A data-driven approach to the design and implementation of retrofit lidar assisted control systems

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Overview

- We report a successful and safe demonstration of load reduction using lidar assisted control (LAC) on an active stall turbine on a commercial wind farm*
- The project dimensions and commercial requirements were a test bed for concepts aimed at reducing the barriers to commercial LAC deployment
  - Utilisation of a data-driven design approach
  - Use of a simplified lidar prototype
- Baseline and lidar-assisted load measurements were aligned with design simulation predictions across a range of operational conditions.
- The prototype wind lidar was stable and flexible with performance matching or exceeding expectations

*This work is part of the 'RELACs' collaboration between RES, ZX Lidars and KK Wind Solution

Mitigation of Barriers to Commercial LAC Deployment

Barrier / Dimension	Project Approach

Design: Complexity, safety, scalability	• Design goals and restrictions
	    • Safely reduce fatigue loads with minimal to no AEP impact
	• Streamlined and simplified design process
	    • Data driven design (avoid the necessity of aeroelastic models)
	    • 'SLOW' turbine model
	• No modifications to the existing feedback control
	• Region 2 operation: no operation in active stall region (safety)
	• Multistep test and deployment protocol:
	    • Simulation → passive → hardware in the loop → staged active deployment
	• LAC activation fade in and fade out control limits (safety)

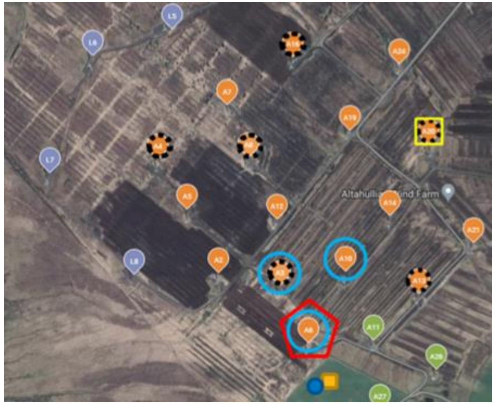
Turbine integration	• Lightweight, nacelle mounted lidar, with minimal physical connections (PoE) • Simple data interface: 10 Hz Modbus TCP/IP Rotor Effective Wind Speed (or filter code) • FF loop provided a zero-mean blade pitch angle offset to the existing FB pitch angle • Safety interface design and testing

Deployment: Quality, reliability, availability, maintainability	• A prototype lidar with high data availability and no moving parts
	    • Single lidar enclosure with small footprint
	    • No lidar maintenance requirements over extended design life
	• Exploration of fade in/fade out control implementation
	    • Safe and graceful handling of periods of reduced lidar availability

Project outline

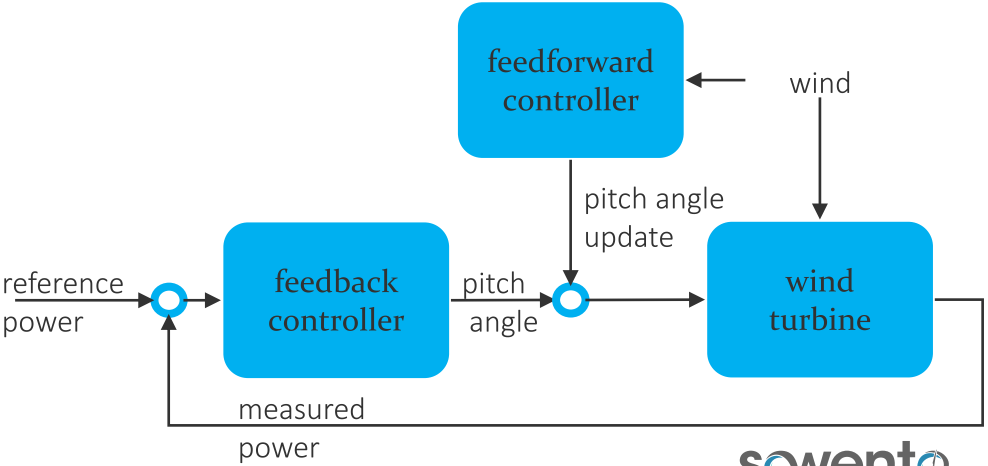
The test turbine was part of an operational wind farm in NW Europe

