Authors' Response to the Reviewer RC1 Comments on Manuscript WES-2024-184

April 23, 2025

Major comments

- **Comment 1** *Overall, the authors provide a good review of turbine control and an interesting concept that uses a combination of a wind speed estimate (WSE) and a LIDAR measurement to inversely solve for the ideal blade pitch and generator torque controls of the wind turbine.*

  Response. Thank you for the time and effort that you have spent on our manuscript.

- **Comment 2** *Many components of the controller (and the ROSCO baseline) are described in great detail but are not novel contributions in this article. Could those sections be streamlined for this audience?*

  Response. We shortened parts of Sections 2.5 and 4.2, while still keeping the introductions of concepts that are essential for controller design and keeping the manuscript accessible to a wider audience.

- **Comment 3** *The controller relies heavily on the C_p surface. It's an interesting result that using the same C_p surface in the wind speed estimator can relieve biases in the C_p surface. Are there constraints (smoothness, monotonicity) that are required to get a unique pitch and torque at each time step?*

  Response. We thank the reviewer for raising this important question, which may not have been addressed sufficiently clearly in the first submission. The generator torque in the NOR controller is always given through an explicit formula, as well as the blade pitch angle in Region 2, so there are no issues with uniqueness and existence of solutions. For the case of finding blade pitch angle is in Region 3, we have added Remark 4.1 to explain why the torque balance equation (36) always yields unique solutions.

- **Comment 4** *It is interesting that the authors don't use any time delay or buffering in their LIDAR measurements. This can be a source of difficulty when using LIDAR measurements. I'm guessing that the controller performance then changes with wind speed because the lead time of the LIDAR changes, while the lag time of the WSE should be relatively constant. I wonder if you are reporting better performance at high wind speeds because the lead time of the LIDAR is lower and similar to the lag of the WSE.*

  Response. In the first submission, we noted in the concluding section that the LIDAR signal could potentially be improved by buffering with a time delay based upon the wind speed. The reviewer's comment inspired us to investigate the improvements that might be obtained in this way, and these have been included in Section 3.3 of the revised paper as follows.

  Fu *et al* (2023) employed a buffer time given by equation (26). For NOR+I&I+LIDAR, we used (27), decreasing the buffer time by the delay of the I&I estimator, in order to equalize the lead time of LIDAR and the lag time of I&I. We found that this more accurate REWS estimate improved performance compared to the version without buffering, and we updated the results section based on these new simulations. Furthermore, we added Figure 8, which illustrates how the averaged LIDAR and I&I estimate is obtained, including the buffered signal as in Fu *et al* (2023) as well as our modification.

  Finally, we now also study different weightings of I&I and LIDAR than just a simple average. For that the buffer time is modified to (28). See Figure 14 in Section 6 for the results.

- **Comment 5** *The reporting of results in time series form could be improved. Right now, the reader must scroll between figures and pages to evaluate long time series with subtle differences. Is there a short, illustrative section of time that demonstrates the difference between your NOR controller and ROSCO. One that shows the impact of LIDAR measurements? Another way to demonstrate differences is by binning the results in time and plotting against wind speed.*

  Response.

  We thank the reviewer for this helpful comment and have added several new figures to better illustrate the differences between the controllers. Figure 8, which we mentioned in our response to Comment 4, compares the different wind speed estimates. Figure 13 compares ROSCO, the LAC of Fu *et al* (2023), and NOR+I&I+LIDAR on a 3 minute interval. This demonstrates how NOR+I&I+LIDAR achieves significant reductions in tower and blade DELs and pitch rate. Figure 12 shows the results binned in time and plotted against mean wind speed.

