Shooting into the Wind with Laser Beams

Lidar Wind Measurements in the Offshore Test Field open up New Horizons

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Project information: Development of LiDAR measurement techniques for the German offshore test site (LIDAR I)

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Project partners:
- ForWind – Center for Wind Energy Research, University of Oldenburg
- FGW – Federation of German Windpower
- German Aerospace Center (DLR)

Project information: Development of nacelle-based lidar technology for the measurement of power performance and the control of wind turbines (LIDAR II)

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Project partners:
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- University of Stuttgart, SWE – Stuttgart Wind Energy
- FGW – Federation of German Windpower

Wind turbines are getting taller and taller, with hub heights of 120 to 150 metres and more now quite common. The taller the turbine, the greater the work involved in the erection of met masts that can measure the wind conditions so that wind turbines can be operated efficiently. At the same time, turbulent airflow determines the wind conditions at such heights. On land the wind turbines are also often situated in complex terrain: hills, valleys, mountains or even buildings in the wider surroundings also ensure complicated wind flow patterns. New measuring methods are needed in order to be able to make more reliable statements about such wind conditions at blade tip heights of 50 to 300 metres. One of the most promising procedures to date is shooting laser beams into the wind!

While this might initially sound like something out of "Star Wars", not only can it be used to measure the wind speed directly in front of the rotor, but also to capture complete wind fields along with their currents and the resulting loads on the wind turbines, thereby enabling better micro-siting when planning a wind farm. This applies both offshore and onshore. It is thus no wonder that the lidar research is one of the RAVE Initiative's largest projects. On completion of the four-year Lidar I project the scientists continued their research in the follow-up project Lidar II.

12.1 How It Works

Lidar (light detection and ranging) devices shoot laser beams into the air at the speed of light. There they can hit even the smallest particulate material, such as dust particles, that are almost always to be found in the air: the so-called aerosols. The most frequently occurring aerosols above the sea are salt crystals. These particles always move in the current wind direction, and when hit by a laser beam they reflect a fraction of the laser light back towards the lidar device, which then evaluates the signal. If pulsed laser beams are used, it is possible to measure the wind at different distances and heights above the ground or surface of the sea simultaneously, just as radar is used to measure the distance to an object. This thus gives not just one wind speed at one position, but a complete "wind field" in the surrounding air. In other words, it can do a lot more than the conventional wind meters usually found in meteorological stations, which can only capture and measure at one single point.

12.2 Not Just Research for Research's Sake

So we have an abundance of topics, with an abundance of institutes involved. Lead partners in the research project "Lidar Wind Measurements for the Offshore Test Field" were Stuttgart Wind Energy (SWE) at the University of Stuttgart and the ForWind Center for Wind Energy Research at the University of Oldenburg. The German Wind Energy Institute (DEWI) was called in for power curve measurements, while the German Aerospace Center (DLR) supported the project both with its knowledge of lidar and with its own long-range lidar. While cooperation between the wind industry and the aerospace industry might otherwise offer room for improvement, on the lidar project it was conspicuous.

The Federation of German Wind Power (FGW) played a lead role in passing on the research findings to the German industry and in the guidelines resulting therefrom. All in all, this was not just research for the sake of it, but research that has direct consequences for the wind industry and for the further development of wind energy technology. Sometimes it is only possible to see the real value of the work in hindsight, which is why independent research is so important.

12.3 Lidar Technology

12.3.1 Snowfall Test in Swabia

Almost 1,000 kilometres south of Alpha Ventus; not on the high seas, but in truly complex terrain: the first test for the research project with a lidar instrument took place in 2008 on the roof of Stuttgart Wind Energy (SWE), not far from the Swabian Jura. The test used a French-made instrument that can measure winds of up to 30 m/s at heights of 50 to 200 metres (Fig. 12.1), hence far above the normal cut-out wind speed for wind turbines. It can also capture several measuring heights simultaneously. The reference instrument used later for comparison and to investigate the wind in the wake flow of wind turbines was a pulsed Doppler wind lidar with 2 µm wavelength from DLR in Bremerhaven.

