Authors' Response to the Reviewer RC2 Comments on Manuscript WES-2024-184

April 23, 2025

- **Comment 1** *The paper presents a wind turbine control design using the nonlinear output regulation (NOR) method to reduce fatigue loads. The topic is interesting and relevant, but the motivation could be more clearly articulated. Given that the authors have published similar work in 2021, it would be helpful to clarify the specific motivation for employing the NOR method in this study.*

  Response. We thank the reviewer for their generally supportive comments. Regarding our earlier work in this area, We added Remark 4.2, where the proposed NOR controller is compared to the EOR controller from our previous work, and the advantages are pointed out. We also adapted the abstract, introduction and conclusion to make the paper's novel contributions more apparent.

- **Comment 2** *The proposed controller maximises power output by tracking the rotor speed set-point, which is computed based on a static C_p surface and the optimal tip-speed ratio. This approach closely resembles the traditional $K\Omega^2$ law. However, unlike the $K\Omega^2$ squared method, the proposed approach relies on estimated wind speed, introducing additional sources of uncertainty. From an industrial perspective, this could be a potential drawback compared to the traditional method.*

  Response. We acknowledge and agree that heavily relying on a model for a controller is undesirable, and that controllers should either be designed without the need of an exact model or to compensate model errors. Note that the constant k in the $k\Omega^2$ method is computed from several parameters like the optimal tip speed ratio, optimal power coefficient and air density, which are subject to uncertainty. Any difference between reality and the model parameters may cause the $k\Omega^2$ controller to track a slightly wrong tip speed ratio. As our controller heavily uses the C_p surface, we understand the reviewer's concerns about the effect of model uncertainty.

  Additionally, when including LIDAR preview information, the LIDAR signal is subject to uncertainty and may have a bias compared to the actual REWS, i.e., usually be slightly higher or lower. In fact, our initial simulations with NOR using LIDAR or the averaged I&I+LIDAR estimate led to significant errors, where Region 3 average power was around 16MW when it should be 15MW. This indicates that our C_p surface (or LIDAR signal, or both) has significant bias.

  Nonetheless, even with imperfect model information, NOR is able to achieve good control performance, for the following reasons. Firstly, the combination of NOR+I&I compensates errors in the C_p surface, as detailed in Appendix A. Both I&I and NOR use the same C_p model. Suppose the power coefficients are assumed too high, then the I&I estimator overestimates the aerodynamic torque caused by any given wind speed. This leads it to underestimate the wind speed based on the actual aerodynamic torque's effect on the rotor speed. The NOR controller now works with an underestimated wind speed estimate and an overestimated C_p surface. These two compensate each other in the formula (4) for the aerodynamic torque, so that the torque and pitch controls (34) and (36) are computed based on the actual aerodynamic torque that the wind turbine experiences, even when the C_p surface is biased.

  Regarding biases in the LIDAR signal compared to REWS, we used the mean correction technique of the NOR+I&I+LIDAR controller, which is now described in the new Section 4.1.1. This extends the error compensating effect of NOR+I&I to NOR+I&I+LIDAR. The idea is that the resulting error corrected LIDAR signal has the same mean as the I&I estimate. This compensates any existing biases between LIDAR and the actual REWS, and makes it so that biases in the C_p surface for the NOR controller are compensated. Our simulations with NOR+I&I+LIDAR show very accurate power tracking in Region 3 (see Figure 12 of the revised version), which confirms that accurate rotor speed tracking is achieved despite mismatches in the C_p surface and the LIDAR signal.

- **Comment 3** *Additionally, the title suggests that the paper focuses on reducing fatigue loads, yet Algorithm 1 does not explicitly account for fatigue mitigation. Is this achieved through peak shaving* *or another mechanism? Providing further details on this aspect would strengthen the paper's contribution.*

Response. We apply the same form of peak shaving to all our controllers, therefore this is not the source of the fatigue load reduction that we found for NOR+I&I+LIDAR compared to ROSCO and the newly added LIDAR assisted controller (LAC). Fatigue mitigation is achieved by two things.

Primarily, the fatigue load reductions are 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 $\dot{\Omega} = \mu(\Omega_{\mathrm{ref}} - \Omega)$ 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; likewise in transitioning from Region 3 to 2, the pitch control decreases sooner. In both cases it 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.

- **Comment 4** *The paper also states that averaging the estimated wind speed with LIDAR measurements improves the estimation of low-variation real-time wind speed. It would be helpful to elaborate on why simple averaging was chosen over a weighted sum. What was the motivation behind this decision?*

  Response. In the first submission, we used a simple average for simplicity, but as part of this revision we studied the effect of different weightings. This is theoretically introduced at the end of Section 3.3. Figure 14 shows the effect of different weightings of I&I and LIDAR for NOR on performance. Overall, equal weighting performs best. This is likely due to the I&I and LIDAR estimates having similar variance/high frequency energy. When taking a weighted mean between two identically independently distributed random variables, the variance of the mean is minimized at equal weighting. Presumably this is the reason why our equally weighted average works best, because it leads to minimal variance/high frequency energy in the wind speed estimate and consequently pitch and torque commands, which not only reduces actuator usage, but also leads to smoother control with less extreme peak torques and thrusts, which reduces fatigue loads (this is also demonstrated in the newly added Figure 13).

- **Comment 5** *Finally, while the results show that the proposed method outperforms ROSCO, this is perhaps expected given that it incorporates a DAC approach and LIDAR. A more informative comparison might be against other LIDAR-assisted control methods to better assess the advantages of the proposed approach.*

  Response. We thank the reviewer for this very helpful suggestion. We undertook a search of the recent literature on LIDAR assisted control (LAC) and found that the recent method of Fu *et al* (2023) would be suitable for including in out performance comparisons. Thus we have added Section 4.3 to briefly describe this LAC modification of ROSCO. We also improved our I&I+LIDAR estimate based on this existing research, particularly buffering our LIDAR estimate as described in Section 3.3 of the revision. Our simulations show that NOR+I&I+LIDAR matches the LAC method of Fu *et al* (2023) in rotor speed regulation, but reduces pitch rate by around 40% and blade flapwise lifetime DEL by 6.7%, which, with a Wöhler exponent of 10, roughly doubles the lifespan. In all other lifetime performance metrics NOR+I&I+LIDAR matches or is superior to the LAC method of Fu *et al* (2023). We also compare the performance at mean wind speed of 18m/s in isolation; this is shown in Table 7 of the revised manuscript and discussed in the revised results section.

We closely replicated the blade flapwise DEL and rotor speed tracking improvements that Fu *et al* (2023) reported for their LAC method compared to feedback-only ROSCO. NOR+I&I+LIDAR roughly doubles these reductions in tower fore-aft and blade flapwise DEL, and also reduces pitch rate significantly. Hence, our proposed controller leads to significantly better performance than the existing LAC method in lifetime metrics as well as in Region 3 in isolation. The improvements are due to NOR's ability to use LIDAR preview information in both wind regions and in a smooth manner at the region switching. Furthermore, the I&I+LIDAR average is mainly responsible for the large reduction in pitch travel and part of the fatigue load reductions.

- **Comment 6** *Given these points, I believe the paper would benefit from further clarification and refinement. I encourage the authors to address these concerns, as doing so would strengthen the manuscript significantly.*

  Response. We thank the reviewer for their valuable suggestions. They have helped us to better expressing the contributions of our work, and we believe that adopting the suggestion to include a LAC method in our comparisons has provided further evidence of the performance improvements that the NOR method can provide, relative to control methodologies from the recent literature.

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.