- **Comment 6** *How exactly are you limiting the maximum thrust and fatigue loads to the levels in Section 2.5? What part of the controller (Algorithm 1) contributes to fatigue load reduction? The reduced variation in generator torque? A control engineer in practice will want to adapt these loads, and see the downstream effect on power. Are you able to do this with your control scheme? This would be an interesting result of the control concept.*

  Response. Regarding the limiting of the maximum thrust, this is achieved by the same peak shaving procedure used in ROSCO, where a minimum pitch schedule is calculated that limits thrust force below a certain threshold. The pitch angle output of the NOR controller is always at least this minimum pitch schedule; it is equal when the controller operates in Region 2 and higher when in Region 3 (due to the monotonicity of the C_p surface).

  The fatigue load reductions are indeed obtained largely by reducing the variation in generator torque and blade pitch controls. This is achieved by NOR's seamless switching between Regions 2 and 3, where at any time exactly one of the torque and pitch controls is saturated, and these control signals are continuous in time across the region switching. Assuming that the wind speed estimate is perfectly accurate, the closed loop has the same first order stable dynamics $\dot{\Omega} = \mu(\Omega_{\text{ref}} - \Omega)$ it is designed for in either region. This is further enhanced by using LIDAR in both regions. When switching from Region 2 to 3, the torque control increases sooner due to LIDAR, and the pitch control is smoother as a consequence. This is illustrated in Figure 13, which we added as part of this revision, where the effect of this smoother torque and pitch actuation on tower and blade loads is apparent. Specifically the averaging of I&I and LIDAR creates a low variation estimate with little high frequency content, which leads to smoother pitch and torque controls and, consequently, lower DELs. We adjusted several sections of the manuscript to make these facts clearer, particularly in the introduction, Section 4.1 (on NOR) and conclusion section.

  Lastly, we agree that it is desirable to adapt fatigue loads directly in the design of the controller, and then investigate their impact on the power generation. NOR permits a trade-off between rotor speed tracking performance and actuator usage by adjusting controller gains, as well as permitting trade-offs between thrust-related DELs and power sacrifice by adjusting maximum thrust in peak shaving.

Minor comments

- **Comment 7** *Line 175: there is, in most cases, a power sacrifice near rated power when using peak shaving control.*

  Response. We updated the formulation in Line 175 to clarify that due to the flatness of the C_p-surface (see Figure 1) at low θ, this power sacrifice is relatively small.

- **Comment 8** *Section 2.5: I don't understand your units on the fatigue loads. Are these DELs? They should have the same units as the load, N-m. What are the nominal loads of the baseline control? How do these compare?*

Response. These values were intended to be typical maximum blade tip and tower top displacements (in metres, not DELs), to give the reader an idea of the extent of the bending. To avoid confusion, we removed these figures.

- **Comment 9** *Results: it may make more sense to only compare RMS rotor speed error above rated wind speeds.*

  Response. We agree and changed our formula for the RMS error on page 24 to only account for times when the REWS is above rated.

  Comment 10 *L498: Should $\hat{M}_a$ have $\hat{v}_x$ in it?*

  Response. Our intention here was to introduce the function $\hat{M}_a$ of rotor speed, wind speed and blade pitch angle, which differs from the actual aerodynamic torque model M_a. Nevertheless, we changed it to $\hat{v}_x$ and added a short sentence to explain the role of $\hat{M}_a$.

Editorial comments

- **Comment 11** *openFAST should be OpenFAST.*

  Response. fixed.

- **Comment 12** *Figs 4 and 5 could be combined; they look very similar to the ones in the ROSCO paper.*

  Response. done.

- **Comment 13** *The capitalization and font size in figures should match the text. Also there are labels like "windspeed" that should be "Wind speed (m/s)," for example. Fig 5 has a legend with a variable, and it's not defined in the caption.*

  Response. We adapted the capitalization in several figures. Many of the figures with oversized font were generated with the two column version in mind to be the size of one column. We will make sure to appropriately format the figures for the final version.

- **Comment 14** *When substituting equations, it could help the reader to add a few descriptive words referencing the equations from earlier.*

  Response. We made such adjustments in several places in the manuscript, particularly the appendices.

We again thank the reviewer for their very insightful comments that have lead to numerous valuable improvements to the manuscript. We have provided an acknowledgement of their contribution in the Acknowledgements section.