The French lidar works on the ground, so it's not attached to the nacelle of a wind turbine. The first test on the roof of the institute in Stuttgart was carried out in wintry conditions (Fig. 12.2). There was snow and ice all around, but the instrument worked. The lidar was modified by SWE and fitted with a more flexible scanner unit.

The lidar emits up to 10,000 laser impulses or shots in the four main wind directions (north, south, east, west) and at up to ten predefined heights. Each measurement cycle takes half a second. A further half-second is needed to calculate the readings received, to turn another 90 degrees to the next compass point and then to shoot the next laser beam.

Fig. 12.1 Measurement principle of the lidar system. © Leosphere

Fig. 12.2 Initial test on the roof of Stuttgart University. © SWE University of Stuttgart

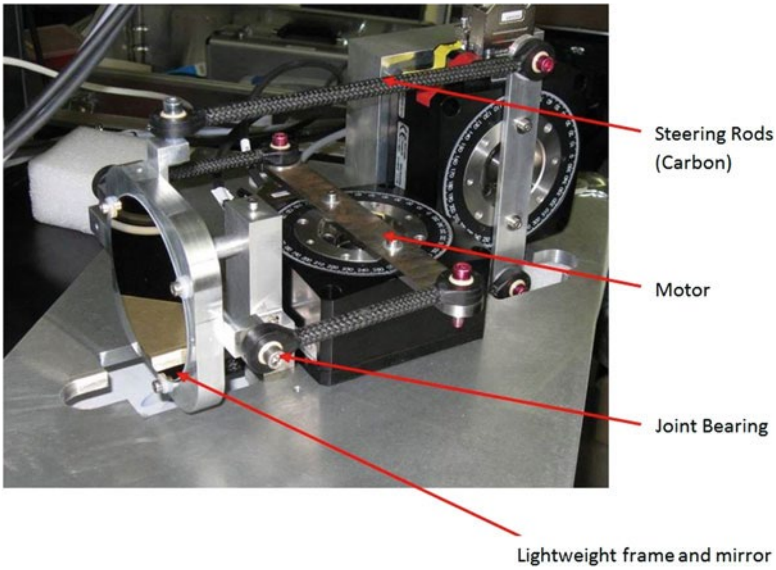

Fig. 12.3 View of the SWE scanner system. © SWE University of Stuttgart

The course of the scan describes the volume of a cone. The whole measuring period for six different measuring heights is just 1.5 seconds. Two things are important for a precise measurement: first a particular minimum concentration of aerosols in the air needed to reflect the beams, and secondly a high laser power in order to get a clear signal from the backscattered light beams.

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12.3.2 Scanner System and Specification Offshore

Scanner and reflector are the crucial factors for developing a simple lidar to reach new heights – for use on the nacelle of a wind turbine. A scanner system with a control unit was developed for nacelle-based lidar measurements (Fig. 12.3). The reflector is used to steer the laser beam in any desired direction.

The scanner and control unit were integrated in a second casing that can be connected to the lidar. This way – depending on the assembly – you can capture the wind field in front of or behind the wind turbine – and in each case with a range of several hundred metres. Furthermore, the wind field is now captured three-dimensionally, resulting in a complete flow pattern. Thanks to the scanner and reflector it is possible to direct the laser beam in the desired, predefined positions. With several thousand laser shots within half a second it only looks like continuous blind shooting – but the points have in fact been clearly defined beforehand. The scanner in the lidar follows the predefined times and points. By measuring at five points along the laser beam you can measure the so-called "radial velocity". Parallel to this the researchers developed the necessary simulation software.

The initial test of the new nacelle-based lidar scanner system was not carried out on a rooftop in Swabia. The trial was done in 2009 near Alpha Ventus, but still on land: on the prototype of the Adwen AD 5-116 outside Bremerhaven, where the system was mounted on the roof of the nacelle. This was done quite traditionally, using scaffolding clamps and poles. With this experimental scanner it was now possible to use the lidar for measuring the power curve and the load measurements.

