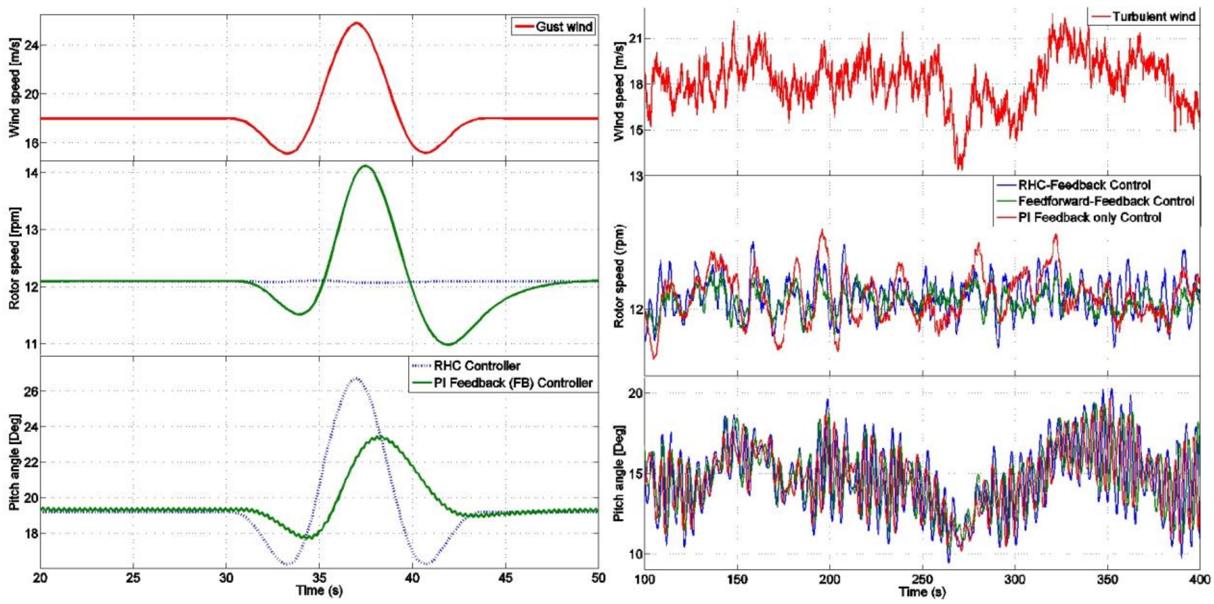

Figure 5. Simulation result with (left) gust wind (right) turbulent wind

- **Gust wind** an extreme operating gust (EOG) wind profile of 18 m/s on the hub height is disturbed to the wind turbine rotor without vertical share. Figure 5 left shows the gust wind profile, the rotor rotation speed, and pitch command input from the simulation. Comparing to the PI FB controller, RHC keeps the rotor rotation speed more constant.
- **Turbulence wind** Operational turbulent wind interacts with wind turbine continuesly. Figure 5 right shows the result with an operational turbulent wind with mean wind speed of 18 m/s and turbulent intensity of 16%. Comparing to the PI FB controller, the RHC shows slightly better result on reducing of the fluctuations of the rotor speed, but not better than the FF/FB controller. This is mainly due to uncertainty on the linearized norminal model of the wind turbine. Since within this article, only 2 DOFs out of 18 on the FAST model are used for the linear norminal model.

5. Conculusion

In this article we proposed a new control approach, 2DOF RHC/FB method with Lidar assisted wind preview measurements. Based on the simulation veladition, a significant improvement is shown on extreme operating gust wind condition in comparison to the standard PI FB control. However, due to the model uncertainty, it does not show much improvement in the turbulent wind conditions. Further development is needed for the RHC gain tunning as well as the norminal model improvement.