- 1.3 MW, fixed speed, active-stall
- Hub height 68 m, rotor diameter 62 m
- Strain gauge package was installed and signal integrated into SCADA



The design target for LAC was to reduce fatigue loads on the tower and blades with minimal impact on AEP

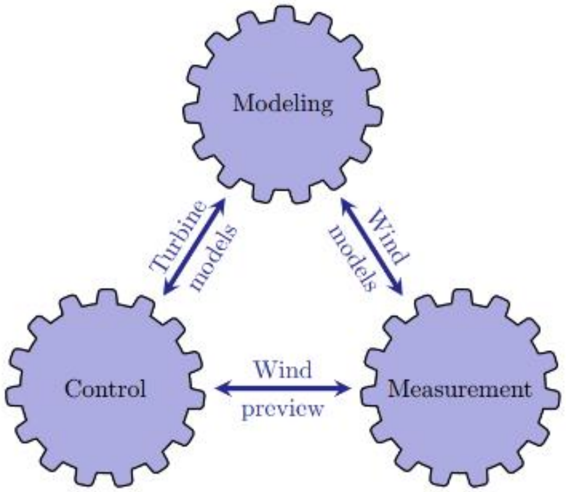
- Load reduction can be used to extend wind turbine lifetime and hence reduce LCOE



Safety and verification were paramount throughout the design, test and implementation phases

Retrofit LAC: Test and verification

- Turbine integration
- Turbine and lidar 10Hz data synchronization
- SLOW model verified
- Lidar wind speed preview quality assessment
  - Coherence bandwidth
  - RMS error
- Simulation and *in situ* open-loop (passive) testing
- Hardware-in-the-loop bench testing
- Phased LAC deployment
  - 0% → 50% → 100% active
  - Safety tested at each phase
- Load reduction performance test



Data-Driven: SLOW and Lidar preview

ZX Lidars

For retrofit, a full aerodynamic wind turbine model and/or a SCADA REWS estimate may not be available:

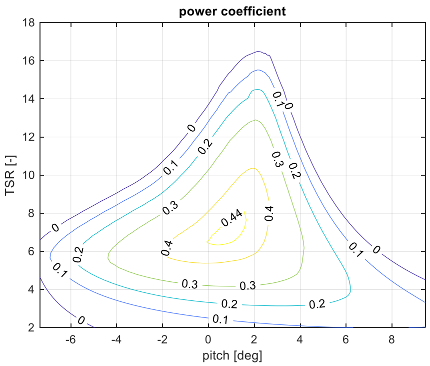
- A Simplified Low Order Wind (SLOW) model of the wind turbine and feedback controller was used to design the Lidar Data Processing and the feedforward controller
  - The SLOW model was verified using 10Hz SCADA data
  - LAC was designed to modulate the existing feedback pitch control (provide a “delta pitch” request signal that was added to the feedback controller pitch)
- A prototype nacelle-mounted wind lidar was used for Wind Field Reconstruction
- To determine the wind preview quality of the prototype lidar in the absence of any SCADA Rotor Effective Wind Speed estimator, we used wind measurements from a scanning nacelle-mounted lidar for a period ahead of the LAC deployment
  - 50 Hz CW, beam scanned at 1 Hz (ZX TM)

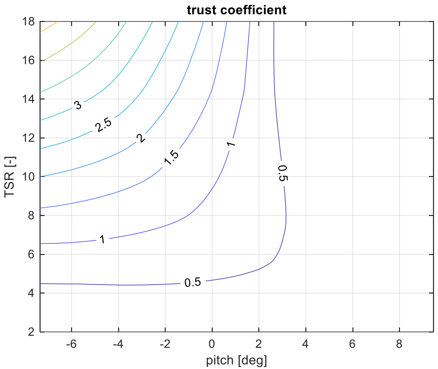
The SLOW model is simplified (but not simple!), needs fewer inputs and can be analyzed orders of magnitude more quickly than higher order models