12.3.3 Wind Measurement Buoy on the Crest of a Wave?

The ground-based lidar also shows what it can do offshore: it was installed on the Fino 1 platform, but still ground based. There it also demonstrated a good correlation with the anemometer measurements from the met mast. It was also possible to achieve good availability of the instrument at all heights off-

Fig. 12.4 First measured prototype in Bremerhaven and the met mast. The lidar (not visible in the photo) is located about 10 m from the met mast. © SWE University of Stuttgart

shore as well. This is down to the high concentration of aerosols over the North Sea, which enables a better reflection of the laser beams. Incidentally, lidar instruments are also suitable for "offshore spin-off inventions" and lead to other developments. One example is a buoy the so-called "Floating lidar". These float on the waves and make it possible to carry out wind potential measurements offshore without the need for massive, stationary ground foundations.

12.4 The Burden of the Power Curve

12.4.1 From Wmo to Demo

A look back at the days before lidar: up to now the power curve for a wind turbine (▶ Sect. 20.5) was measured with a point measurement of the wind speed and wind direction, ideally with a distance from the met mast to the turbine of 2.5 times the rotor diameter – according to an International Electrotechnical Commission (IEC) guideline. The "power curve measured in accordance with IEC" is the central benchmark for the wind turbine and the basis of the yield calculations. Measuring a power curve with these parameters at locations with weaker wind strengths can require several up to nine months until enough data for all occurring wind speeds can be gathered.

In the case of the Adwen AD 5-116 prototype in Bremerhaven the lidar was initially installed directly adjacent to the met mast (Fig. 12.4) – and the comparative values were very good. So the lidar does also work without met mast onshore (wmo).

For the offshore test it was once again back to the roof. The ground-based lidar system was erected on the roof of a container on the Fino 1 research platform in the North Sea, ten metres from the met mast (Fig. 12.5). Here it was easily possible to compare the data with that from the "conventional" cup and ultrasonic anemometers and wind vanes. In the case of the cup anemometer the availability at all heights was just short of 100 %, and with the ultrasonic anemometer it was 97.5 %. At all measuring heights on Fino 1 the availability of the lidar was 98 %. At the new windy height of 200 metres without met mast the availability dropped to 91 %. This is due to the fact that the signal-to-noise ratio decreases with increasing height – so here we need further development, especially powerful laser devices.

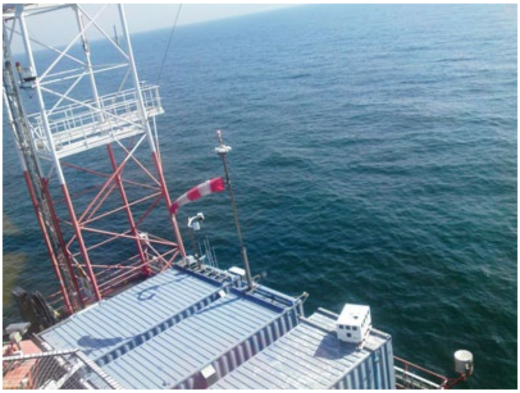

Fig. 12.5 Position of the lidar on the container (*right*) on the Fino 1 offshore research platform. © UL International (DEWI)

Peripheral Anecdote (I): A bit too hot
The sun and the north both have their own laws. When used on the Adwen AD 5-116 prototype in Bremerhaven the new lidar scanner worked for ten months without any problems. Well, almost without any problems. On hot summer days the temperature inside the casing reached 40 degrees Celsius, with the result that the software thought it had "a bit of a temperature" and so switched the whole system off automatically. To avoid this happening out at sea the lidar used on Alpha Ventus had a sunshade fitted.
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At met mast height the lidar achieved similarly good results as the conventional devices, not just regarding availability but also with the actual measurements. The offshore lidar trial on Fino 1 lasted one year. The ten-minute average readings showed over 99 % conformity with the anemometers. The discrepancies between lidar and anemometer are thus smaller than the measurement uncertainty of the met mast.

