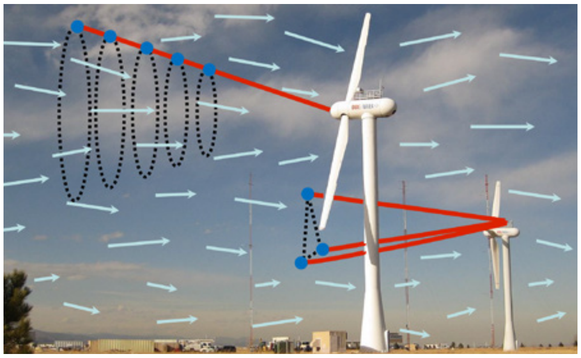
Preview Control of Wind Turbines

Wind is not only the energy source for wind turbines but also the main disturbance to the control system. Thus, knowledge of the incoming wind is valuable for optimizing energy production and reducing structural loads. "Preview control" techniques can incorporate this knowledge.

Advances in lidar technology provide new opportunities for preview control of wind turbines; however, even with state-of-the-art lidar systems, the disturbance cannot be measured perfectly. This requires control research to address two coupled aspects. On one hand, the complex wind field can be reduced to wind characteristics such as speed, direction, or shears, and a control problem can be formulated to address changes in the disturbances. On the other hand, the performance of the preview controller depends on how well the deduced disturbances correlate with the actual disturbances acting on the turbine. A thorough understanding of the nature of the wind, as well as signal processing and wind measurement principles, are mandatory for developing accurate estimation techniques that enable successful preview control algorithms.



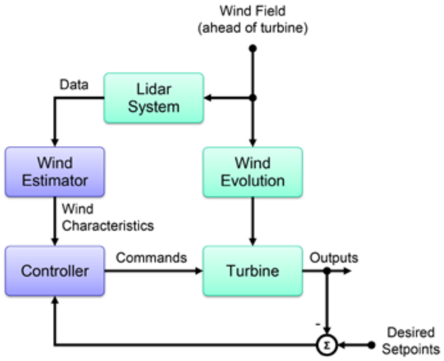
Example lidar configurations: A lidar mounted in the hub of the two-bladed turbine (in the foreground) measures wind speeds by scanning multiple circles in front of the turbine. A nacelle-mounted lidar on the three-bladed turbine (farther away) measures wind speeds by focusing three beams at different locations in front of the wind turbine.

Control Challenges

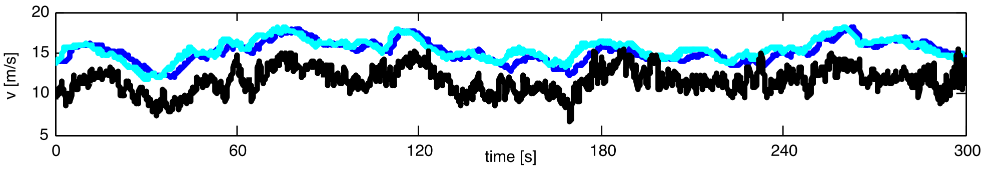
Control strategies need to be robust to the changing information quality of preview wind measurements and the long-term uncertainties present in wind modeling assumptions. The highly flexible turbine structure reacts to disturbances in many ways; thus, baseline controllers must be enhanced by added feedback loops to damp dominant tower and blade modes. Further application of preview control must address multiple complex control goals while coping with changing information quality.

Estimation Challenges

Extracting information from measured lidar data is challenging for several reasons. First, the incoming wind is an evolving three-dimensional vector field. Second, current lidar systems can only detect the speed of aerosols in the line-of-sight direction of the laser beam, which makes exact detection of the three-dimensional wind field impossible. Third, the turbine itself has an (induction-zone) effect on the wind approaching it. In the near term, estimating simplified wind characteristics such as the rotor effective wind speed can be useful for control design. In the long term, estimating more complete incoming wind field information may further improve control performance.



General block diagram of preview control of wind turbines



Rotor effective wind speed estimated from turbine data (dark blue) and preview wind measurements from lidar data (light blue). Single-point wind speed measurements from a nacelle anemometer (black) show reduced speeds due to the induction-zone effect.