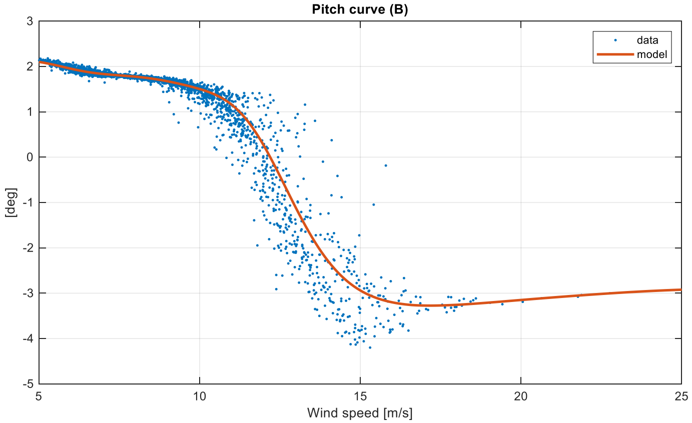
sowento

Simplified Low Order Wind (SLOW) turbine model

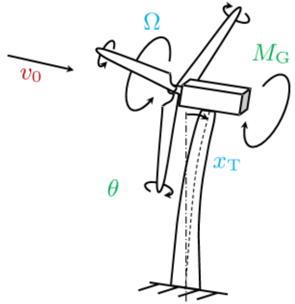
$$J\dot{\Omega} = M_\mathrm{a} - M_\mathrm{G}$$
$$m\ddot{x}_\mathrm{T} + c\dot{x}_\mathrm{T} + kx_\mathrm{T} = F_\mathrm{a}$$







- Reduced rotor and tower motion model
- Parameters from basic data (e.g. tower top mass, rotor radius)
- Use of LM29 Blade designed for Stall-regulated turbines
- Aerodynamic properties with Qblades from NACA airfoils and public report
- Adjustment of pitch vector to fit to data



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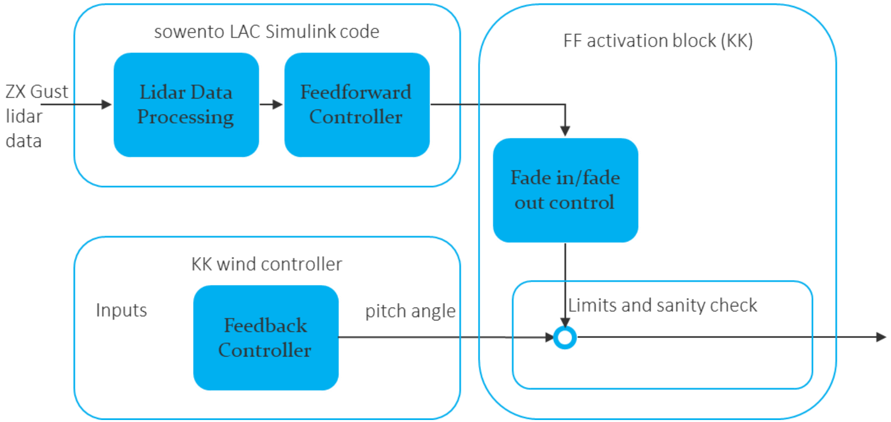
Lidar Assisted Control Overview

Simplified Block Diagram of LAC System



Three main blocks:

- Existing feedback (FB) controller
- New feedforward (FF) controller
  - The lidar, lidar data processing (LDP) and controller.
- Safety interface (FF activation block)