The wind profiles and turbulence intensities at sea are different from those on land. In this respect it may prove beneficial to differentiate between a power curve with unrestricted wind inflow and turbulence intensities of 5 to 10 %, and a power curve within a wind farm with significantly greater turbulence intensities. This could enable an easier measurement method using lidar within an offshore wind farm – and make a major contribution in ensuring that planners, operators and turbine manufacturers have a fast instrument for verifying wind power yields at their disposal.

The influence of the vertical wind profile and the turbulence intensity on the dynamic performance characteristics was also investigated. To this end, the lidar wind measurement was carried out at five different measuring heights within the rotor diameter of the Adwen AD 5-116. The capturing of the whole swept rotor area can improve the accuracy of the dynamic performance characteristic. This not only applies to the vertical wind profile – the course of wind speed and wind direction with the height – but also for measuring the turbulence characteristics across the whole swept rotor area.

12.4.2 Lidar on the Nacelle

Can you also get reliable power and load curves from nacelle-based lidar measurements? Here the lidar is not on the ground, but on the nacelle or directly on or in the spinner, e. g. on the roof of the nacelle as with the tests using the Adwen AD 5-116 near Bremerhaven. In the practical test the nacelle-based lidar system with scanner apparatus also achieved results highly comparable with those of conventional anemometers in this area of application. And that is not all: due to the lidar being on the nacelle it is possible to measure the whole wind field in front of a wind turbine for the first time; and not just the vertical wind inflow conditions "above and below", but the whole wind field across the gigantic swept area including the inclined flow (Fig. 12.6).

This not only provides a lot of new data about the movement of the wind, but possibly also a better understanding of the "interaction of wind and wind turbine". And with the inclined flow it identifies a cause for a weaker power yield or stronger, temporarily occurring loads on a wind turbine. It shows that with nacelle-based lidar wind measurement there is a good correlation between wind speed and power output of a wind turbine.

Nacelle-based lidar measurements can in any event measure the transient performance charac-

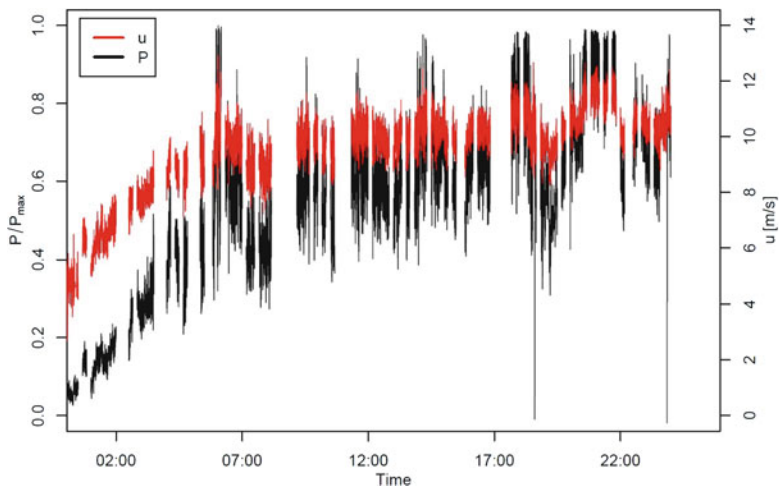

Fig. 12.6 Measured data for wind speed (*red*) at a distance of 116 m and the turbine output. © ForWind – University of Oldenburg

teristics as well as the power curve of a wind turbine significantly faster and in more detail than a ground-based measurement, because the measuring system turns with the wind direction – and thus also with the nacelle of the wind turbine. Provided of course that the lidar instrument in/on the nacelle is robust and powerful.