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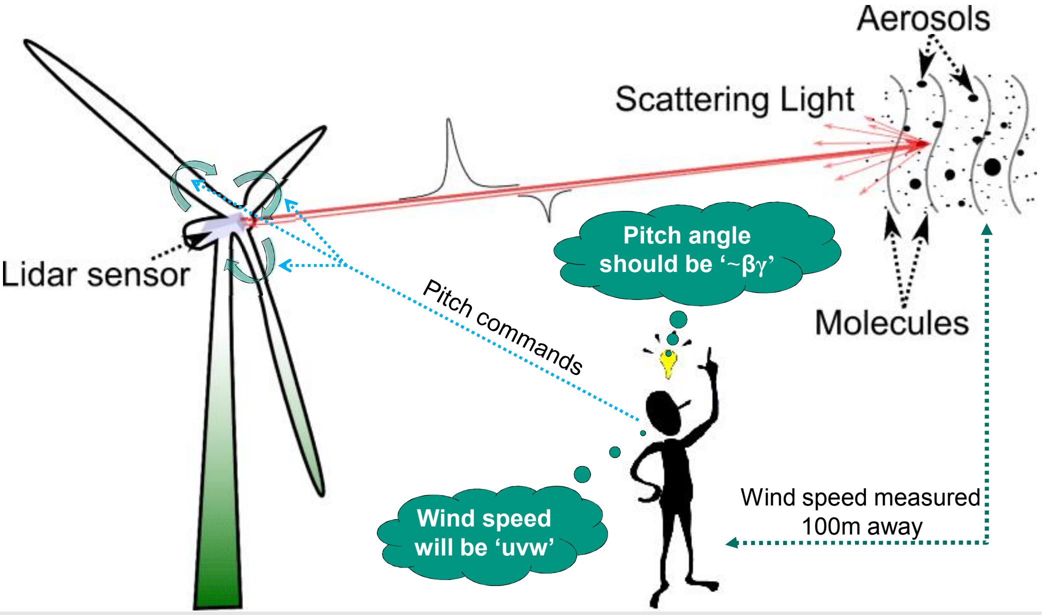
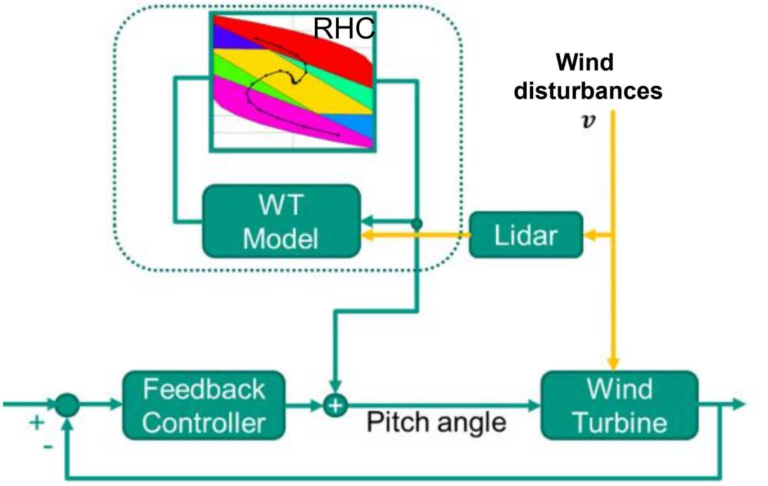


Introduction

- Need of **Renewable Energy** sources growing strongly
- **Wind turbine** and **Wind farm** construction on the **rise**
- High **Stress level**, significant **Wear and Tear**
- **Predictive control** system with **Lidar** wind forecasting

Our approach A combination of 2DOF control & RHC



Wind turbine linear model

$$x(k+1) = Ax(k) + \underbrace{B\Delta u(k)}_{\text{Control inputs}} + \underbrace{\Gamma\Delta v(k)}_{\text{Wind disturbances}}$$

$$y(k) = C_y \cdot x(k)$$

$$z(k) = C_z \cdot \underbrace{x(k)}_{\text{System states}}$$

Cost function

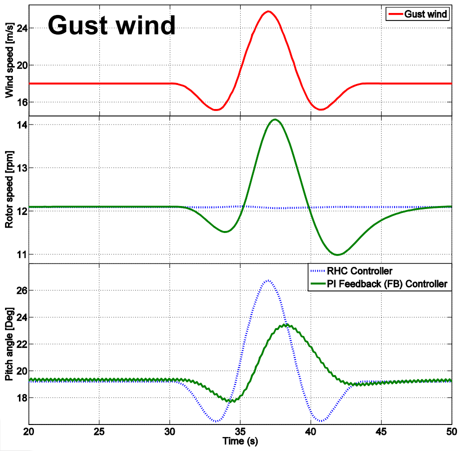
$$J_k[x(k),u] = \sum_{j=1}^{N} \underbrace{\|z(k+j|k) - z_r(k+j|k)\|^2_{Q(j)}}_{\text{Tracking errors}} + \sum_{j=0}^{N_c-1} \underbrace{\|\Delta u(k+j|k)\|^2_{R(j)}}_{\text{Control inputs [differential pitch angles]}}$$

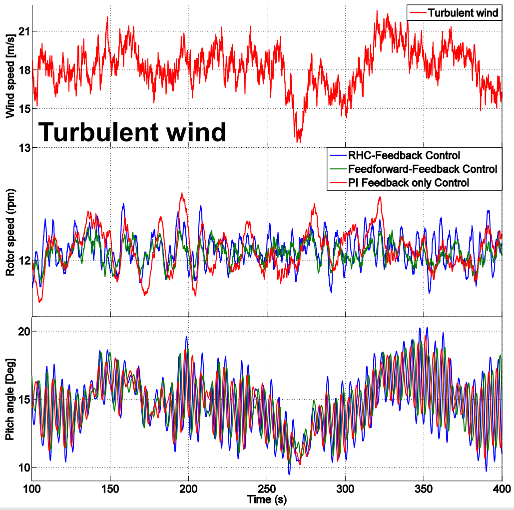
Constraints

$$z_{min} \le z(k+j|k) \le z_{max},\ j = 1,\cdots,N$$

$$\Delta u_{min} \le \Delta u(k+j|k) \le \Delta u_{max},\ j = 0,\cdots,N_c-1$$

Simulation results





Conclusion

- Better performance comparing to industrial PI-Feedback controller ✓
- Effects on reducing fluctuation ✓
- Need more optimization to reach ✓ Feedforward-Feedback performance

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