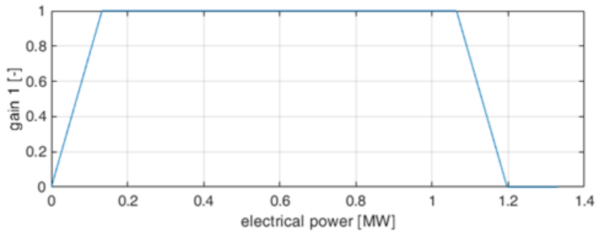
Feedforward controller generates a zero-mean pitch angle modulation

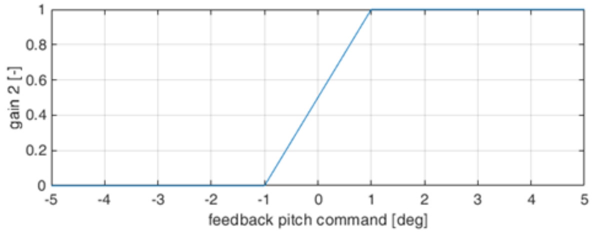
- Strict (conservative) quality control was applied to wind measurement data
- Lidar Data Processing applies a low pass filter to remove uncorrelated wind field frequencies and a high pass filter to remove lidar measurement bias

(A notch filter at the tower eigenfrequency is also applied to eliminate the possibility of resonances)

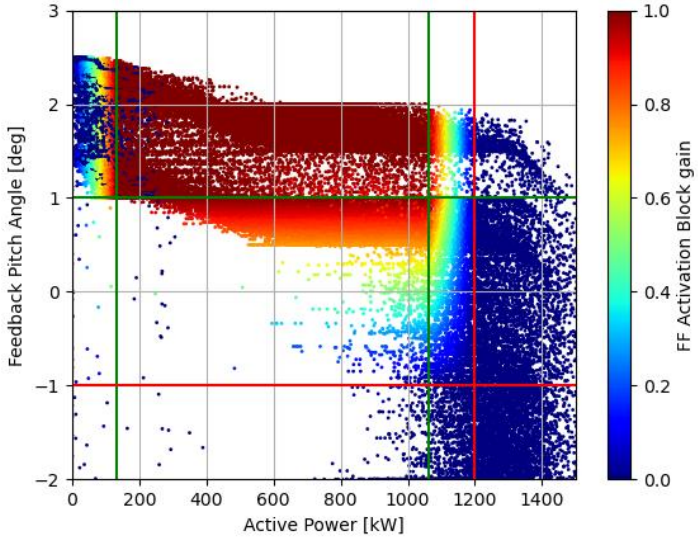
Safety first!

- What if the lidar signal is unavailable/inaccurate/imprecise?
- An intensive Failure Mode and Effects Analysis (FMEA) led to the following restrictions for the active stall turbine:
  - The original feedback controller was unaltered (no retune)
  - Feedforward modulation (“delta pitch”) was limited to ±2°
  - FF/FB signal integration controlled by an activation/safety block
  - LAC was not permitted to drive the pitch angle beyond 2°
  - LAC was conservatively and gracefully faded out during periods of reduced lidar signal availability
- Design simulations were checked both passively and actively
- Extensive hardware-in-the-loop bench testing
- Feedforward activation and operation was field tested against expected bench test behavior
- Result of the FMEA actions was that any issues with lidar data led to a reduction in performance but avoided any safety issues