12.5 Turbulent Wind Fields in Front and Behind

12.5.1 Inflow from the Front, Initial Investigations into System Control

Gusts of wind, inhomogeneity of the incoming wind field (vertical and horizontal wind gradients, when the wind decreases near ground level, partial gusts) are currently the main load factors affecting wind turbines. This is expressed in terms of high load peaks and frequent alternating loads, with up to 100 million alternating loads in the lifetime of a wind turbine. At present, load reductions can only be actively achieved with control measures by changing the rotor speed or through collective pitch adjustment, after the wind impulse – i. e. the load impact – reaches the turbine. But at that stage the load has already hit the turbine or is already past! A fast wind field forecasting system within the short-term range of 5 to 30 seconds could help remedy the situation, an anticipatory and proactive system that relays the relevant information to the turbine control system before the wind reaches the wind turbine. Such systems have already been simulated – what is lacking is the practical implementation …

Peripheral Anecdote (II): Open the flap!
In the wind tunnel at the University of Oldenburg they are following new paths "in the search for turbulences". Here they place a heavy grating in the tunnel, which consists of 126 individually moveable panels and flaps. The flaps can be moved in a variety of directions by means of 16 axes, also against one another. This way the researchers try to generate air vortices and reproduce the turbulences that prevail in front of a wind turbine. In conventional wind tunnels there is just an even flow of wind in one direction, which then flows over a rotor blade, for example. This is rather an unrealistic model – reality and nature are wilder.
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12.5.2 Simulation Is Part of Testing

The Witlis (wind turbine lidar simulator, Fig. 12.7) was developed as the preliminary step to creating such a system. The lidar system to be developed

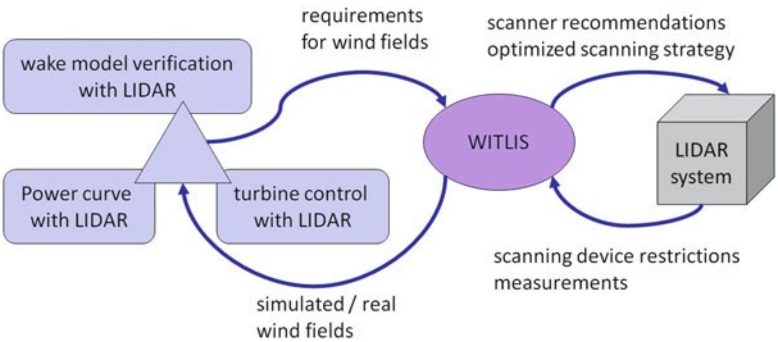

Fig. 12.7 Scanner development concept with Witlis. © SWE University of Stuttgart

should provide wind fields for wake verification, for power curve measurement and for controlling a wind turbine. In other words, very different tasks with rather different requirement profiles: for measuring the wind vortex – the air turbulence behind a wind turbine – you need high-resolution spatial measurements, but for controlling you require rather more high-resolution temporal measurements. And this in turn means the scanning system has to be more flexible.

There is a lot of development potential in the system controller, and there has been a lot of experimentation and trials. For example, a lidar-based controller was compared with a standard controller and checked in ten-minute wind fields. In a second step, Witlis was paired with a commercial aeroelastic simulation tool. In the first trials, virtual tests were made of identified options with considerable (up to 30 %) load reductions of the tower bending moment.

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12.5.3 Like a Smoke Trail – the Wind Loads Behind the Turbine

The wind flow field behind a wind turbine has a considerable impact on the wake – before it reaches the next turbine in the second or third row in the wind farm. Even where the distances between the turbines are greater, only on statistical average does it appear to be like the "even" shadow impact of a building structure. In reality this wind in the wake moves slowly to and fro to the stream – and as "wave meandering" it resembles more the billows of smoke from a tall chimney or the vapour trail behind a large passenger plane! And this "wake" additionally creates an irregular load on the main components of the wind turbine behind.

While an accurate determination of the wake flows of multi-megawatt turbines is desirable, this can only be achieved with elaborate scientific simulation techniques (CFD), which require a lot of computing time. This means that broader industrial use is hardly practical at present.