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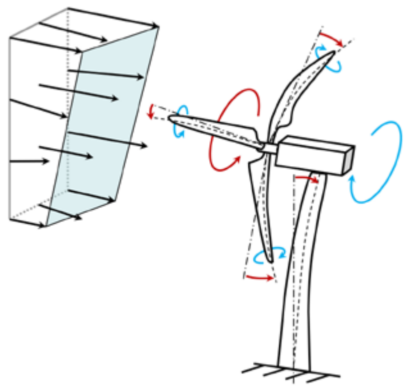
Controller: Current State of the Art and Initial Results

Traditional feedback controllers for wind turbines consist of several single-input, single-output (SISO) loops. They are disturbed by diverse wind characteristics, and wind preview measurements can be used to improve performance. In high wind speeds, preview control can assist the blade pitch controller in regulating the rotor speed as well as mitigating structural loads. This can lead to lower operational and manufacturing costs. Basic feedforward controllers have already been tested successfully on real wind turbines, and more advanced "optimal" controllers such as model predictive controllers (MPCs) have been shown to achieve higher load reductions in simulations.

To reduce the structural loads introduced by the inhomogeneous wind over the rotor disk, the blades are often pitched individually based on blade bending measurements. Several feedforward and MPC-based controllers show further load reductions if the blade-effective wind speeds or the wind shears are known in advance.

Although optimizing energy production has also been addressed, assisting the generator torque controller in low wind speeds is challenging due to its nonlinearity, and only minimal improvements have been achieved with preview control. More promising are approaches to prevent shutdowns due to overspeeding and to use wind direction preview to improve yaw control.

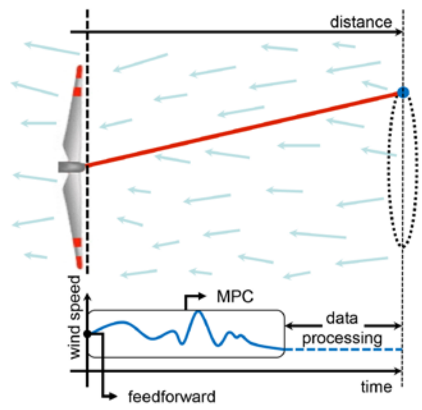


The wind vector field is reduced to rotor-effective wind speed and horizontal and vertical shears. Main turbine modes (red): rotor motion and tower and blade bending. Control inputs (blue): blade pitch angles and generator torque.

Estimator: Current State of the Art and Initial Results

Wind characteristics (e.g., wind speed) are usually predicted from the raw data measured in front of the turbine using reduced-order models of the wind and lidar system. Initial preview controllers have generally assumed that the turbulence in the flow is unchanged as the wind approaches the turbine at the mean speed, the estimate of which is continuously adjusted.

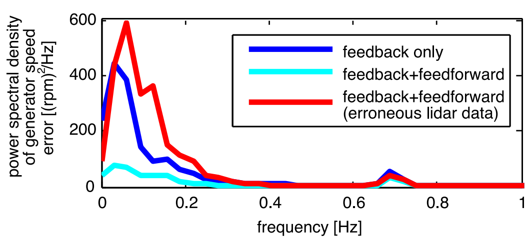
Comparing the wind prediction to the delayed disturbance estimate from turbine data and models reveals that only low-frequency measurement data are correlated to the wind sensed by the turbine. This has been confirmed by theoretical correlation models, which can also be used to optimize the lidar scan configuration and to design optimal prefilters. Filtering is necessary to avoid harmful control action due to measurements at uncorrelated frequencies.



Lidar measurements at a fixed preview distance are used to predict the incoming wind. Some feedforward methods use only the expected wind speed at the rotor plane, whereas more complex methods such as MPC use the entire preview.

Next Steps/Continuing Challenges

Initial field test results of lidar-based collective-pitch feedforward control show significant improvement in speed regulation when wind speeds are estimated well. However, in the case of low correlation between the preview wind measurements and the wind speeds that affect the turbine, the feedforward controller has a negative impact. Therefore, adaptive elements in estimator and control design are crucial to improve preview control of wind turbines reliably and will pave the way to applying advanced multivariable controllers in the nonlinear transition between partial and full power production, where most of the structural loads occur. Furthermore, developing appropriate dynamic wind models and advanced estimators is necessary for successful individual blade pitch preview controllers on real turbines.



Field test results: Generator speed regulation can be improved significantly with feedforward control if there are "good" preview wind speed measurements.

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