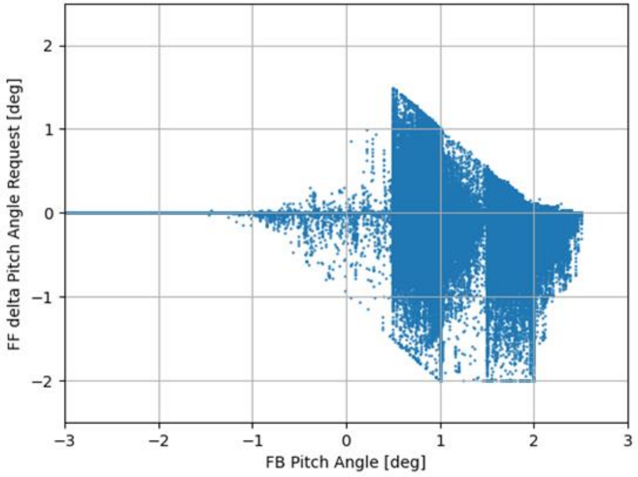


Operation of Activation Block



- The plot illustrates the Activation Gain block
- FF gain fades out for active power below 10% and above 80% of rated power and for (FB) pitch angles less than +1°
- Active stall blade dither is clearly visible

(The blue dots at low active power are from periods of small generator operation where LAC was disabled)



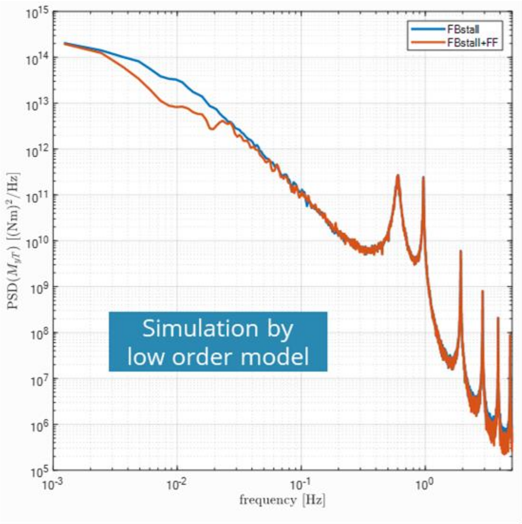
Results

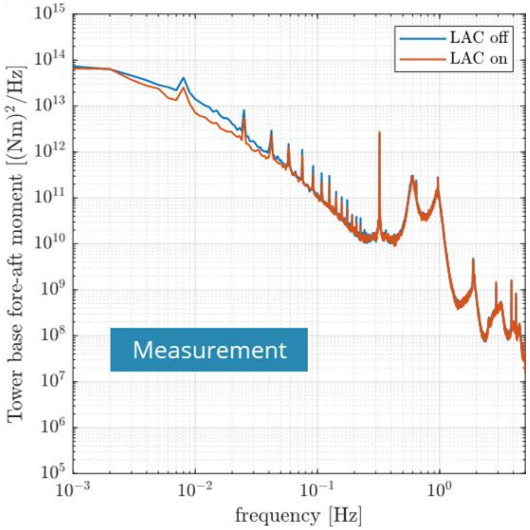
The LAC scheme was "toggle-tested" with a 50-minute interval to best match atmospheric and turbine operation state for "LAC on" and LAC "off" periods

Strain gauge data was processed to extract fore-aft tower base bending moments

The resulting data was inspected as spectra and processed with the rain flow algorithm to calculate Damage Equivalent Load (DEL)

An early result demonstrated qualitative agreement between model and measurements and that LAC was having a positive effect