» We still don't know enough
In recent years there have been huge advances in all areas of wind technology. And yet we still don't know enough. At best, we can only describe the incoming wind flow on to the rotor blades in broad terms. But new knowledge also opens up new possibilities.
Dr. Matthias Wächter, ForWind, Institute of Physics, University of Oldenburg

A simulation model for the dynamics of the wake of multi-megawatt wind turbines was developed during the research project. This Disc Particle Model (DPM) now makes it possible to generate synthetic time series of wakes for the most different atmospheric situations. Great turbulences in the atmosphere that can alter the wind direction shift

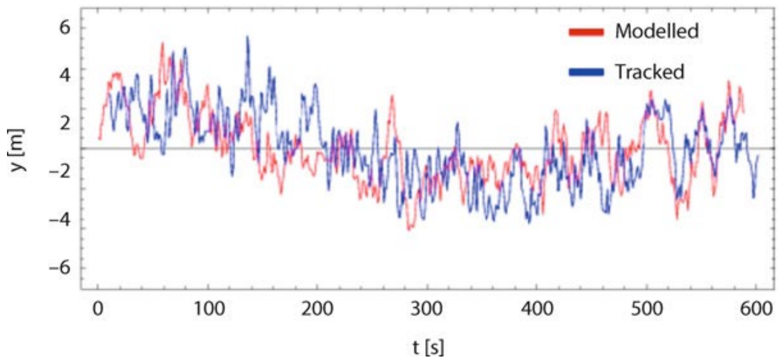

Fig. 12.8 Comparison of modelled (*red*) and measured (*blue*) time series of the wake position. © John Wiley & Sons

the wind wake in lateral and vertical direction – almost like a body. In contrast, smaller turbulences do not alter the wind direction, but do cause a mixing-up of the wake. In science, similar models are used for modelling the distribution of contaminants and toxic gases in the atmosphere. The whole trail of smoke is reconstructed using a large number of particles. The models make it possible to observe the behaviour of the particles and thus also the smoke trails for different atmospheric stratifications.

The wake simulation model that was developed was compared with the real lidar measurements. This showed a large degree of congruence between simulation model and lidar measurements (Fig. 12.8). It also turned out that the lidar instrument measures with higher temporal resolution – in millisecond range – and spatial resolution than conventional anemometers.

These simulation models for wind turbine wake loads need to be developed further. By taking better account of the wind wake behind the first row of turbines it would be possible to develop recommendations for improved positioning of the turbines in the second or third rows of a wind farm.

12.6 Quo Vadis? New Offshore Measuring Method and FGW Guidelines

The results with the new ground-based lidar measurements mean that it is possible to use the ground-based lidar system along with a reference mast to measure the power curve. This has been included in the IEC norm and the corresponding Federation of German Wind Power (FGW) directive. As far as the nacelle-based results are concerned, they also have some influence on the FGW guideline activities, and the same goes for the non-stationary power curve measurements. The experiences gathered from the lidar research will be made available to the entire wind industry.

12.7 When the Nacelles Have Lidar

A start has been made with the Lidar I research project, but lidar work continues. In the near future we can expect to see multi-megawatt turbines with output capacities of 10 MW and more. Ten-megawatt wind turbines will have rotor diameters of around 250 m, with a swept area the size of five football pitches. Such power plant scale turbines require new, adapted control and monitoring strategies. Here it will be crucial to reduce the enormous wind loads effectively and under minimum use of control systems. The goal is to feed their generated electricity into the grid with an already optimised yield while thereby being able to identify small deviations from intended normal operation early on.

12.7.1 Modern Control Systems First React upon Wind Impact

Despite many advances in all areas of wind energy technology, this vision faces one fundamental obstacle: there are too many uncertainties and too little knowledge about what can at best be described as statistical inflow onto the swept rotor area. And the current control concepts for wind turbines can only react to changes in the incoming wind field which have already provoked rotor speed or load changes.

In assessing the average or momentary output it is unclear which wind conditions on the special site in the wind farm have caused them. A precise variance analysis is therefore impossible.