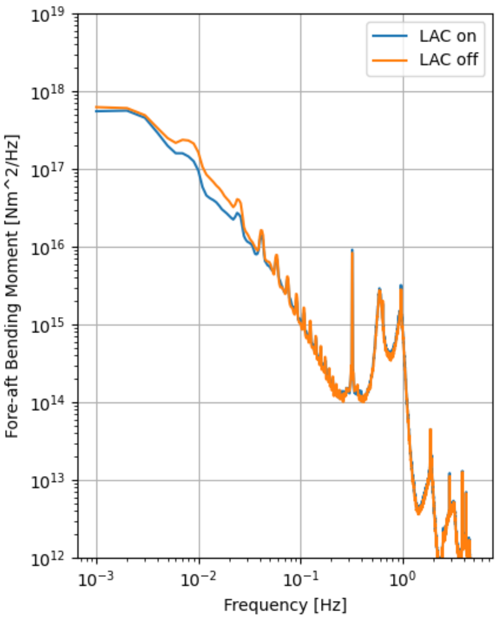


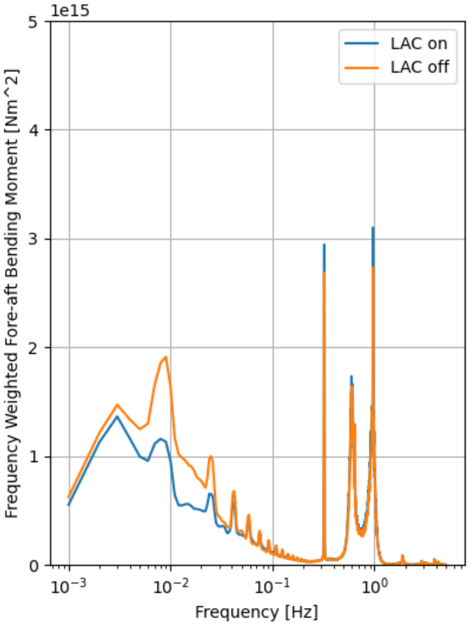


Results: Spectrum of Tower Base Fore-Aft Bending Moment

Each 50-minute block was split into sections of 1,000 seconds and filtered for mean wind speeds between 7.0 and 10.0 m/s (based on the nacelle cup)

Data below is otherwise unfiltered and includes wakes and periods of lower lidar availability



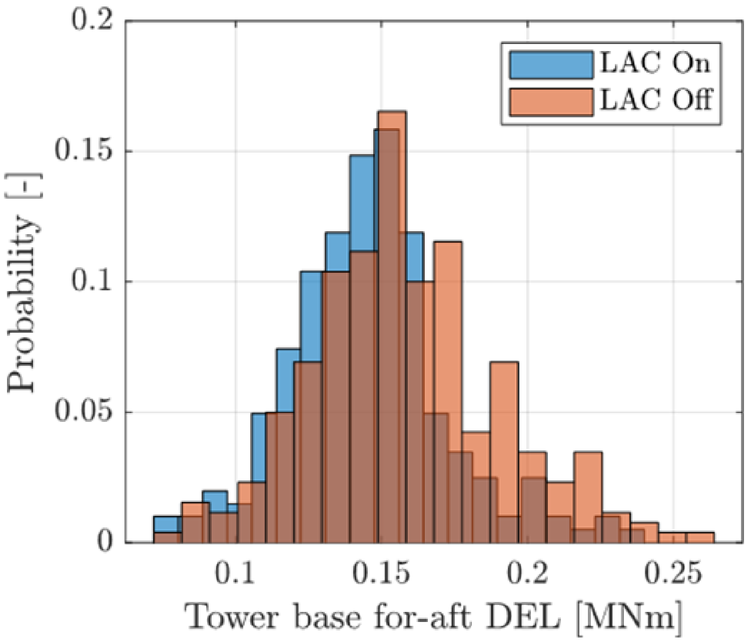


Left: power spectra of tower base fore-aft bending moment

Right: Frequency weighted spectra (the area under the curve is proportional to the variance in the time domain)

DEL reduction is proportional to lidar availability, but was achieved over the trial period despite operation restrictions and the use of a very simple, low power lidar prototype

Histogram of Tower Base Damage Equivalent Load



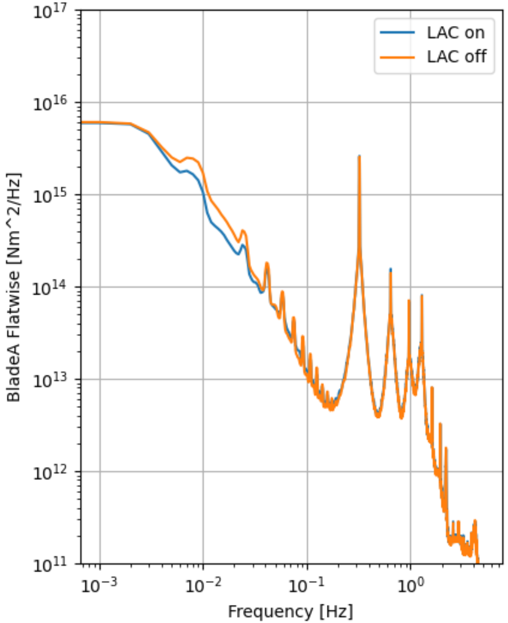
Over lapping histograms of DEL for each 1,000-second period clearly illustrate the DEL reduction when LAC is applied

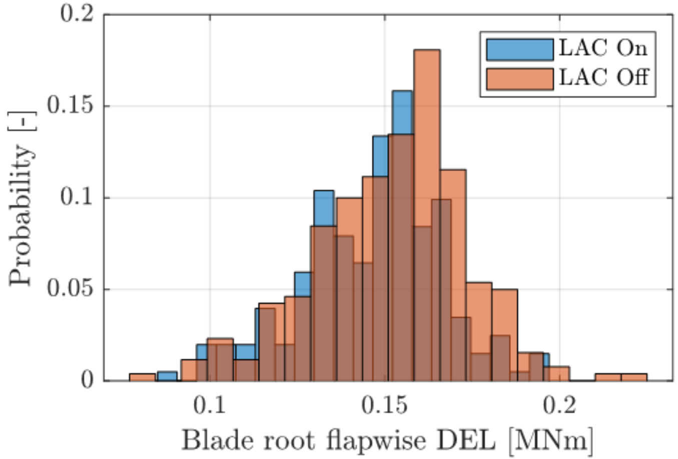
Provisionally estimated DEL reduction of 8.6% for wind speeds between 7 and 10 m/s

Spectrum and Histogram of Blade Root Flapwise Bending Moment

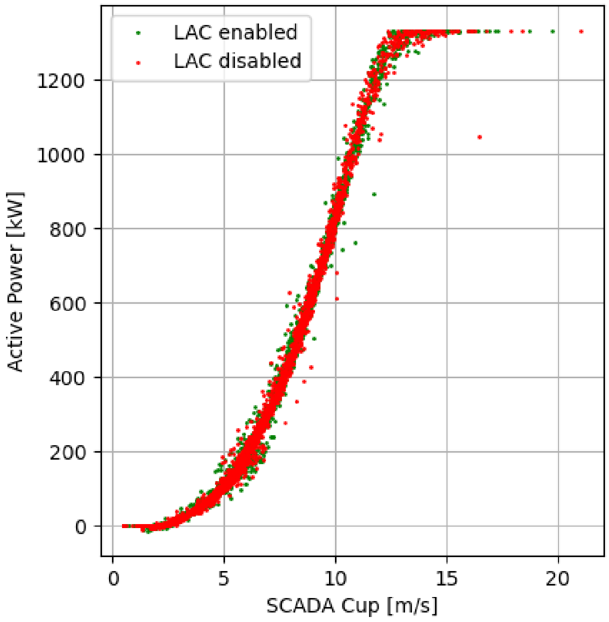
As for tower fore-aft bending moment, a consistent reduction in DEL was observed for the blade root flapwise load

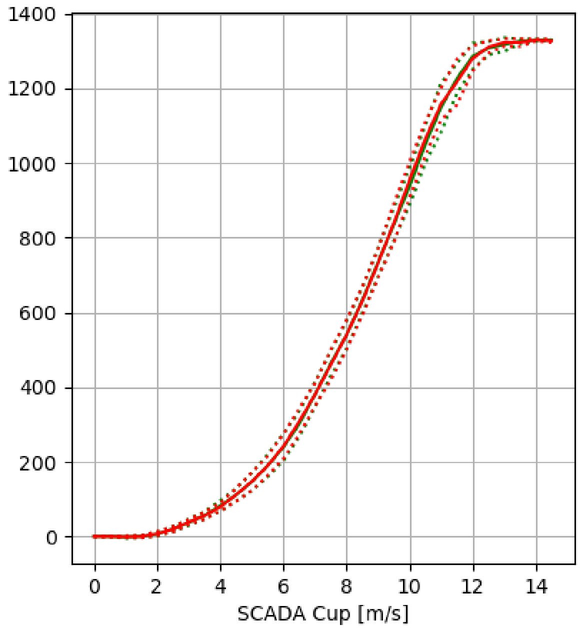
Provisionally estimated DEL reduction of 4.4% for wind speeds between 7 and 10 m/s