The follow-up research project Lidar II "Development of nacelle-based lidar technology for the measurement of power performance and the control of wind turbines" should develop several technological components.

12.7.2 Robust and Suitable for Industrial Use

One of the main goals of the project is to continue to develop a lidar system for nacelle-based use on wind turbines that is "robust, cost-effective and suitable for industrial use". The series price of the new instrument must be competitive with the ultrasound anemometer technology used to date. Ideally it would be best to integrate the lidar in the spinner of the wind turbine, but if necessary it could also be mounted on the roof of the nacelle. Here it would be necessary to use modern, reliable components to guarantee low-maintenance automated operation all-year round. A prototype could be tried out in Alpha Ventus within the scope of the project. The "commercialisation" of the new device starts now, straight after the completion of the project in 2015 – in other words: marketing and preparations for series production.

Based on the nacelle-mounted lidar wind measurement, other methods were also developed during the project, which meet the requirements for power curve measurement in accordance with the international IEC guideline (IEC 61400-12) and at the same time determine the dynamic performance characteristics in the fast 1-Hz range. Result: the direct measurement of the incoming wind using a nacelle-based lidar leads to a shortening of the measuring time necessary for determining the power curve and to a significant reduction of uncertainties about the incoming wind field. Lidar instruments are not of course to be seen as a total substitute for the nacelle-mounted anemometers normally used today, because in a very few weather conditions – such as snowfall – lidar measurements are not possible and it is necessary to fall back on conventional sensors. Lidar devices can however measure and process important information about the incoming wind field faster and more accurately – before the wind field has reached the wind turbine. Because, as opposed to permanent, continuous laser beams, pulsed laser "points" enable multiple measuring distances simultaneously as well as a constant measurement volume, the project decided to use the pulsed lidar method.

For examining the stationary performance and yield potential the lidar scanner that was developed was tested offshore on the nacelle of a Senvion wind turbine in Alpha Ventus – on turbine AV4 on the north-western edge of the wind farm. The location had the advantage of being a distance of 400 metres (corresponding to 3.2 times the rotor diameter) to the Fino 1 research platform and its wind measurement data could be used immediately for comparison. Due to the device not being watertight and the resulting water penetration there were several hardware breakdowns during the four measurement campaigns. The measuring period was therefore extended into the spring of 2015 so that the planned measurement campaigns could be successfully completed.

12.7.3 Collective "Blade Feed Forward Control" Before the Wind Hits?

In the continued lidar project a monitoring method was developed that enabled continuous monitoring of the performance behaviour. A more precise, early regulation of a wind turbine with a nacelle-mounted lidar system can also increase the energy yield – by means of a more exact wind realignment and improved speed control. But first and foremost the lidar system should significantly reduce the extreme and fatigue loads of wind turbines. Trials and experiments were carried out here as well in order to develop and test the most suitable control strategies.

The favourite by far is a control concept for collective blade angle feed forward control that, thanks to lidar measurements, receives the necessary information about the incoming wind field and can thus proactively intervene as the situation demands. In a complex process a lidar feed forward control was successfully developed and simulated for an Adwen wind turbine (Turbine AV7 in the wind farm). This demonstrated that with the collective blade angle feed forward control there could for example be a load reduction of up to 20 % on the tower. Whether the feed forward control is largely used for load reduction, for positioning activity or speed variability, depends mainly on the decision of the wind turbine manufacturer when designing "his" turbine. A more complex individual blade feed forward control was also developed during the project, which however only offers minor advantages over the collective blade feed forward control.

At the end we have here a technology transfer of research results from Alpha Ventus to the entire German wind industry, especially to the technical committee conference of the Federation of German Wind Power (FGW) – and significantly beyond. As a result we now have "Wind Task 32" of the International Energy Agency concerned with "wind lidar systems for wind energy development", which in the meantime deals with eleven lidar topics, ranging from wind field reconstruction to nacelle-based power curve measurement. The know-how transfer is in full swing.

12.8 Sources

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