Power performance





- Data was selected for periods of normal turbine operation (SCADA)
- The resultant data was down-sampled to 10-minutes and power curves plotted using the nacelle cup as the wind speed reference
- No detectable effect on AEP was observed

Lidar Availability and Pitch Activity

LAC availability was 80 to 90% during periods of turbine operation and suitable wind speeds

- 100% lidar system availability
- This allowed for demonstration of LAC benefit (DEL reduction is proportional to lidar availability)
- Not representative of potential performance due to conservative data filtering, fade in/fade out criteria and reduced power prototype lidar
  - For a refined design, availability over 95%+ would be expected

Expected and actual pitch activity was increased by 40%:

- Analysis complicated by active-stall wind turbine pitch dither
- Future possibility to disable dither during periods of LAC and reduce or eliminate the higher pitch activation

Next steps

The trial provided robust and consistent results even in sub-optimal operation conditions

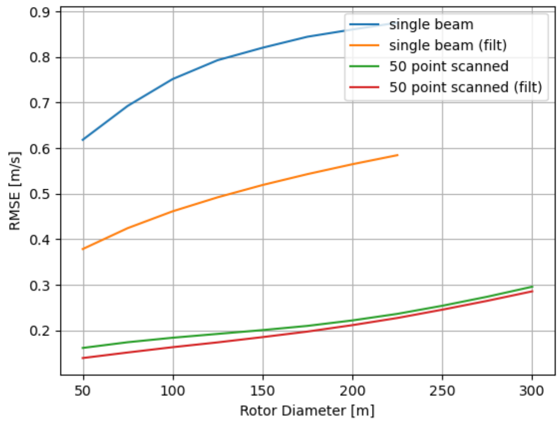
Expand the limits and operation on the active stall turbine

- operation limits, fade in/out, dither, region 3 operation

Apply the design/deployment process used here but on variable speed, pitch-mediated turbines:

- Region 3 operation
- Pitch activity reduction, rotor speed smoothing
- Refine the fade in/fade out lidar and feedforward control behaviour
- Optimized (retuned) feedback controller
- Spinner mount the existing lidar system for improved preview quality and data availability

Expectation: Improved load reduction benefit



(Results using code from Simley *et al*, IEA WIND Task 32 Workshop #2, 2016, illustrate that single-beam is feasible for smaller rotors but that scanning/multibeam is required for modern turbines)

Conclusion

- FOIK demonstration of lidar assisted control (LAC) technology load reduction as a retro-fit on an active stall turbine (on a commercial wind farm)
- The LAC benefit was aligned with the design predictions and was measurable across a range of operational conditions
  - Spectra and DEL reduction with potential lifetime extension and neutral measured AEP impact
- Multiple LAC ‘barriers’ explored and mitigated using a data-driven design approach
- Opportunities to expand the work to a variable speed, pitch regulated turbines using lessons learned, the same core lidar technology and a mirrored design process.
- Field trial testing provides an avenue to increased utilization of lidar assisted control technology

Acknowledgements

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- This work is part of the ‘ReLACs’ collaboration between RES, ZX Lidars and KK Wind Solutions for the development of products to upgrade the performance of existing wind farms
- ZX and sowento would like to specifically thank the collaboration partners and TRIG, the British investment trust where the trial took place, for their contributions and continued support

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